

Haptic discrimination of doubly curved surfaces

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Abstract. Active haptic discrimination of mathematically well-defined surfaces was investigated. The quadric surfaces were defined in terms of 'shape index'—a quantity describing shape—and 'curvedness'—a quantity describing overall curvature. In these experiments shape index was varied and curvedness kept constant. The influence of laterality (unilateral versus bilateral discrimination) was tested in separate sessions.

No influence of shape on the discrimination of solid objects was found. From the results an estimate can be made of the just-noticeable difference in terms of shape-index units. There was a significant effect of laterality on discrimination: performance with unilateral (successive) examination (both with left and with right hand) was better than with bilateral (simultaneous) examination.

1 Introduction

Haptic shape recognition and discrimination have received relatively little attention compared with visual shape recognition or discrimination (eg Loomis and Lederman 1986). Quantitative studies have been mainly focussed on curvature (eg Davidson 1972; Gordon and Morison 1982) and have often been restricted to small stimuli applied passively to the skin (eg Goodwin et al 1991; Goodwin and Wheat 1992). Studies in which the more challenging field of three-dimensional shape recognition or discrimination have been addressed are all of a qualitative nature (eg Gibson 1963; Klatzky et al 1985).

Recently, we introduced a method to investigate haptic shape identification with the aid of mathematically well-defined objects (Kappers et al 1994). A series of quadric surfaces (including elliptical, hyperbolic, spherical, and cylindrical paraboloids) of varying curvature were used to determine performance in terms of percentage correct identification. Both shape and amount of curvature turned out to have a significant influence on shape identification. In this paper we describe a surface-discrimination experiment in which the same objects were used.

Our aims in the present study were threefold. First, we investigated the discrimination of surfaces of solid objects. From our previous study (Kappers et al 1994) in which subjects had to identify the shape (in terms of shape index, see section 2) of solid objects, it followed that concave surfaces yield larger errors than do convex ones. Moreover, there were some indications that hyperbolic surfaces are more difficult to identify than are elliptic ones. Our second objective was to determine how much two quadric surfaces have to differ in shape in order to be discriminated by the subject. An estimate will be given for a just-noticeable difference. The third question addressed possible differences between unilateral and bilateral discrimination. Bilateral discrimination has the advantage that both shapes can be explored simultaneously. However, this advantage requires that the two hands have equal discriminative power and, moreover, that their perceptions can be compared. These requirements were checked by comparing the unilateral discrimination performances of the right and the left hands. Alternatively, unilateral discrimination could profit from a more direct comparison, be it successively, of attitudes of the same hand. In a completely different type of experiment, Appelle and Countryman (1986) have shown that bilateral

matching of the orientation of rods yields more errors than does unilateral matching. The differences were only small, however, if, during the task, congruent scanning movements could be made. In our experiments subjects were allowed to rotate the surfaces to best advantage and as all surfaces could be placed symmetrically in front of the subject, we should expect at most minor differences between unilateral and bilateral discrimination.

2 Method

2.1 Stimuli

In the current experiment, the stimuli consisted of a subset of the quadric surfaces used by Kappers et al (1994). Such doubly curved surfaces are fully defined when the two perpendicular principal curvatures κ_1 and κ_2 are specified.⁽¹⁾ Together they determine the 'shape index', S , a measure of shape, and the 'curvedness', C , a measure of overall curvature⁽²⁾ (Koenderink 1990; Koenderink and van Doorn 1992). The quadric surfaces are especially important because arbitrary smooth surfaces can be approximated by quadrics to arbitrary precision in a sufficiently small neighbourhood of any particular point. Thus the quadrics effectively exhaust 'local shape'.

In figure 1 a number of different quadric surfaces are schematically illustrated along the shape-index scale which ranges from -1 to $+1$. Negative and positive shape-index values correspond to concave and convex surfaces, respectively. Surfaces with a shape index between -0.5 and $+0.5$ are hyperbolic (saddle shaped); in the remaining ranges elliptical surfaces (bowl and dome shapes) can be found. It should be noted that all possible quadric surfaces are represented on the shape-index scale. For example, an elongated convex ellipsoidal surface has a shape index somewhere between $+0.5$ and $+1$. An earlier experiment has shown that the way quadric surfaces are ordered along the shape-index scale appears to be quite natural, even to naive subjects (Kappers et al 1994).

