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Haptic and visual perception of roughness

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Abstract

In this study, we are interested in the following two questions: (1) how does perceived roughness correlate with physical roughness, and (2) how do visually and haptically perceived roughness compare? We used 96 samples of everyday materials, such as wood, paper, glass, sandpaper, ceramics, foams, textiles, etc. The samples were characterized by various different physical roughness measures, all determined from accurately measured roughness profiles. These measures consisted of spectral densities measured at different spatial scales and industrial roughness standards (R_a, R_q and R_z). In separate haptic and visual conditions, 12 naïve subjects were instructed to order the 96 samples according to perceived roughness. The rank orders of both conditions were correlated with the various physical roughness measures. With most physical roughness measures, haptic and visual correspondence with the physical ordering was about equal. With others, haptic correspondence was slightly better. It turned out that different subjects ordered the samples using different criteria; for some subjects the correlation was better with roughness measures that were based on higher spatial frequencies, while others seemed to be paying more attention to the lower spatial frequencies. Also, physical roughness was not found to be the same as perceived roughness.

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1. Introduction

In the haptic perception of materials, roughness is a very important parameter, as was shown by a number of multi-dimensional scaling experiments (e.g., Bergmann Tiest & Kappers, 2006; Hollins, Faldowski, Rao, & Young, 1993; Picard, Dacremont, Valentin, & Giboreau, 2003). However, in daily life, most objects are perceived first and foremost visually (Schifferstein, 2006; Schifferstein & Cleiren, 2005). This means that, often, perception of the surface properties of an object is based on visual information. Since roughness is such an important surface property, both the visual and haptic systems must be able to perceive it. Therefore, it might be interesting to see how these two systems compare to each other in terms of correspondence with instrumentally measured, objective, roughness.

Most of the relevant literature is summarised in Lederman and Klatzky (2004). The relationship between visual and tactual material perception was pioneered by Binns (1936) using wool samples, although he looked at the parameters of softness and fineness. He let subjects put six wool standards in order using vision or touch. No clear difference in performance was found between the two modalities. Later, there have been a number of studies that specifically looked at roughness perception in vision and touch. Most used sandpaper stimuli (Björkman, 1967; Heller, 1982; Jones & O'Neill, 1985; Lederman & Abbott, 1981; Rexroad & White, 1987), but also wood (Brown, 1960) and fabric (Guest & Spence, 2003) have been used. A basic question is, which modality is better at roughness perception? The answers have not been unanimous in the case of sandpaper stimuli: In a matching experiment with seven standard samples and four subjects per condition, Björkman (1967) found somewhat smaller variances in the visual condition than in the tactual condition. In contrast, no difference in visual, tactual and combined roughness perception was found for sandpaper in a matching task with 12 subjects and nine samples, and a magnitude estimation task with six subjects and 11 samples (Lederman & Abbott, 1981). In these experiments, subjects were unable to see their own hand touching the samples in the combined condition. This fact was found to be significant by Heller (1982), who, in contrast, observed superior performance in the combined condition in a discrimination task with 10 sandpaper samples. Superior performance was maintained in a condition where the hand movements could be seen, but the sample texture could not. From this, it was concluded that the higher performance was a result not of the combination of visual and tactual roughness information, but of the visual guidance of the hand during tactual exploration. Superior performance in the combined condition was confirmed in a discrimination experiment with 42 subjects and six sandpaper samples (Rexroad & White, 1987). However, in a discrimination and a same/different experiment with 45 subjects and 10 sandpaper samples by Jones and O'Neill (1985), the performance in the combined condition was found to lie between the visual and tactual performance, while the three were very close together. In short, differences in performance between the modalities in the sandpaper experiments were not always found, and when they were found, they were small.

The experiments with other types of stimuli seem to agree with this finding of very little difference between the modalities: Brown (1960) asked 41 subjects to make pairwise comparisons of nine wood samples in several visual, tactual and combined conditions. Performance was expressed in terms of surface irregularity, as measured with an electronic instrument. For skilled subjects, there was no difference between tactual, combined and visual conditions with oblique lighting. Also, in roughness discrimination of textiles, no difference between tactual and visual perception was found in an experiment with 10 subjects and four fabric samples (Guest & Spence, 2003).

