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Haptic discrimination of paper

Ian R. Summers, Richard J. Irwin and Alan C. Brady

Introduction

This chapter describes a study on the haptic discrimination of different types of plain paper. The experiment is designed to replicate features of a 'banknote' scenario in which it may be possible to identify a counterfeit on the basis of only a few seconds contact. Multidimensional scaling (MDS) techniques are used to investigate the perceptual dimensions involved in the discrimination task. A related study of tactile perceptual space is summarised in Appendix 1.

It is an everyday experience to handle paper – turning the page of a book, opening mail, handling a banknote – and it takes only a short time to assess the paper in terms of its characteristic 'feel'. (See Lederman and Klatsky's investigation [1] of manipulation strategies for obtaining information about objects in general.) The present study investigates some of the perceptual processes which are involved in making such assessments, particularly in relation to features which are significant in the handling of banknotes. (In the United Kingdom, the distinctive feel of banknotes is officially recommended as an indicator for the detection of counterfeits, and there is anecdotal evidence that counterfeits may indeed be detected in this way.) Such features might include gross physical parameters such as paper thickness and stiffness, as well as parameters which relate to surface texture.

There have been few previous studies on the perception of thickness or stiffness for material in the form of thin sheets. Thickness discrimination might in principle be based either on direct perception of thickness (for example, when holding a sheet between finger and thumb, in terms of joint angle) or on perception of stiffness (which is determined both by the thickness of sheet and the mechanical properties of the material). Such discrimination has been investigated by John, Goodwin and Darian-Smith [2] and Ho [3]. The author of the latter study proposed an explanation of results from both investigations on the basis that, when sheets are sufficiently thin to deform under finger contact, thickness discrimination is based primarily on perception of the curvature of the deformed sheet.

The majority of published material on tactile perception of surface texture concerns the response to well-defined artificial surfaces such as gratings [4–6] or embossed patterns [7]. There are a few studies involving the surface texture of everyday objects, which is often difficult to describe objectively. In an early study, Katz [8] describes an experiment on the tactile discrimination of 14 types of paper (chosen with a wide range of properties and each intended to be clearly discriminable from the others) and develops the concept of *Modifikationen* (qualities), which provide scales on which surfaces may be rated. Hollins, Faldowski, Rao and Young [9] studied the dimensionality of 'natural' tactile stimuli such as wood, sandpaper, velvet, etc., and suggested that three perceptual dimensions were involved: one corresponding to roughness/smoothness, one to hardness/softness and a third tentatively ascribed to 'springiness'. In further studies [10–12], Hollins and co-workers have provided evidence for a sticky/slippery dimension, and demonstrated the role of Pacinian corpuscles in the tactile perception of surface roughness. In an experiment involving discrimination of a very wide range (124 types) of flat surface, Tiest and Kappers [13] identified four perceptual dimensions, none of which was well matched to measured values of surface roughness or surface compressibility.

In the case of paper, although it is possible to characterise the surface by means of a range of parameters such as mean height of surface features, typical separation of surface peaks, etc., it is not easy to predict how these parameters will contribute to aspects of perceived surface texture. Lyne, Whiteman and Donderi [14] found three main factors which influenced the perceived quality of paper towelling – rigidity, surface softness and embossment pattern. However, the tactile features of paper towels are rather different from those of the typing or photocopying paper used in the present study.

The literature also contains a variety of studies relating to 'fabric hand', i.e., the way in which a textile may be evaluated in terms of its characteristic feel. Kawabata [15] relates fabric hand to various measured properties of the textile: tensile properties, shearing and bending properties, thickness and compression properties, surface roughness and surface friction. Picard, Dacremont, Valentin and Giboreau [16] describe experiments which suggest a four-dimensional perceptual space for textiles stretched over a flat support.

The present study was designed to replicate some features of a 'banknote' scenario in which it is necessary, when handling a sequence of notes, to identify a counterfeit on the basis of only a few seconds contact (and generally without the advantage of comparing two notes directly). The intention was to investigate a set of relatively similar stimuli, with a view to establishing which aspects are important for discrimination of small differences between papers. Subjects were required to handle rectangles of various types of paper, each for a few seconds. The rectangles were presented in sequences of three, in an 'odd-one-out' task. Discrimination scores between the various papers were obtained, as the basis for constructing a multidimensional perceptual space for the papers. Broadly similar experimental strategies are described by Hollins, Bensmaia, Karlof and Young [10], involving tactile investigation of a wide range of everyday surfaces, and by Cooke, Steinke, Wallraven and Bülthoff [17], involving haptic exploration of object shape.