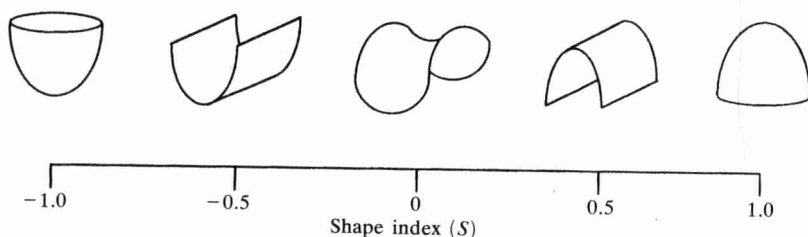


Figure 1. Schematic illustration of the shape-index scale. At $S = +1$ and $S = -1$ paraboloids with equal principal curvatures, convex and concave, respectively, are found. For $S = 0$ the principal curvatures are equal but of opposite sign, resulting in a symmetric hyperboloid. The cylindrical paraboloids at $S = +0.5$ and $S = -0.5$ mark the borders of the elliptical and hyperbolic regions. Although only five surfaces are actually drawn, it should be noted that on this scale all possible quadric surfaces are represented.

⁽¹⁾ The quadric surfaces $z(x, y)$ can be described as $z(x, y) = \frac{1}{2}(\kappa_1 x^2 + \kappa_2 y^2)$.

⁽²⁾ Shape index S is defined as

$$S = -\frac{2}{\pi} \arctan \frac{\kappa_1 + \kappa_2}{\kappa_1 - \kappa_2},$$

with $\kappa_1 \geq \kappa_2$, and curvedness C is defined as

$$C = \left(\frac{\kappa_1^2 + \kappa_2^2}{2} \right)^{1/2}.$$

The shape-index values actually used in the experiment are given in table 1, together with the corresponding principal curvatures. By convention κ_1 is always larger than or equal to κ_2 . A number of important features should be observed. First, the curvedness is kept constant (at a value of 1 m^{-1} which equals the curvature of a sphere with a radius of 1 m) which follows from the fact that the sum of squares of κ_1 and κ_2 remains constant. Second, κ_1 and κ_2 cover the same range of curvatures. Third, the principal curvatures of positive and negative shapes with the same absolute value of shape index differ only in sign. This shows that they exactly fit each other as stamp and mould. Finally, the stimuli are equally spaced along the shape-index scale.

Table 1. Values of the principal curvatures κ_1 and κ_2 of the surfaces (indicated by their shape index S) used in the experiments.

Shape index	Principal curvature/ m^{-1}		Shape index	Principal curvature/ m^{-1}	
	κ_1	κ_2		κ_1	κ_2
0	1.0	-1.0	0	1.0	-1.0
-0.125	1.176	-0.786	0.125	0.786	-1.176
-0.25	1.307	-0.541	0.25	0.541	-1.307
-0.375	1.387	-0.276	0.375	0.276	-1.387
-0.5	1.414	0	0.5	0	-1.414
-0.625	1.387	0.276	0.625	-0.276	-1.387
-0.75	1.307	0.541	0.75	-0.541	-1.307
-0.875	1.176	0.786	0.875	-0.786	-0.176
-1.0	1.0	1.0	1.0	-1.0	-1.0

The stimuli were manufactured out of polyurethane foam impregnated with synthetic resin, the mechanical structure of which is comparable to beech wood. The bottom was flat, the top was the smooth curved surface. The diameter of all stimuli was 20 cm. The height ranged between 3 and 5 cm. For a more detailed description of the stimuli refer to Kappers et al (1994). An example of the stimuli can be seen in figure 2.