The consensus seems to be that the visual and haptic systems are equally good at perceiving roughness. This is somewhat surprising since roughness might be thought of primarily as a haptic material property. The term 'haptic' is used here since its meaning comprises both the cutaneous and kinaesthetic senses, and both sources of information are available when a material is touched dynamically. But the question remains whether the equality of both modalities is due to the limited scope of the materials used in the experiments. How would subjects' performance in the two modalities compare when a stimulus set was used that varied in more respects than just roughness? What aspects of the material are subjects paying attention to when assessing roughness? It has been suggested that perceived roughness is related to the spatial density of the features on the surface. In experiments with artificially created raised dot patterns, the bias towards either modality depended on whether the subjects were asked to judge roughness or spatial density (Lederman, Thorne, & Jones, 1986). This indicates that, although it may contribute to the perception of roughness, spatial density is not identical to perceived roughness. Wall and Harwin (2001) investigated the relationship between spatial density and perceived roughness in virtual textures, but found both positive and negative correlations in both modalities, indicating that virtual textures may be unsuitable for this kind of experiment.

So far, we have discussed perceived roughness. Physically, however, roughness can be expressed in a number of ways, which are all based on the amount of height difference on the surface. These height differences can occur at different spatial scales. The term 'roughness' is therefore not unambiguous, even in the physical sense. Furthermore, it may be that the perception of roughness is not only limited to just physical roughness, but also includes other physical aspects, such as friction. In mechanical engineering, a number of standards have been defined to specify roughness. They are used to specify the maximum roughness of, for example, machine parts. Which standard to choose depends on the application (e.g., Kalpakjian & Schmid, 2001). It is not known which of these physical roughness definitions, if any, agrees with the perception of roughness, be it visual or haptic.

Although the results of earlier experiments have been consistent, they have been limited to a single type of material (wool, wood, sandpaper or textile). The perception of roughness (visual or haptic) within the context of a wide range of materials has not yet been studied. Therefore, as a first step, we have performed an experiment in which a large number of different materials were to be ordered in a sequence of increasing roughness, both visually and haptically.

2. Method

The experiment consisted of having subjects arrange material samples in the order of increasing perceived roughness in a haptic and a visual condition. We did not use the combined condition, so that the same subjects could participate in both conditions. In a combined condition, they could form a relationship between the visual and haptic roughness of this particular stimulus set, which might have influenced the result in the other conditions.

2.1. Materials

The 96 materials were a subset of the materials described in Bergmann Tiest and Kappers (2006). The set comprised a wide range of materials, such as woods, ceramics, cloths, plastics, glass, metals, abrasive materials, paper, cardboard, foams, rubber, felts, etc. These were cut into squares of 10×10 cm and mounted on a medium density fibreboard (MDF). The set was designed to provide the widest possible range in roughness of materials encountered in daily life. Apart from roughness, the materials also varied in other dimensions such as compliance, friction, thermal conductance, colour and reflectance. Of the stimulus set described in Bergmann Tiest and Kappers (2006), 24 of the smoothest materials were left out because their difference in haptically perceived roughness was found to be below threshold in pilot experiments. Some other, anisotropic, materials were not used because their perceived roughness depended on the direction in which they were felt. There still remained some anisotropic stimuli in the set, but it was found that the direction of feeling (e.g., parallel to the yarns of a fabric or at an angle) did not influence the sensation.

Of all materials, a surface profile with a length of 10 mm was obtained using a profilometer. The spacing between the points in the profile was 1.5 μm, resulting in 6666 height measurements for each material. From these surface profiles, several physical roughness measures can be calculated. Firstly, a power spectral density was calculated from each profile using a windowed Fourier transform procedure. From the spectral density, averages were extracted of three 0.20 mm^{-1} wide-frequency bands centered around spatial frequencies of 0.10, 1.0 and 10 mm^{-1}. These numbers describe the physical roughness (amount of height differences) at low, medium and high spatial frequencies. Furthermore, a weighted average over the whole spectrum was calculated, where the weighing function was determined through principal component analysis (PCA). This means that the most weight is given to those spatial frequencies at which the stimuli differ the most. This turned out to be mostly at the lower spatial frequencies.

