Tactile discrimination of paper
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Abstract
In a study on the discrimination of 10 different
types of plain paper in the form of 135 × 69
mm rectangles, a 3-alternative forced-choice
procedure was used with twelve subjects to
obtain a measure of the dissimilarity of each of
the 45 possible pairs of papers. Using
multidimensional scaling techniques, two
perceptual dimensions were found to
satisfactorily represent the data. Ranking of the
same papers in terms of subjective roughness
and subjective smoothness produced data with
a good correspondence to the perceptual
dimensions derived from the discrimination
data. Conventional objective methods for
characterisation of paper were found to be
poor predictors of subjective roughness and
subjective stiffness.

1. Introduction
It is an everyday experience to handle paper –
turning the page of a book, handing over a
banknote, reading a newspaper – and it takes
only a fraction of a second to assess the paper
in terms of its characteristic “feel”. The
principal goal of the present study is to
establish which objective features of paper are
important for making these subjective
assessments. 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 & Darian-Smith (1989) and Ho
(1991). 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 (Lederman, Loomis &
Williams, 1982; Taylor & Lederman, 1975;
Sathian, 1989), or embossed patterns (Culbert
& Stellwagen, 1963). There are few studies
involving the surface texture of everyday
objects, which is often difficult to describe
objectively. Hollins, Faldowski, Rao & Young
(1993) 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 the case of paper, although it is
possible to objectively 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 subjective surface texture.

found three main factors which influenced the
perceived quality of paper towelling - rigidity,
surface softness and embossment pattern. However, the tactile features of paper tissue in
the form of towelling are rather different from
those of the typing or photocopying paper used
in the present study.

One of the most important uses of
paper discrimination in everyday situations is
in identifying counterfeit banknotes. 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 forgery on the basis of only a few seconds contact (and without the advantage of comparing two notes directly). 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 & Luxford (1990), who found that accuracy for texture recollection was very high, suggesting that memory effects are not a major consideration in the present investigation.

2. Method

2.1 Stimuli

Each stimulus was a rectangle of paper with dimensions 135 mm x 69 mm, corresponding to the size of a common UK banknote. Stimuli were produced from different types of plain white paper, intended for typing or photocopying, acquired from several stationery stores. Twenty-eight 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 eighteen papers, ten which appeared in an informal assessment to be perceptually similar were selected for use. These varied in thickness from 0.098 to 0.131 mm and in area density from 0.073 to 0.102 kg m$^{-2}$. A large number of rectangles was prepared from each of the ten selected papers.

2.2. 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 to 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”.

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 training period in advance of the testing, subjects were allowed to perform the task without masking in order to become familiar with the exact procedure, with necessary 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 includes results from 48 trials for each of the 45 pairs of papers. There are 6 possible patterns for a single trial with a given pair of papers (ABB, BAB, BBA, BAA, ABA, AAB), 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.

2.3. Subjects

These were 12 unpaid volunteers: graduate students in the age range 22-27, 9 male and 3 female. Two of the males were left-handed; the remainder of the subjects were right-handed.

2.4. 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 % to 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.

3. Analysis of Results

3.1. MDS procedure

Tables produced by Craven (1992) were used to convert the percent-correct discrimination score for each paper pair to a corresponding value of discrimination index $d'$ (for example, 95% in the 3AFC test is equivalent to a $d'$ of 4.8, 66% converts to $d' = 2.3$, and 33% converts to $d' = 0$).

Perceptual spaces of various dimensions were constructed for the 10 papers using multidimensional scaling (MDS) techniques. For a given dimensionality, points corresponding to each paper were positioned within the space so that their interpoint distances $d_{ij}$ matched the corresponding interpaper discrimination-index values $d'_{ij}$ as closely as possible. The optimum configuration was obtained by minimising the stress (Kruskal, 1964), defined by:

$$\text{stress} = \frac{\sum (d_{ij} - d'_{ij})^2}{\sum d''_{ij}^2}^{0.5} \quad (1)$$

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., Kruskal, 1964), 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 1, 2, 3, and 4 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 3 or more dimensions is not appreciably lower than that in 2 dimensions). The optimised configuration of papers in the two-dimensional space is shown in Fig.1(a).

The robustness of this configuration with respect to variability in the data was checked by randomly dividing the subject group into two subgroups of 6 subjects, and calculating two-dimensional configurations for each subgroup, shown in Fig.1(b) and Fig.1(c). It can be seen that there are no significant discrepancies between the two configurations obtained, and both are very similar to the Fig.1(a) configuration for the complete data set. This suggests that the principal features of the configuration in Fig.1(a) do not derive

![Figure 1: Minimum-stress configurations for the 10 papers in a 2D perceptual space: (a) derived from data for all 12 subjects; (b) derived from first subgroup of 6 subjects; (c) derived from second subgroup of 6 subjects. Note that the overall orientation of the configuration (i.e. with respect to displacement and rotation) is arbitrary.](image-url)
from random variations in the data but are indeed “real” features.