2.2 Subjects and apparatus

Three right-handed subjects [strongly right handed according to definitions used by Coren (1993)] participated in the experiment, including two of the authors. None of them reported any haptic deficiencies. Although it was not necessary for the experiment, all subjects were familiar with the shape-index measure. Subjects were seated behind a curtain in front of a table. The curtain prevented subjects from seeing the experimenter, the stimulus, or the cupboards containing the shapes. Depending on the experimental condition, the subjects put either one or two hands under the curtain in order to be able to touch and explore the surfaces placed on the table by the experimenter. This setup can be seen in figure 2.

2.3 Procedure

During each trial two surfaces were simultaneously presented to the subjects. Their task was to determine whether or not these two surfaces were equal. The subjects were instructed to attend only to the shape of the surfaces and to disregard minor differences in height or texture. Subjects were free to explore the surfaces in whatever way they liked, provided that the contours were not scanned systematically. This latter requirement was only necessary in order to avoid the strategy of direct height comparisons at the contours; given the nature of our stimuli, this should not be considered as a serious constraint. The flat bottom of each shape remained on the

table. Subjects were allowed to rotate the surfaces in order to align their hand with one of the two principal axes. Exploration time was unlimited and unrecorded; typically, a session took 30 to 50 min. Subjects noted down their responses on a special response list.

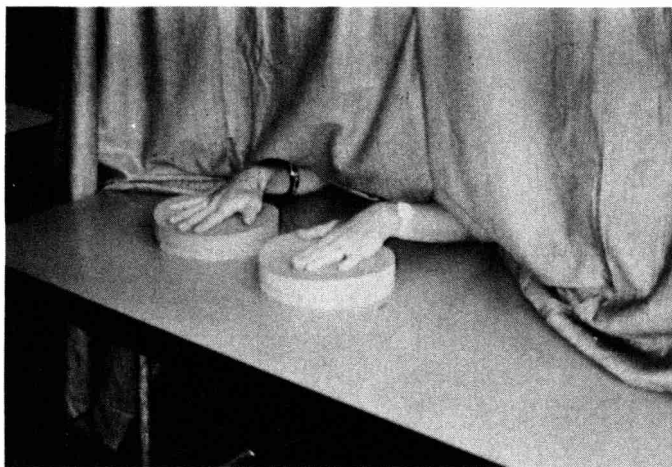


Figure 2. Photograph of the hands of a subject exploring the stimuli in the bilateral condition.

In each experimental condition 416 pairs of surfaces were tested. These pairs were randomly distributed over 8 sessions on different days. All subjects participated in all experimental conditions. In conditions 1, 2, and 3, the 416 pairs were obtained by pairing each of the surfaces with shape index between -0.75 and $+0.75$ (see table 1) sixteen times with themselves ($13 \times 16 = 208$ pairs), eight times with their left neighbour shape ($13 \times 8 = 104$ pairs), and eight times with their right neighbour shape ($13 \times 8 = 104$ pairs). For condition 4 the surfaces were not paired with their neighbours but with surfaces $+0.25$ or -0.25 away on the shape-index scale. The way the surfaces were presented to the subjects (ie which of the two surfaces was placed to the right and which to the left) was balanced across the sessions of each condition.

In conditions 1 and 4 the subjects were allowed to touch the surfaces only with the right hand. They were permitted to explore both surfaces as often as they thought necessary. Similarly, in condition 2 the subjects used only their left hand. In condition 3 the right surface was touched with the right hand whereas the left surface was touched with the left hand. The subjects were free to move their hands either simultaneously or successively.

3 Results

In figure 3 the results of experimental conditions 1 and 4 are shown for all three subjects. Scores, in terms of percentage correct responses, are given as a function of shape index. As might have been expected, subjects performed significantly better when the difference between the surfaces of a pair is larger in terms of shape-index units. Results of the three subjects differ only quantitatively.

Figure 4 shows the results of conditions 1, 2, and 3 for the three subjects. Again, percentage correct responses are given as a function of shape index. A full ANOVA revealed that the results do not depend significantly on the shape index ($F_{12,100} = 1.2$, $p > 0.28$). There were significant main effects for conditions ($F_{2,100} = 18.9$, $p < 0.0001$) and subjects ($F_{2,100} = 23.8$, $p < 0.0001$). There were no significant interactions.