In addition to these spectral roughness measures, a number of industrial standards for specifying roughness were used. In this paper, the measures R_a, R_q and R_z are used, because these are the ones that are the most common in industry. R_a is the mean absolute deviation from the average height, while R_q is the root-mean-square deviation. They are calculated as follows: First, a Gaussian filter with a cut-off length of $\lambda_c = 0.25$ mm is applied to the profiles. This removes the low-frequency 'waviness' from the profiles. Then, with h_i the measured heights after filtering and N the number of measurements, R_a and R_q are given by

$$R_a = \frac{1}{N} \sum_{i=1}^{N} \left| h_i - \overline{h} \right| \tag{1}$$

$$R_q = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(h_i - \overline{h} \right)^2}. \tag{2}$$

Here, $\overline{h}$ is the average height. R_z is found by dividing the profile into five equal portions and averaging the difference between the highest peak and the deepest valley in each portion. R_a is the most basic industrial roughness measure and is largely superseded by R_q, which is a little more refined. These measures are mainly used when a machined part has to satisfy certain visual or tactual criteria. R_z is more sensitive to extremes in the roughness profile and is, therefore, mainly employed when the roughness of sliding parts has to be specified. Owing to the cut-off length used in the Gaussian filter, the industrial roughness parameters depend mostly on the higher spatial-frequency components of the surface profiles.

The physical roughness of the stimuli around $1.0\,\mathrm{mm}^{-1}$ is shown in Fig. 1. The gap where the stimuli were left out of the original set is clearly visible, but the remaining set spans three orders of magnitude of roughness.

2.2. Subjects

Twelve subjects, seven male and five female university students, between 20 and 25 years of age, participated in the experiment. They were paid for their efforts. Before the experiment, they were tested for stereoscopic vision (TNO, 1972) and colour blindness (Ishihara, 1989). One subject had a slight red/green colour deficiency. Two others had no stereoscopic vision. The others had no deficiencies. None of the subjects had any vision problems in daily life, so all were included in the study since we wanted to stay as close as possible to the daily-life situation. The same subjects participated in both conditions, so that a comparison could be made between modalities, as well as with the objective order. Four subjects did the whole experiment twice, to assess intra-subject consistency.

2.3. Procedure

The subjects were instructed to arrange the stimuli in the order of increasing roughness. They were not given a definition of this concept. A few subjects specifically asked the experimenter for this. They were told that roughness referred to the amount of relief on the surface, but more specific instructions were not given. Tables in a classroom were arranged in a square to accommodate the line of stimuli that was almost 10 m in length. The subject was in the middle of the square in a caster chair. On the ceiling, there were rows of fluorescent lights, providing both direct and indirect lighting. The windows in the room were blinded and all lights were on to provide even and reproducible lighting conditions. The light level was that of a normal office. Half of the subjects participated first in the visual condition and then in the haptic condition, and the other half the other way around. In the visual condition, subjects were not allowed to touch the stimuli. The experimenter placed them in the

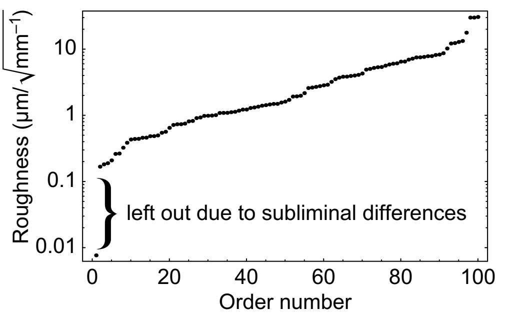

Fig. 1. Power spectral density of the height profile of the stimuli around a spatial-frequency of $1.0\,\mathrm{mm}^{-1}$, in increasing order. The roughness range where stimuli were left out of the original set is indicated.

line according to the subject's instructions. The subjects were allowed to move around and look at the stimuli from all directions. In the haptic condition, the subjects were blindfolded and the experimenter helped them to place the stimuli in the line. The subjects could feel the stimuli as often as they wanted. When they were almost finished, the subjects were encouraged to go over the whole line of stimuli with their eyes or hand. An out-of-place stimulus would then pop out and could be put in the correct place.

The time taken for the visual condition ranged from 18 min to 58 min, and for the haptic condition from 49 min to 90 min. After a short break, four of the subjects repeated the entire experiment in the same order. In this way, there was a visual condition between the haptic conditions, and vice versa. Due to this fact, combined with the high number of stimuli (96), memory effects are expected to be small.