Method

Subjects were 12 unpaid volunteers: graduate students in the age range 22–27, nine male and three female. Two of the males were left-handed; the remainder of the subjects were right-handed.

Each stimulus was a rectangle of paper with dimensions 135 mm × 69 mm, corresponding to the size of a common UK banknote. Stimuli were produced from different types of plain white paper – one of these was rag paper of the type used for banknotes (in an unprinted state and consequently with somewhat different handling properties to actual banknotes) and the rest were intended for typing or photocopying, acquired from several stationery stores. 28 different types of paper were considered; ten were discarded after an initial inspection because of various anomalies, such as large surface features related to the watermark. From the remaining 18 papers, ten which appeared in an informal assessment to be perceptually similar were selected for use, including the rag paper. (Similar papers were selected in order to focus on the known acuity of discrimination in this context; this choice also facilitates the determination of discrimination indices d', as described below.) The selected papers varied in thickness from 98–131 μm and in area density from 73–102 gm m^{-2}. A large number of rectangles were prepared from each of the ten selected papers.

Procedure

The experiment used an 'odd one out from three' format with a three-alternative forced choice (3AFC), in which three samples of paper were presented in sequence to the subject, two being of the same type and the other of a different type. Subjects were instructed to pick up each sample with one hand (from a tray on which the experimenter had previously placed the required type of paper rectangle), pass it to the other hand, and then put it back down on the tray. No direct comparison between two papers was permitted and approximately one or two seconds was allowed for the complete operation. Subjects responded verbally to indicate which of the three papers in each trial was the 'odd one out'. It is clear that short-term memory of tactile stimuli may play an important part in such a task. This aspect of memory has been investigated by Bowers, Mollenhauer and Luxford [18], who found that accuracy for texture recollection was very high, suggesting that memory effects are not a major consideration in the present investigation.

Auditory and visual masking was present throughout testing, using white noise *via* headphones and opaque goggles, to ensure that only tactile cues were available. In a brief (around 10 min) familiarisation period in advance of the testing, subjects were allowed to perform the task without masking in order to become accustomed to the exact procedure, with feedback being given to correct any errors in procedure or timing.

Subjects were instructed to carefully wash and dry their hands prior to participating in the experiment in an attempt to minimise inter-subject variation in skin conditions. Air humidity and temperature in the test room were monitored to ensure that testing was not carried out under extreme conditions which might affect the paper characteristics (since paper is hydrophilic) or the subject's skin conditions (as a result of perspiration). Values recorded were typically on the order of 22°C for temperature, and 26% for humidity.

Each trial (i.e., each sequence of three papers) involved discrimination of a particular pair of papers. Each test block consisted of 45 trials – one for each of the 45 possible pairs available from the ten types of paper, with the sequence of pairs varied from subject to subject to avoid any order effects. Each subject completed four test blocks. Hence pooled data from all 12 subjects include results from 48 trials for each of the 45 pairs of papers. There are six possible patterns for a single trial with a given pair of papers (ABB, BAB, etc.), and the sequence of patterns within the test blocks was permuted so that all patterns were equally represented in the trials for a given pair of papers.

Results

Overall discrimination scores for the various paper pairs range from 15/48 to 47/48, i.e., from just below the chance score of 33% to just below the maximum score of 100%. Mean scores for each subject over all paper pairs range from 51–78%, with no obvious anomalies in terms of particularly good or particularly poor performance. The mean score for all subjects over all paper pairs is 67%, with a standard deviation of 8%, this moderate overall performance reflecting the initial selection of perceptually similar papers.

MDS procedure

Tables produced by Craven [19] were used to convert the percent-correct discrimination score for each paper pair to a corresponding value of discrimination index d'.

Perceptual spaces of various dimensions were constructed for the ten papers using multidimensional scaling (MDS) techniques [20]. For a given dimensionality, points corresponding to each paper were positioned within the space so that their Euclidean interpoint distances d_{ij} matched the corresponding inter-paper discrimination-index values d'_{ij} as closely as possible. The optimum configuration was obtained by minimising the stress [21], defined by:

$$\text{stress} = (\Sigma[d_{ij} - d'_{ij}]^2 / \Sigma\, d'^{2}_{ij})^{0.5} \qquad (1)$$

where the summations are over all pairs of points. (The stress is the r.m.s. error for the configuration divided by the r.m.s. value of the 'target' interpoint distances d'_{ij}.)