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.

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 & Swets (1966) suggest that this should in general be the case, and data from Fig.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.

3.2. 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 Fig.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 experiment was carried out without auditory or visual masking. The participants were 10 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 range 1.0 to 9.3 and mean values for stiffness rank in the range 1.7 to 9.4 (the available range in each case is 1.0 to 10.0).

In order to investigate the possible correspondence of subjective roughness or subjective 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 $\theta$ to the ‘dimension 1’ axis. For each value of $\theta$, 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 $\theta$ for the maximum correlation was determined. This procedure was repeated for the mean stiffness ranks. In each case the maximum correlation was very high: $r = 0.93$ at $\theta = -21^\circ$ for the roughness data and $r = 0.98$ at $\theta = 85^\circ$ for the stiffness data (see Fig.2, full lines).

For both roughness and stiffness, the graph of correlation coefficient versus $\theta$ is somewhat flat-topped around the maximum, i.e., small changes in $\theta$ from the optimum value produce little decrease in the correlation. Hence, since the optimum values of $\theta$ for the two attributes differ by close to 90° (see Fig.2), it is possible to force an overall fit between orthogonal projections of the MDS space and subjective roughness and subjective stiffness, with little reduction in the individual correlations. Such a procedure, minimising the sum of the two correlation coefficients, gives $r = 0.92$ at $\theta = -13^\circ$ for the roughness data and $r = 0.97$ at $\theta = 77^\circ$ for the stiffness data (see Fig.2, dotted lines). In this way it is possible to
Figure 2: The minimum-stress configuration for the 10 papers, showing the directions $R_1$ and $S_1$ (full lines) onto which the configurations can be projected to give the best match to mean roughness rank and mean stiffness rank respectively. Also shown are the directions $R_2$ and $S_2$ (dotted lines) which give the best match if orthogonal directions are specified.

establish the optimum correspondence between the MDS space and a two-dimensional “attribute space” whose orthogonal principal axes correspond to subjective roughness and subjective smoothness, as determined in the subsidiary experiment. This correspondence is shown in Fig. 3 – panel (a) shows the MDS space of Fig. 1(a), rotated through 13° but otherwise unchanged; panel (b) shows the “attribute space”, with scale factors for the axes chosen to give the best correspondence. It can be seen that, although there are small differences between the two configurations, the overall arrangement of the 10 papers is very similar.

3.3. Comparison with objective data

A range of parameters is used by paper manufacturers to characterise their products. Amongst these, surface roughness is described by a variety of measures derived from stylus profilometry (Rust, Keadle, Allen, Shalev & Barker, 1994), relating to the amplitude or separation of surface features, and by a roughness parameter obtained from the Bendtsen method (Heinemann, 1996), obtained by measurement of pressurised-air leakage under a metal edge resting on the paper surface. Stiffness is described by Instron Stiffness, measured in terms of the force required to pull a rectangular paper sample 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. Fig. 4 shows a representative selection of roughness measures for the 10 papers, plotted against mean roughness rank (from the subsidiary experiment). Fig. 5 shows Instron stiffness for the 10 papers, plotted against mean stiffness rank (from the subsidiary experiment). It is clear that none of the objective measures of surface roughness is a good predictor of subjective roughness. The match between Instron stiffness and subjective stiffness is a little better but, even with the exclusion of the
anomalous paper with the lowest value of Instron stiffness, the relationship is only approximately monotonic.

4. 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 space which can be constructed for the 10 papers from data for mean roughness rank and mean stiffness rank shows a very close correspondence to the MDS perceptual space derived from the discrimination experiment. This gives a further indication of the success of the MDS analysis, and provides persuasive indication that the two dimensions of the MDS perceptual space correspond to subjective roughness and subjective stiffness. There is no evidence of distinct subgroups of subjects in terms of the strategies used for discrimination – an important point, since the utility of the perceptual space in Fig.1(a) would be seriously diminished if it were to represent an average over subjects using different discrimination tactics.

The cumulative value of discrimination index $d'$ across the range of the “roughness” dimension 1a in Fig.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 is interesting to note from Fig.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.

Although no evidence was obtained in this study for the involvement of more than two perceptual dimensions in paper discrimination, it seems likely that discrimination of a wider range of paper stimuli (or a less restrictive procedure for the handling of the papers) might involve further dimensions, perhaps corresponding to softness/hardness or apparent coldness/warmness. In addition, 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) provide a particularly strong cue for discrimination. As mentioned earlier, Lyne, Whiteman & Donderi (1984) found that three dimensions (rigidity, surface softness and embossment pattern) were required to describe paper towelling.

Conventional objective methods for characterisation of paper are poor predictors of
the subjective 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 objective measurements 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 objective and subjective features might 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 objective measures of paper, or combinations of such measures, which do correspond to the principal perceptual dimensions. For example, confocal laser scanning microscopy (Moss, Retulainen, Paulapuro & Aaltonen, 1993) 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, which should produce results of commercial as well as intrinsic interest.

References