3. Results

3.1. Correlation with physical roughness

The rank order made by the subjects was correlated with the rank order that followed from the different physical roughness measures, using the Spearman rank order correlation coefficient. As an example, the Spearman correlations for the roughness around 1.0 mm^{-1} and for the parameter R_q are shown in Fig. 2. Based on an assumed distribution of the Spearman correlation coefficient using Fisher's z-transform, 95% confidence intervals were estimated. These are indicated by error bars in Fig. 2. Overall, correlations for the 1.0 mm^{-1} case are about the same for the visual and the haptic conditions. A paired two-sided t-test confirms this ($p = 0.32$). This means that subjects perform about equally well visually as haptically, when their ordering is compared with the ordering based on measured medium-frequency roughness. In the R_q case, the haptic correspondence with the physical ordering of one subject (C) is significantly better than the visual, according to a two-sided test and Fisher's z-transform ($p = 0.013$). For the other subjects, visual and haptic correlations are about the same. Over all subjects, the haptic condition had a slightly but significantly better correspondence with the ordering based on R_q than the visual condition (paired two-sided t-test, $p = 0.029$). Also for the 10 mm^{-1} and R_a measures, the difference was significant ($p = 0.041$, 0.012). For the other roughness measures,

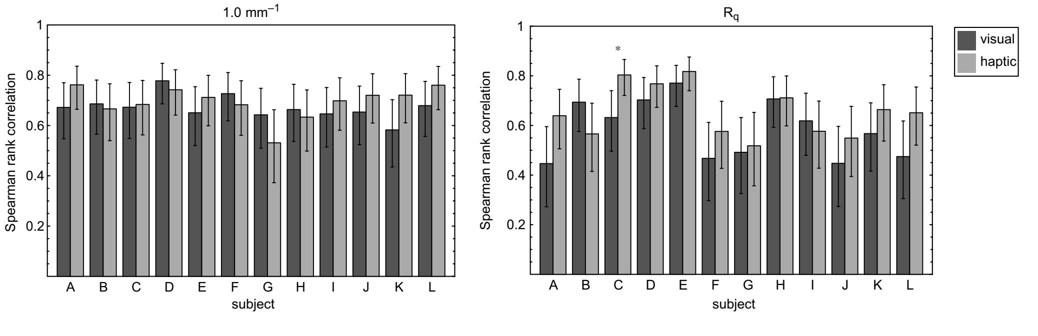

Fig. 2. Spearman rank correlation for the 12 subjects in the visual and haptic condition for the roughness around 1.0 mm^{-1} (left) and the parameter R_q (right). The error bars indicate the 95% confidence interval. The asterisk indicates a significant difference between the haptic and visual correspondence.

it was not ($p > 0.05$). In short, correspondence with the physical ordering was mostly the same haptically and visually, and whether subjects do better in either modality depends on the roughness measure used for comparison. So, which roughness measure do the subjects actually use? In other words: with which roughness measure does the ordering made by the subjects correlate best? This can be seen in Fig. 3, in which the correlation with the various physical roughness measures is plotted for all subjects in both modalities. There is a large