It should be noted that this procedure, in contrast to many MDS techniques (e.g., [21]), produces a configuration whose interpoint distances are matched to the experimental data in terms of magnitude rather than in terms of rank order only, and hence a configuration whose interpoint distances *d* directly correspond to discrimination index *d′*.

Optimisation was achieved using a purpose-written iterative computer program which, starting from a random initial arrangement of points, moved each point in turn in a direction that reduced the stress. In this way the configuration homed in on a stress minimum – local minima were excluded by running the program from a wide range of initial conditions.

By repeating this procedure for spaces of different dimensions, it is possible to find the minimum number of dimensions which adequately fit the data. In this case, values of stress for one, two, three and four dimensions are 0.264, 0.124, 0.118, and 0.118, respectively, indicating that two dimensions are sufficient to fit the data (since the stress in three or more dimensions is not appreciably lower than in two dimensions). The optimised configuration of papers in the two-dimensional space is shown in Figure 1(a). (The plot is shown with an arbitrary displacement and rotation – neither the absolute displacement of the configuration nor its absolute angular position is constrained by the MDS procedure. A convenient choice for the absolute angular position is suggested below.)

The robustness of this configuration with respect to variability in the data was checked by randomly dividing the subject group into two subgroups of six subjects, and calculating two-dimensional configurations for each subgroup, shown in Figure 1(b) and Figure 1(c). It can be seen that there are no significant discrepancies between the two configurations obtained, and both are very similar to the Figure 1(a) configuration for the complete dataset. This suggests that the principal features of the configuration in Figure 1(a) do not derive from random variations in the data but are indeed 'real' features.

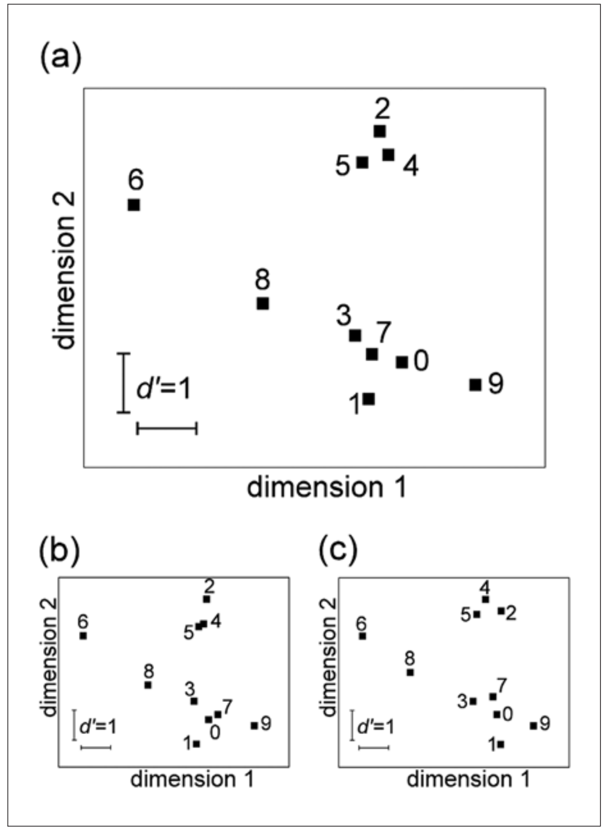

FIGURE 1.
Minimum-stress configurations for the ten papers in a 2-D perceptual space: (a) derived from data for all 12 subjects; (b) derived from first subgroup of six subjects; (c) derived from second subgroup of six subjects. The overall orientation of the configuration (i.e., with respect to displacement and rotation) is arbitrary.

The fact that each of the two subgroups of subjects produces a similar perceptual space may indicate that all subjects used similar tactics to discriminate the papers, i.e., they made use of similar perceived aspects of the papers. To investigate this point further, the distribution pattern for correct responses over the 45 paper pairs was determined for each subject. Cross correlation between these patterns produces a measure of the similarity between individual subjects in respect of answer patterns, from which it is possible, using similar MDS techniques to those already applied to the *d′* data, to construct a two-dimensional 'subject space' (in which the interpoint distances correspond to inter-subject dissimilarity in respect of answer patterns). The configuration of subjects in this two-dimensional space shows a single cluster of points – there is no evidence of distinct subgroups of subjects within the configuration. This reinforces the above suggestion that all subjects used similar tactics for the discrimination.