As there was no significant influence of shape index, the results can be clarified by averaging over the different surfaces. The result is shown in the histogram of figure 5. The significant effect of condition is due to condition 3 (bilateral discrimination), for which performance is worse than for the unilateral conditions (1 and 2).

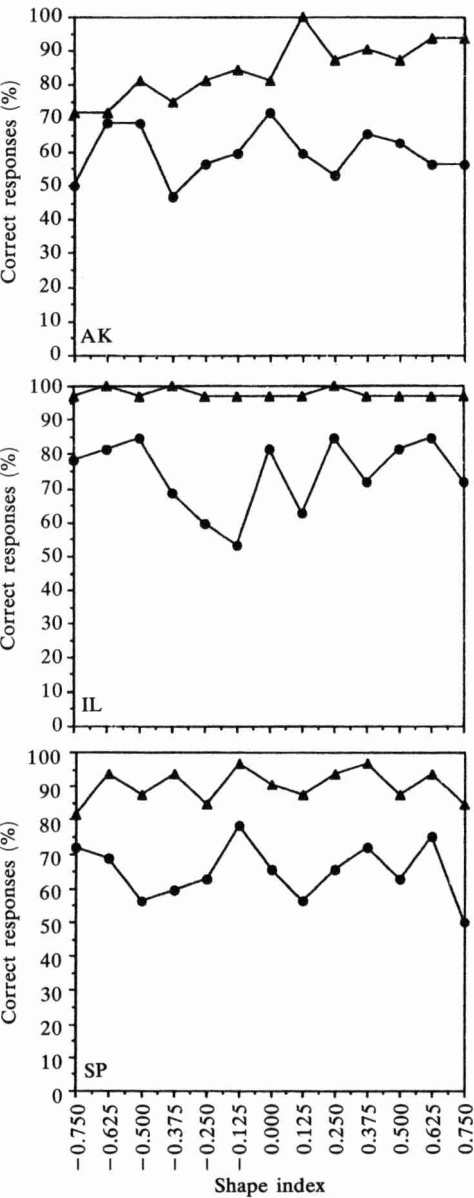


Figure 3. Percentage correct responses as a function of shape index for conditions 1 (circles) and 4 (triangles) for all three subjects: AK, IL, and SP. The two surfaces of a pair have equal shape-index or differ by 0.125 (condition 1) or 0.25 (condition 4). Subjects touched the surfaces only with their right hand.

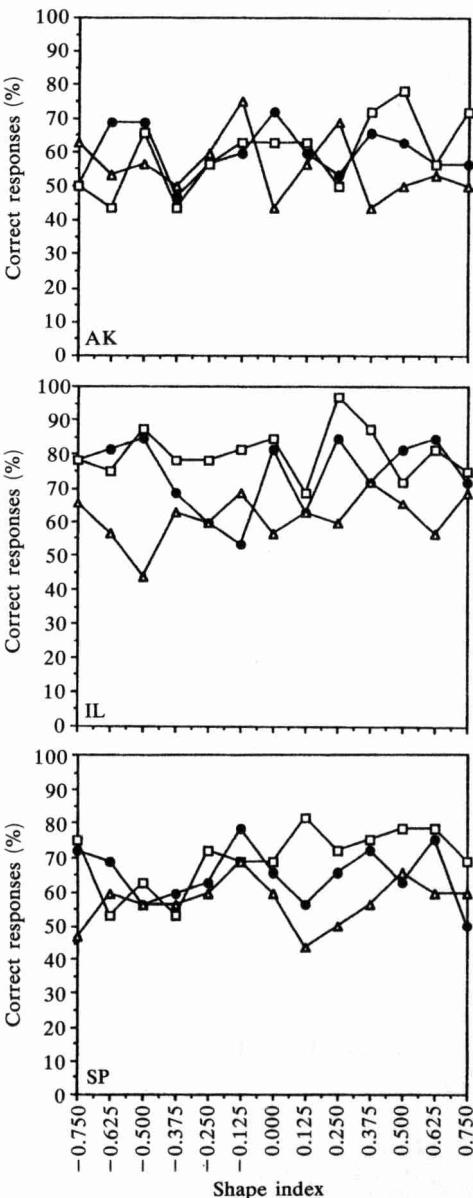


Figure 4. Percentage correct responses as a function of shape index for conditions 1 (circles), 2 (squares), and 3 (triangles) for all three subjects: AK, IL, and SP. The two surfaces of a pair have equal shape index or differ by 0.125. Subjects touched the surfaces with their right hand (condition 1, filled circles), their left hand (condition 2, open squares), or each hand touched one of the surfaces (condition 3, open triangles).