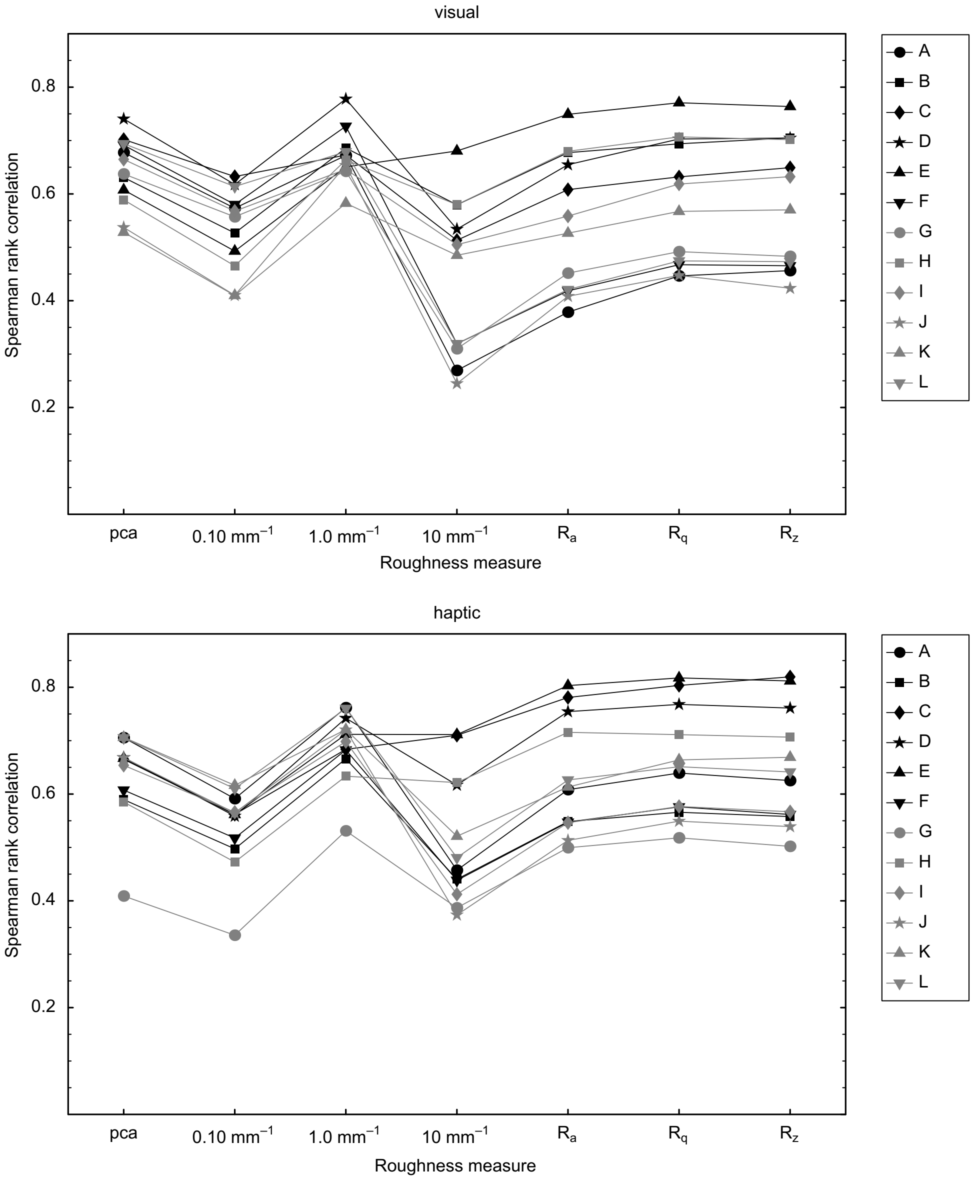

Fig. 3. Spearman rank correlation for all subjects (A–L) and all roughness measures in the visual (top) and haptic (bottom) condition.

spread in correspondence with the physical ordering across the different subjects, but one thing is clear: the order of the subjects, in terms of increasing correspondence with the physical ordering, is almost the same within the three 'low-frequency' roughness measures (pca, 0.10 mm^{-1} and 1.0 mm^{-1}) and also within the four 'high-frequency' roughness measures (10 mm^{-1}, R_a, R_q and R_z). But between these two groups, an interesting reversal occurs: some subjects who score high with the 'low-frequency' measures score lower with the 'high-frequency' measures, and vice versa. In the visual condition, there are some typical 'low-frequency' subjects (A, F, G, J and L) and a 'high-frequency' subject (E). In the haptic condition, the 'low-frequency' subjects are B, F, I and J, while the 'high-frequency' subjects are C and E. It is striking that this division in 'low-frequency' and 'high-frequency' subjects is not the same for the visual and the haptic conditions. Thus, different people use different criteria for judging roughness in different conditions. Subject C, for instance, pays more attention to 'low-frequency' features in the visual condition and more attention to 'high-frequency' features in the haptic condition.

No effects of gender or the order of the conditions were found. The results of the subjects with colour or stereo vision deficiencies did not seem to differ from the other subjects.

3.2. Correlation between conditions

The orderings in the visual and haptic conditions have also been correlated, with results as shown in Fig. 4. For most subjects, the correlation between visual and haptic ordering reflects the similarity between their patterns in Fig. 3. For instance, E shows a very similar pattern in the haptic and visual case in Fig. 3, and also has a high correlation between his visual and haptic orderings. Conversely, G's patterns in Fig. 3 are quite different, which coincides with a low correlation between the orderings. Notable exceptions to this are C and H. While C's patterns in Fig. 3 are very different, her correlation in Fig. 4 is quite high. The reverse seems to be true for H: his patterns are very similar, but the correlation coefficient is not very high. This suggests that at least in some cases, subject's orderings are partly determined by factors other than any of the roughness measures discussed here.