It is implicit in the above analysis that d' values add vectorially within a perceptual space. Green and Swets [22] suggest that this should in general be the case, and data from Figure 1(a) are consistent with this – comparison of the interpoint distances d_{ij} with the 'target' distances d'_{ij} shows no obvious trend to suggest that a non-linear transformation of the d' data would produce a better-matched configuration in perceptual space.

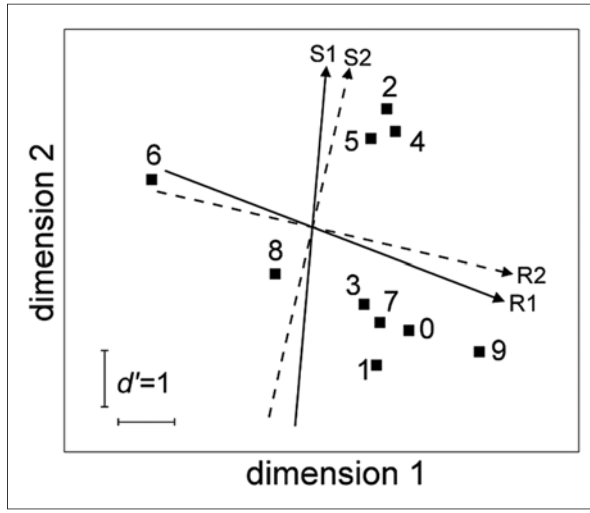

Figure 2.
The minimum-stress configuration for the ten papers, showing the directions R1 and S1 (full lines) onto which the configuration can be projected to give the best match to mean roughness rank and mean stiffness rank, respectively. Also shown are the directions R2 and S2 (dotted lines) which give the best match if orthogonal directions are specified. The overall orientation of the configuration (i.e., with respect to displacement and rotation) is arbitrary.

Interpretation of MDS findings

The MDS analysis suggests that discrimination of these papers is dominated by two perceptual dimensions. It was hypothesised that these dimensions were roughness and stiffness – informal comments offered by subjects after the testing often mentioned these attributes as giving important cues.

In order to test this hypothesis, a subsidiary experiment was carried out to establish subjects' estimates of roughness and stiffness for the ten papers, with a view to correlating these estimates with the perceptual space of Figure 1(a). Subjects were presented with samples of each of the ten papers and asked to arrange them in a row on a table, first in order of roughness and then in order of stiffness. (They were told that they could take as much time as they wanted to complete the task, and that they could compare the papers in any way that they thought necessary. They were also able to re-assess their initial orderings and make modifications.) In contrast to the main experiment, this subsidiary experiment was carried out without auditory or visual masking. Visual masking was removed because it would have seriously complicated the task of arranging the papers in rank order. Auditory cues were minimal in practice and so it was decided to also remove the auditory masking. A potential concern is that the multimodal assessments in the subsidiary experiment might not correlate well with the haptic-only assessments in the main experiment. However, comparison of the results from the two experiments (see below) shows a good correlation, suggesting that essentially the same aspects of roughness and stiffness are involved in the two experiments.

The participants in the subsidiary experiment were ten of the original 12 subjects (two were unavailable). For each paper, the average rank for roughness and the average rank for stiffness was calculated over the subject group. This procedure achieved a good separation of the papers giving mean values for roughness rank in the