The task of the subjects was to report whether or not the two surfaces of a pair were equal. Under all conditions, half of the pairs of surfaces were equal. It is interesting to see whether the percentage correct responses differs for the two situations. Such a difference, or bias, can be expressed as follows: $\text{bias unequal/equal} = \text{percentage correct responses (surfaces of a pair are different)} - \text{percentage correct responses (surfaces of a pair are equal)}$. In figure 6a this bias, for each of the three subjects, is shown for the four conditions. Clearly, the subjects used different strategies in performing their task. Subject AK shows a preference to respond that the two surfaces differ. Possibly, her responses are influenced by small differences in texture or height of the surfaces. Her strategy remains the same over the conditions with the possible exception of the bilateral condition. Subject IL does not show any bias, whereas subject SP shows a tendency to report that the two surfaces are equal.

Finally, the influence of the placement of the surfaces, ie which of the two different surfaces of a pair is placed at the right and which at the left side, should be examined.

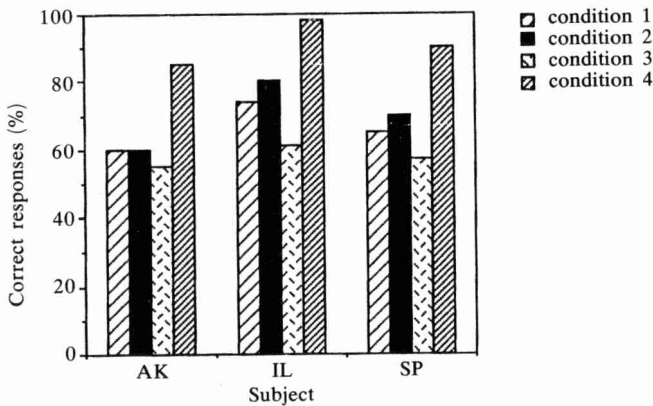


Figure 5. Total percentage correct responses averaged over all surfaces for all conditions for the three subjects.

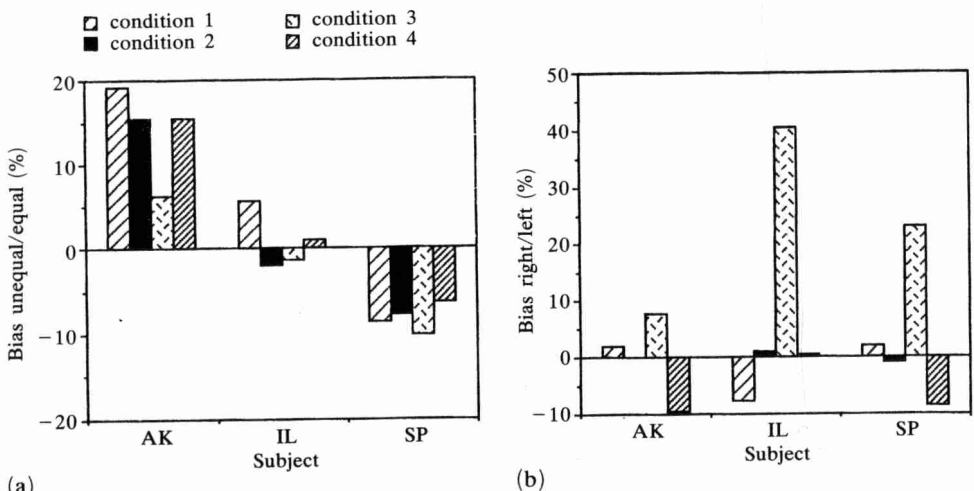


Figure 6. (a) Bias unequal/equal for all conditions and all subjects. The bias is defined as follows: $\text{Bias unequal/equal} = \text{percentage correct responses (surfaces of a pair are different)} - \text{percentage correct responses (surfaces of a pair are equal)}$. (b) Bias right/left for three conditions and all subjects. The bias is defined as follows: $\text{Bias right/left} = \text{percentage correct responses (right surface has a higher shape index than does the left surface)} - \text{percentage correct responses (left surface has a higher shape index than does the right surface)}$.