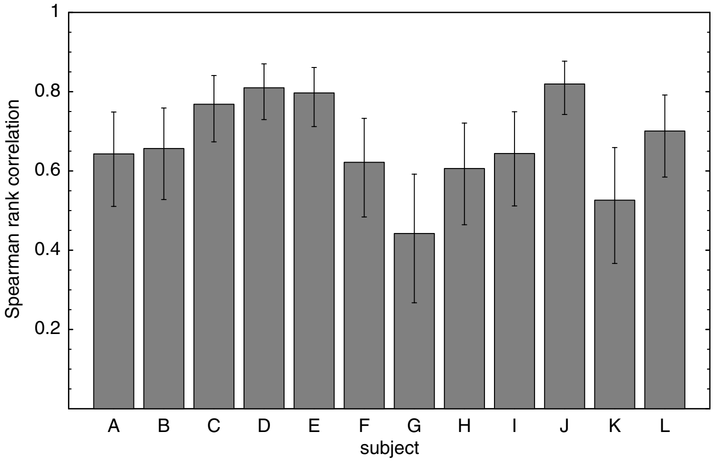

Fig. 4. Spearman rank correlations between visual and haptic conditions. The error bars indicate 95% confidence intervals.

3.3. Inter-subject correlation

The orderings made by the subjects have also been correlated with each other. The Spearman values ranged from 0.40 to 0.87 in the visual condition and from 0.46 to 0.94 in the haptic condition. They are presented visually in Fig. 5. The subjects who show a high correlation with each other are not always the same subjects who show a similar pattern in Fig. 3. So, the fact that two subjects pay more attention to, say, the 'high-frequency' features does not mean that their orderings are more alike.

3.4. Intra-subject consistency

To assess whether the rather low correlations with the physical roughness measures and between modalities were the result of the task being too difficult, the experiment was repeated with four subjects (I–L). If the differences between some stimuli were below the discrimination threshold, then the resulting ordering would be fairly random. If, on the other hand, the subjects showed a high degree of consistency in the repeated task, then we can assume that the orderings are not random but, indeed, are the result of the subject's roughness perception. In Fig. 6, the Spearman correlations between the repeated orderings are shown. Three of these four subjects show a very high correlation ($\geqslant 0.9$) in both modalities. The consistency exceeds their best correlation with a physical roughness measure (horizontal line in the bar) by a large margin. This difference is highly significant for subjects I, J and L ($p \leqslant 0.000068$), but not for subject K ($p = 0.049$, 0.18 for the visual and haptic conditions, respectively). Still, this indicates that in general, there is a low degree of randomness in the subjects' orderings.

3.5. Common misplacements

For each subject and each condition, a top-10 of farthest-misplaced stimuli was made, that is, those stimuli that have the biggest difference between perceived and physical

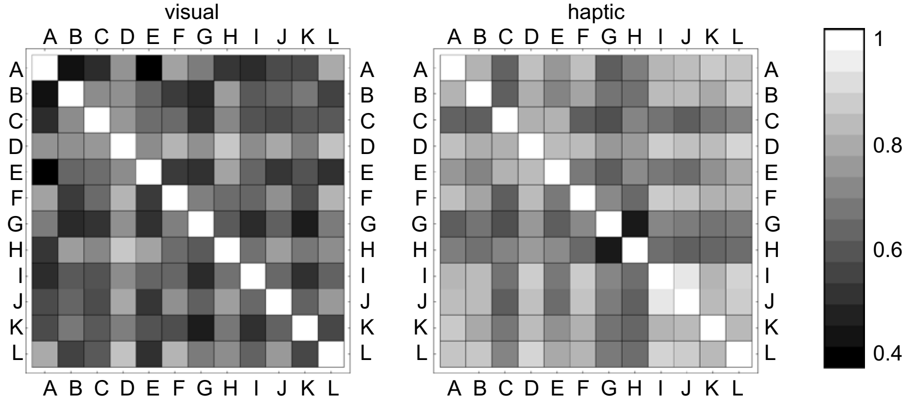

Fig. 5. Spearman rank correlation between subjects in the visual (left) and haptic (right) condition. The data are reflected across the diagonal. All correlations are significant, because they are all greater than 0.4 so the probability of the zero-hypothesis is at most $p = 0.000027$ at $r_s = 0.4$ and $N = 96$.