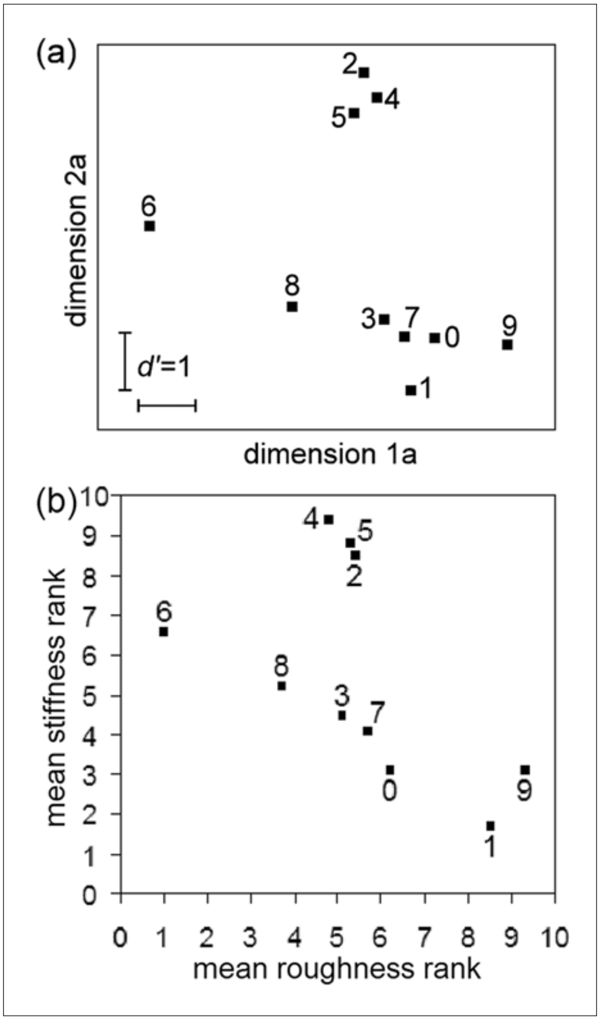

FIGURE 3.
(a) The minimum-stress configuration for the ten papers, as in Figure 1(a) but rotated through 13° counterclockwise (see text); (b) plot of mean (perceived) roughness rank versus mean (perceived) stiffness rank for the ten papers.

range 1.0–9.3 and mean values for stiffness rank in the range 1.7–9.4 (the available range in each case is 1.0–10.0, with higher numbers indicating higher roughness/stiffness).

In order to investigate the possible correspondence of perceived roughness or perceived stiffness to a dimension of the MDS space (Fig. 1(a)), one-dimensional projections of the points in the MDS space were obtained at various angles θ to the 'dimension 1' axis. For each value of θ, correlation coefficients *r* were calculated between the positions of the points in the one-dimensional projection and the mean roughness ranks from the subsidiary experiment, and the value of θ for the maximum correlation was determined. This procedure was repeated for the mean stiffness ranks. In each case the maximum correlation was high: $r = 0.93$ for the roughness data and $r = 0.98$ for the stiffness data, with an angle of 106° between the optimum values of θ for the two attributes (see Fig. 2, full lines labelled R1 and S1).

For both roughness and stiffness, the graph of correlation coefficient *versus* θ is somewhat flat-topped around the maximum, i.e., small changes in θ from the optimum value produce little decrease in the correlation. Hence, since the optimum values of θ for the two attributes differ by close to 90° it is possible to force an overall fit between *orthogonal* projections of the MDS space and perceived roughness and perceived stiffness, with little reduction in the individual correlations. Such a procedure, maximising the sum of the two correlation coefficients, gives $r = 0.92$ for the roughness data and $r = 0.97$ for the stiffness data (see Fig. 2, dotted lines labelled R2 and S2). Hence a rotation of the plot in Figure 2 (and also in Fig. 1(a)), so that the R2 and S2 directions become the principal axes, provides a convenient choice for the absolute angular position of the configuration. Such a rotation provides the optimum correspondence between the MDS space and a two-dimensional 'attribute space' whose orthogonal principal axes correspond to perceived roughness and perceived stiffness, as determined in the subsidiary experiment. This correspondence is shown in Figure 3 – panel (a) shows the MDS space of Figure 1(a), rotated so that the R2 and S2 directions become the principal axes but otherwise unchanged; panel (b) shows the 'attribute space'. It can be seen that, although there are small differences between the two configurations, the overall arrangements of the ten papers are very similar.