Here, bias can be defined as: $\text{Bias right/left} = \text{percentage correct responses (pairs for which the right surface has the highest shape index)} - \text{percentage correct responses (pairs for which the left surface has the highest shape index)}$. This bias is shown in figure 6b. For subject AK placement of the surfaces seems to be of no influence. Similarly, subjects IL and SP show no such bias for conditions 1, 2, and 4. However, these two subjects both show a clear bias for placement of the surfaces in the bilateral condition. For example, for subject IL this bias is no less than 40%! Given her total percentage correct responses for different surfaces (61%, which can be obtained from combining data in figures 5 and 6a), it follows that if the right surface has the highest shape index her score is 81%, whereas in the opposite order her score is only 41%, which is below chance.

4 Discussion

Statistical analysis of the results of our experiments did not reveal a significant influence of surface shape on discrimination performance. At first sight, this seems to be in contradiction with earlier results (Kappers et al 1994) which showed a significant effect of concaveness on shape identification. However, a significant interaction of curvedness and shape was also observed and inspection of the earlier results shows that shape has a larger influence for smaller curvednesses. The curvedness used in the current experiment lies in the middle of the range used in the identification experiment. Apparently, the effect of shape (concaveness) was too small for surfaces with a curvedness of 1 m^{-1} to be detected in the discrimination experiments described in this paper. On the other hand, the different tasks may explain the dissimilar results. In discrimination experiments the subjects have to make relative judgments, whereas absolute judgments are expected in identification experiments.

Given the limited number of surfaces available for our experiment, a just-noticeable difference (eg thresholds 66.6% correct identifications) can only be estimated. From figure 5 the value of such a threshold can be obtained by linear interpolation between the two different conditions in which the subject explored the surface with the right hand (conditions 1 and 4). This yields the following values for our three subjects. AK: 0.16, IL: 0.09, and SP: 0.13. These results can be compared directly with the results from the identification experiment in which the same surfaces were used (Kappers et al 1994). The standard deviations for the same three subjects (averaged over all surfaces) were: AK: 0.09, IL: 0.11, and SP: 0.13—values which lie very close to the estimated values given above.

In the introduction we hypothesised that if the experiments of Appelle and Countryman (1986) had any bearing on our experiment, only a slight (if any at all) influence of laterality should be expected. In contradistinction to this expectation, a clear influence of laterality was observed, to the disadvantage of bilateral exploration. Performance with left or right hands unilaterally was indistinguishable and thus bilateral discrimination was worse than that when both hands were used separately. Figure 6a shows that subjects do not change their response strategy over the different conditions (with the possible exception of subject AK). In contrast, figure 6b shows a clear influence of the placement of the surfaces on discrimination performance. For subject IL, performance is even below chance when the right surface has the lower shape index of the two, whereas performance is just as good as unilateral discrimination in the opposite situation. The raw data (not shown in this paper) seem to indicate that this asymmetry is restricted to a limited range of the shape-index scale, a range which is different for different subjects. Unfortunately, we do not have enough data to analyse this statistically. At this moment we can only speculate as to the possible mechanisms underlying this asymmetry. The results of a number of pilot experiments seem to indicate that the two hands give rise to different perceptions of

physically identical curvatures (for example, the surface under the right hand might be perceived as more curved than the surface under the left). As the most common strategy of the subjects in the discrimination task is to compare the curvatures of two corresponding principal axes, this could be a plausible explanation for the asymmetry. Clearly, further research is needed to shed light on this question.

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