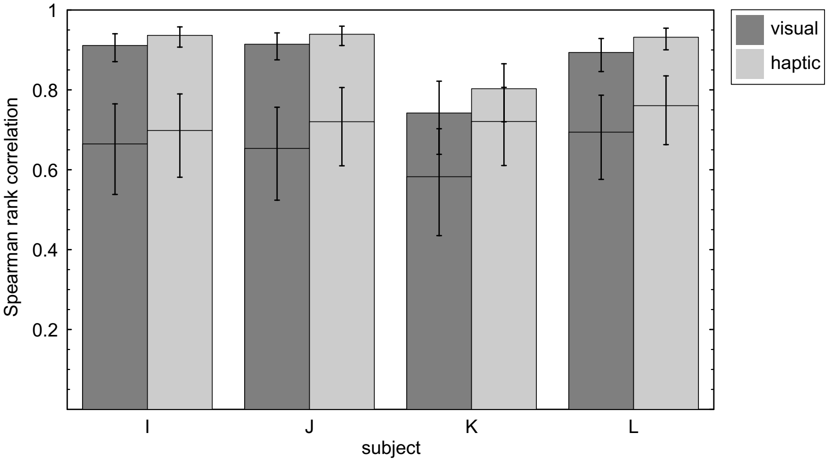

Fig. 6. Spearman correlations between the first and second orderings for the subjects who did the experiment twice. The horizontal line in each bar indicates the best correlation with a physical roughness measure of that subject. The error bars indicate 95% confidence intervals.

roughness rank. For the physical rank, the roughness around $1.0\,\mathrm{mm}^{-1}$ was used. We report here those stimuli that occurred in the top-10s of at least six of the 12 subjects. The numbers in brackets refer to those in the table in Bergmann Tiest and Kappers (2006). In the visual condition, waxed tissue (47) and MDF (100) were judged more rough than measured. MDF consists of fibers which look rough but the finish is smooth. Plastified chipboard (117) was judged more smooth than measured. In the haptic condition, the PE glove (26), some fine sandpaper (62, 63) and the structured floor tile (124) were judged more rough than measured. The fine sandpaper does not have a lot of relief (physical roughness), but causes a lot of friction when stroked. This friction may have contributed to the perception of roughness. The structure on the floor tile is very large-scale, and in the physical sense is part of the shape, but it might have influenced subjects' roughness judgement. Thin rubber foam (45) and bumpy adhesive plastic (101) were judged more smooth than measured. The foam is soft, which may have influenced the roughness judgement.

Using a similar procedure, the orderings in the two modalities were compared. In this analysis, waxed tissue (47) was haptically judged smoother than visually. A sanding cloth (60) and the fine sandpapers (62, 63) were visually judged smoother than haptically. The small grains are hard to see, but they cause a lot of friction when stroked. This might have influenced the haptic roughness judgement.

When asked what they were paying attention to while assessing roughness, subjects mentioned the number, size and depth of indentations, the shininess or dullness and colour of the material, recognising the material and using prior experience, the presence of finger marks or dull spots, the amount of relief when looked at from the side, and the coarseness of the pattern in the visual case. In the haptic case, they mentioned the presence of irregularities, ridges or bits of fluff, whether they could depress the surface, the structure and size of the irregularities, the presence of fine or coarse bumps, whether the material was hard or soft, and whether the fingers slid easily over the surface.

4. Discussion and conclusions

Although repeated measurements were only done for four of the 12 subjects, we can conclude from the high consistency that the orderings, indeed, reflect the perceived roughness of the materials. However, there is apparently not a single *physical* roughness measure that best describes what is *perceived* as roughness. Some subjects' perception agrees more with roughness measures that depend mostly on the high spatial frequencies, while with others the stronger agreement is with roughness measures that depend mostly on the lower spatial frequencies. This illustrates once more that roughness is a very subjective perception. Not only is roughness as a perception different from physical roughness, but also is different for different people. This is also emphasised by the inter-subject correlations that are not strikingly high in most cases.