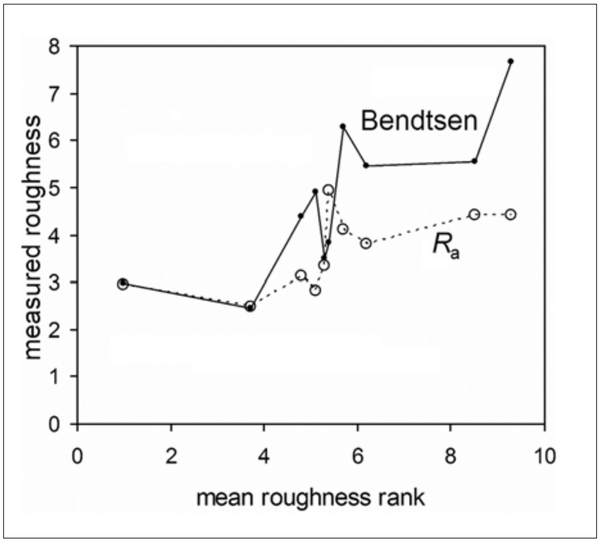

FIGURE 4.
The relation between mean (perceived) roughness rank and measured roughness for the ten papers. Two measures of roughness are shown, both in arbitrary units: (i) from the Bendtsen method; (ii) mean height R_a *of surface features, measured by stylus profilometry.*

FIGURE 5.
The relationship between mean (perceived) stiffness rank and measured stiffness for the ten papers. Two measures relating to stiffness are shown: (i) measured by the Instron method, units of 2 gm wt: (ii) mean paper thickness t*, units of μm.*

Comparison with measured data

A range of parameters is used by paper manufacturers to characterise their products. Among these, surface roughness is described by a variety of measures relating to surface features, which may be derived from stylus profilometry [23]. Surface roughness may also be determined by the *Bendtsen method* [24]: an inverted metal cup, 3 cm in diameter, is placed on the horizontal paper surface; pressurised air at 1.5 kPa is introduced into the cup and leakage under the edge of the cup (machined to be a knife edge) is measured. Stiffness is described by *Instron Stiffness*, measured in terms of the force required to push a square paper sample, standard dimensions 67 mm × 67 mm, through a narrow slot placed under the midline of the sample (i.e., effectively, the force required to fold the paper in half).

Instron stiffness and a range of roughness measures were obtained for each of the papers used in these experiments. Measurements were also made of mean paper thickness – a principal determinant of stiffness, as mentioned above. Figure 4 shows two representative roughness measures for the ten papers, plotted against mean (perceived) roughness rank from the subsidiary experiment. Similarly, Figure 5 shows Instron stiffness and mean thickness, plotted against mean (perceived) stiffness rank. The data in Figure 4 and Figure 5 indicate the ranges of measured roughness and stiffness over the stimulus set which, as discussed above, were chosen to be relatively limited. From Figure 4, it appears that the data for Bendtsen roughness are more successful than the profilometry data as a predictor of perceived roughness: the larger difference in Bendtsen stiffness correspond quite well to the larger differences in perceived roughness, although this relation does not hold for the smaller differences. Similarly, from Figure 5 it appears that Instron stiffness is an approximate predictor of perceived stiffness: the Instron measures (and the closely related measures of paper thickness) suggest a group of six papers which are less stiff and a group of four papers which are more stiff, and this classification is consistent with the ranking of perceived stiffness.

Discussion

The results of this study demonstrate that subjects' discrimination of different types of paper can be successfully represented by a two-dimensional perceptual space – the MDS analysis produces a two-dimensional configuration with an acceptably low value of stress, and which is robust in terms of variability in the data. An alternative two-dimensional perceptual space which can be constructed for the ten papers from data for mean roughness rank and mean stiffness rank shows a close correspondence to the MDS space. This gives a further indication of the success of the MDS analysis, and provides persuasive evidence that the two dimensions of the MDS space correspond to perceived roughness and perceived stiffness.

The cumulative value of discrimination index d' across the range of the 'roughness' dimension 1a in Figure 3(a) is 5.9, and across the range of the 'stiffness' dimension 2a it is 4.8. Hence the two perceptual dimensions contribute in approximately equal measure to the separation of the papers in this experiment.

It can be seen from Figure 2 that the papers fall into two linear groups, one lying parallel to the R1 direction and one parallel to the S1 direction. This may indicate that, for a given paper, one or other of the two perceptual dimensions is dominant with information from the second dimension being masked.

As might be expected in view of the limited range of stimuli selected and the restricted handling procedure, the number of perceptual dimensions required to describe data from the present study is fewer than that suggested in some related studies. Only one perceptual dimension in the present study appears related to surface properties, in contrast to the three or four identified in other studies [9, 10, 13, 16]. It seems reasonable to conclude that the roughness dimension identified in the present study is related to the roughness dimension identified by Hollins, Faldowski, Rao and Young [9].