Since, for most subjects, the correlation between the two conditions is of the same level as their best correlation with a physical roughness measure, we can say that while subjects have their own picture of what is meant by 'roughness', this picture is maintained between conditions. So, to a certain extent, they have defined roughness for themselves independent of the modality in which it is perceived. Judging by the correlations with physical roughness that are quite low for some subjects, this personal definition is different from the physical definition of roughness, i.e. the amount of height difference on the surface. This is consistent with the findings in Bergmann Tiest and Kappers (2006). In that experiment, we analysed the results of a free sorting task using multi-dimensional scaling. It turned out that physical roughness was not aligned with a single dimension in the material space, but rather followed a curved trajectory. The personal definition of roughness may include other aspects, such as friction (Smith, Chapman, Deslandes, Langlais, & Thibodeau, 2002), spatial density of surface features (Lederman et al., 1986) or softness. The perception of roughness may, therefore, be thought of as multi-dimensional in its own right. In that respect, what we have asked of our subjects in the present experiment is, in fact, an exceedingly difficult task. They had to reduce their multi-dimensional roughness impression to a one-dimensional ordering. In this view, it is not surprising that different subjects make different choices for this reduction process.

Of the three frequency bands (0.10, 1.0 and 10 mm^{-1}), the 1.0 mm^{-1} band has the highest correspondence with the subject's ordering for all, but one subject in each condition. So, when we look at just the frequency characteristics of roughness, the medium-frequency band is the most important in judging roughness, both visually and haptically. In the haptic case, this spatial-frequency of 1.0 mm^{-1} is in line with the tactile spatial resolution of the finger, being a spatial period of 1.9 mm. This threshold was measured in a grating orientation discrimination experiment (Van Boven & Johnson, 1994). Although it was measured using static touch, it is indicative of the spatial scale at which tactile perception starts to become more difficult. It is imaginable that when assessing roughness, observers pay the most attention to the smallest features that are still comfortably perceived. Larger features are considered to be more part of the 'shape' of the stimulus instead of the roughness, while smaller features are hard to discriminate. In the visual case, an analogous threshold is not specified in terms of a length scale but as an angle. A typical visual acuity is about $5'$, which corresponds to about 0.2 mm at a viewing distance of 30 cm. Thus, features at a length scale of 0.2 mm are at or below threshold in a normal viewing situation. It is, therefore, not surprising that also in the visual case, observers choose a somewhat larger spatial scale in the order of 1.0 mm to pay the most attention to. The fact that there is still some correlation with the 10 mm^{-1} band, even though the information in this band is not easily accessible by vision or touch, might be explained by a correlation between the different bands. The Spearman rank order correlation of the 1.0 mm^{-1} band with the 10 mm^{-1} band was 0.66. So, the two bands are not independent, and this may explain part of the observed correlation of the subject's ordering with the high-frequency band.

In the consistency measurements with the last four subjects, it is striking that for each subject, the consistency in the haptic condition is slightly higher than in the visual condition. This suggests that in the visual case, there were a few more stimuli that could not be discriminated in terms of roughness and had to be randomly ordered. Apparently, the haptic roughness discrimination threshold for everyday materials is slightly better than the visual. This does not seem to be in agreement with the experiments with just a single type of material (Björkman, 1967; Guest & Spence, 2003; Heller, 1982; Jones & O'Neill, 1985; Lederman, 1981). Evidently, the presence of different kinds of material confuses the visual system more than it does the haptic system. This is an important point to keep in mind when drawing conclusions based on experiments with just one type of material.

A surprising finding is that the visual correspondence with the physical ordering is approximately of the same level as the haptic correspondence. We had expected roughness to be very much a haptic material parameter, when studied in the context of a wide variety of materials. But in general, the correlations turned out to be about the same, although the haptic task took more time. But since there was no time limit, we must assume that subjects did the best they could in both modalities. Therefore, regardless of the time taken, their performance in both modalities is at a maximum and can be compared in a fair way. A number of explanations can be conceived for the near equality of the two modalities. The first hypothesis is that roughness is indeed a haptic perception, but in the visual condition the material is recognised and its roughness, as experienced haptically before in daily life, is retrieved from memory. The second hypothesis is that the visual system is capable of directly judging roughness of materials, almost as accurately as the haptic system, for instance, by determining the surface microstructure of the material. To make a distinction between these hypotheses, one would like to perform an experiment with two stimulus sets; one consisting of very familiar materials and the other of very unfamiliar materials. If the first hypothesis were correct, then visual and haptic agreement in the first set would be much better than in the second. If the second hypothesis were correct, then visual and haptic agreement would be about equal. However, it is difficult to determine a priori which materials might be unfamiliar to a subject. Using virtual textures is also not an option as long as they cannot correctly convey all aspects of perceiving a surface, especially in the haptic domain. At present, aspects such as skin displacement through friction or heat transfer into the material are not represented in haptic interfaces. For the time being, we speculate that both hypotheses play a role in the process of judging roughness.

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