Most papers encountered in everyday situations have gross surface features deriving from watermarks or printing and it seems, on the basis of an informal investigation carried out in conjunction with this study, that such gross features (the perception of which may involve more than one additional dimension) can provide a strong additional cue for discrimination. As mentioned above, Lyne, Whiteman and Donderi [14] found that the three dimensions required to describe paper towelling included one related to emboss-ment pattern. Appendix 1 describes a study of the perceptual space for embossed patterns on a rigid sheet, also carried out in conjunction with the main study described in this chapter – in this case two perceptual dimensions are suggested.

Conventional measures used by paper manufacturers to characterise their products appear to be relatively poor predictors of the perceived attributes which are significant in this study. However, it must be remembered that the papers in this investigation were chosen to be perceptually similar, and so the measurement procedures are each being used over only a small part of their available range. Over a larger range, i.e., in terms of gross changes in roughness or stiffness, a better correspondence between measured and perceived aspects might be expected. (As outlined above, conventional measurement techniques for textiles [15] have been carefully designed to produce results which correlate with perceived attributes. However, conventional measurement techniques for paper have not been designed with this goal in mind, and so a good correlation with perceived attributes is perhaps not to be expected.)

There is no reason to believe that perceptual features of paper derive from anything other than large-scale or small-scale topological or mechanical features. Hence in principle it should be possible to establish measures of paper, or combinations of such measures, which correspond closely to the principal perceptual dimensions. For example, confocal laser scanning microscopy [25] can provide high-resolution topographic data in three dimensions, and can identify coherent surface structures (i.e., bundles of fibres) which are not apparent from a 1-D stylus profilometry scan. This is an area in which further study is required, and which should produce results of commercial as well as intrinsic interest.

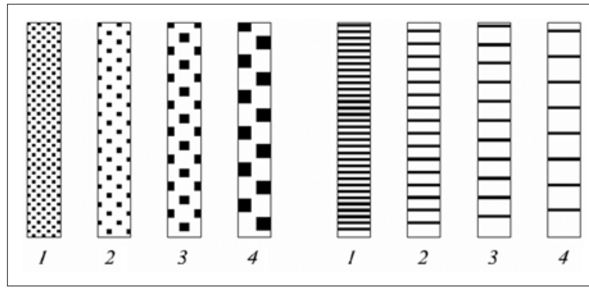

Figure 6.
The stimulus set for identification of embossed surface patterns (raised lines or chequerboards)

Summary

In a study on the discrimination of ten different types of plain paper, a three-alternative forced-choice procedure is used to obtain a measure of the dissimilarity of each of the possible pairs of papers. The experiment is designed to replicate features of a ‘banknote’ scenario in which it may be possible to identify a counterfeit on the basis of only a few seconds’ contact. Using multidimensional scaling (MDS) techniques, two perceptual dimensions are found to satisfactorily represent the data. The nature of the data allows distances in MDS space to be measured in terms of the discrimination index d'. Ranking of the same papers in terms of perceived roughness and perceived stiffness produces a good correspondence to the perceptual dimensions derived from the discrimination experiment. Over the limited range of stimuli selected, conventional measurement methods for characterisation of paper are found to be relatively poor predictors of perceived roughness and perceived stiffness. Appendix 1 presents data for the discrimination of embossed patterns on a rigid surface – raised lines or chequerboards with a surface elevation of 35 µm.

Appendix 1: an example of tactile perceptual space

This study looks at the discrimination of embossed patterns on a rigid surface. It is assumed that the stimulus patterns occupy a multidimensional tactile space and are discriminated tactually on the basis of their different positions in this space.

Measurements were made on identification of embossed surface patterns (raised lines or chequerboards), with a surface elevation of 35 µm, on a rigid substrate of thickness 1 mm and area 10 mm by 70 mm (see Fig. 6). The stimulus tokens were made from commercially available printed-circuit board, using etching techniques to create the embossed patterns. After a period of training, subjects were tested on their ability to identify the different patterns. The test procedure involved the subject picking up the token with one hand, running the index finger of the other hand over the pattern, and then putting the token down again. Subjects were told to take between 1 and 2 s to feel each pattern. Visual masking was present throughout testing, using opaque goggles. Some of the test blocks included only bars, some only chequerboards, and some both bars and chequerboards. Results are presented here for the latter case (both bars and chequerboards), from three subjects.

Figure 7 shows a confusion matrix for all stimuli. Note the bar/chequerboard confusions (cells shaded grey) at both the shortest and longest length scales. (At the shortest scale the pattern features (~1 mm) are not so easily resolved by the sense of touch and the bar/chequerboard distinction is not always clear; at the longest scale the pattern features (~5 mm) are of similar

	bar response				cheq response			
	1	2	3	4	1	2	3	4
bar1	54				6			
bar2	2	56	2					
bar3		8	48	3				1
bar4			10	44			1	5
cheq1	8				52			
cheq2						52	8	
cheq3						9	43	8
cheq4				3			11	46

Figure 7.
Confusion matrix of results for identification of embossed surface patterns. Cells which indicate bar/chequerboard confusions are shaded grey.

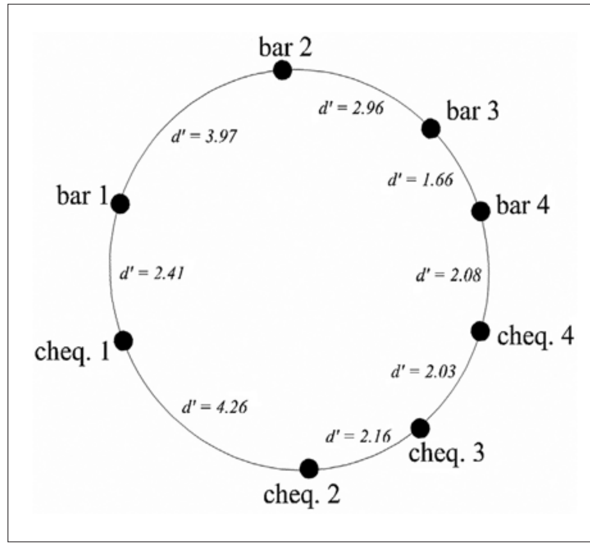

Figure 8.
A suggested perceptual space, constrained to a circle. Nearest-neighbour distances correspond to the inter-stimulus discrimination index d', *with values as shown in the labels.*

size to the contact area of the fingertip and so the two-dimensional organisation of the pattern is not always apparent.)

The information transfer IT from the stimulus set to the subject may be calculated from the confusion matrix using the formula

$$IT = \sum_i \sum_j p_{ij} \log_2 (p_{ij} / p_i p_j) \quad (2)$$

where the index i indicates the various alternatives in the stimulus set, the index j indicates the various alternatives in the response set, p_i is the probability of stimulus i, p_j is the probability of response j, and p_{ij} is the joint probability of stimulus i and response j. The information transfer can be considered to indicate the number N_c of categories perceived by the subject, according to the relation $N_c = 2^{IT}$. In this case, the information transfer is calculated to be 2.2 bits, corresponding to 4.6 discriminable categories (i.e., less than the eight categories presented, as may be inferred from subjects' errors).

A suggested perceptual space, constrained to a circle, is shown in Figure 8. This (non-rigorous) configuration is based on the observation that confusions within the stimulus set are observed between nearest neighbours in the subset of bars, between nearest neighbours in the subset of chequerboards, between bars and chequerboards at the shortest length scale, and between bars and chequerboards at the longest length scale. Nearest-neighbour distances in Figure 8 correspond to the inter-stimulus discrimination index d', which can be calculated from subjects' error patterns (as indicated by the confusion-matrix data) using the method proposed by Braida and Durlach [26]. (This method is designed for a one-dimensional perceptual space, but is here applied along the circumference of the circle.) It is possible to interpret the configuration as a two-dimensional space whose dimensions are related to spatial periodicity and the bar/chequerboard distinction – the rotational orientation of the figure has been chosen so that spatial periodicity runs horizontally and the bar/chequerboard distinction runs vertically.

Acknowledgements

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Selected readings

Hollins M, Bensmaia SJ (2007) The coding of roughness. *Can J Exp Psychol* 61: 184–195

Kennedy JM (2000) Recognizing outline pictures *via* touch: Alignment theory. In: MA Heller (ed): *Touch, representation and blindness*. Oxford University Press, Oxford, 67–98

Klatzky RL, Lederman SJ (2003) The haptic identification of everyday life objects. In: Y Hatwell, E Gentaz (eds): *Touching and knowing*. John Benjamins, Amsterdam, 123–159

Lederman SJ, Hamilton C (2002) Using tactile features to help functionally blind individuals denominate banknotes. *Hum Factors* 44: 413–428