Influence of Local Properties on the Perception of Global Object Orientation

Virjanand Panday, Wouter M. Bergmann Tiest, and Astrid M.L. Kappers

Abstract—In previous studies, the effect on perception of individual features such as curvature and edges have been studied with specifically designed stimuli. However, the effect of local properties on the perception of the global object has so far received little attention. In this study, cylinders with an elliptical cross section and rectangular blocks were used to investigate the effect and relative importance of curvature, change in curvature and edges, as local properties, on the ability of subjects to determine the orientation of the stimuli, which is a global property. We found that when curvature was present the threshold to determine the orientation was 43 percent lower than when curvature was absent. When, in addition, the change in curvature could be felt, the threshold was 37 percent lower than when only curvature could be felt. Finally, when edges were felt during exploration, the threshold increased by 46 percent compared to when the subjects were instructed to avoid the edges in the blocks. We conclude that the perception of curvature and change in curvature improve the performance of humans in perception of the whole shape, whereas edges, when not directly contributing to the task, disrupt performance.

Index Terms—Psychophysics, haptic perception, touch.

1 Introduction

When we feel objects, either to recognize them, or to use them, we explore the local and global properties of the shape with our hands and fingers. It would be interesting to know how the physical properties of shape are perceived by humans and what the effect is of small or local changes in the shape on the global percept that humans have of the shape. Do people ignore local features, or do people use the local features effectively when determining aspects of the global shape? This study investigates the influence of local properties on the haptic perception of global properties of shape.

For the purpose of this investigation, the perception of objects can be split up into the perception of global properties and the perception of local properties. Lederman and Klatzky [1] found that different hand movements were made to perceive different properties of objects. They found that when shape was to be perceived, people tend to enclose the object or trace the contours with their fingers. It is thought that enclosure gives information on the global shape, while following the contour with a finger gives information on the local shape [1].

Lakatos and Marks [2] used this division into enclosure and contour following to investigate perception of the global and local properties, by either limiting the information from contour following or limiting the information from enclosure. They found that if observers are given enough time, both local and global features contribute equally to the total percept for recognition [2].

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Both the global properties of shape and the local properties of shape have been the subject of study. Studies on global properties mostly investigated the ability of humans to recognize shapes and the stimuli used can tell us something about the emphasis of these studies. Local properties have been investigated to determine how well humans can detect these properties and what mechanisms underlie the perception of these local properties. There have been few studies that attempt to merge these two extremes by varying local properties and measuring the effect on the perception of global properties. Below we discuss a few examples of studies on global and local properties and studies that attempt to merge them.

Many studies that investigate global properties, do so by asking subjects to recognize or match shapes. Two examples are given here to emphasize that the stimuli employed in these studies differ greatly with regard to the local properties. In Newell et al. [3] the shapes consisted of constructions built with blocks of Lego, whereas in Norman et al. [4] the shapes consisted of casts of bell peppers. In Newell et al. [3] the surfaces were straight and the shapes cubical, whereas in Norman et al. [4] "natural" shapes with curved surfaces were used. The aim of these studies was to compare visual perception with haptic perception. They therefore only concentrated on the global shape and did not take into account the local properties.

On the other hand, studies that focus on local properties often perform threshold experiments to determine how accurately humans can perceive these properties and to investigate what exactly is being perceived. The effect on global shape perception is not taken into account. Curvature can be taken as an example of a local property that has been studied in depth. Not only have discrimination thresholds been found for one finger [5], parts of the hand [6], or the whole hand [7], [8], but it has also been shown that the main feature on which human observers base their perception, is the change in attitude or tilt, rather than the elevation (zeroth order information) or the local curvature (second order information) of the surface [9].

The influence of local properties on global shape perception has been investigated in some studies, for example, by Roland and Mortensen [10]. In their experiment, subjects were asked to identify the more oblong object by comparing either ellipsoids or parallelepipeds. By comparing the discrimination thresholds for ellipsoids to those for parallelepipeds, they concluded that when curvature is present the discrimination threshold is lower. In this study, local properties such as curvature, edges, and volume were all important for being able to perform the task which involved a perception of the global shape. However, as the shape of the ellipsoids is quite complex, it is difficult to relate the performance of the subject to the local properties of the shape. In Van der Horst and Kappers [11] the shapes were cylinders and blocks. These shapes are somewhat less complex than ellipsoids and, therefore, Van der Horst and Kappers could more accurately relate the presence of curvature to thresholds found for discriminating cylinders with an elliptical cross section from cylinders with a circular cross section. By comparing these thresholds to those found for discriminating blocks with a rectangular cross section from blocks with a square cross section, they concluded that curvature information was employed in a reliable and efficient manner. However, as they write in the discussion, in their experiments the local properties such as curvature or the change in curvature, which is a distinct feature in an ellipse as it has a different curvature at different points along its surface, could not be disentangled and therefore the influence of either could not be directly related to the overall performance. Furthermore, the influence of edges was not taken into account in their discussion.

In this paper, we expand on the work done by Van der Horst and Kappers [11]. By integrating local properties in a task which assesses global properties of the object, we take the step from investigating individual and local properties in an isolated way to the global perception of 3D objects which is influenced by these local properties. To do so, we designed an experiment in which subjects had to assess a global property, in which local properties did or did not give extra information about this task. We asked subjects to indicate, from two possible orientations, the orientation of a block with a rectangular cross section or a cylinder with an elliptical cross section. The orientation of these stimuli is a global shape property, namely the difference between the long axis and the short axis. In the cylinders, the curvature and change in curvature are local properties which give extra information about the orientation. In the block, the edges are local properties, but they do not give extra information about the orientation. On the other hand, the edges define the sides of the block in such a way that two opposing sides are easier to grasp, which may facilitate discrimination.

We investigated three relationships. First, the quantitative influence of curvature is determined. Second, the quantitative influence of the change in curvature is investigated. Finally, the influence of the edges is determined. To assess these three properties an experiment with six conditions was designed. These conditions are depicted in Fig. 1. In the first

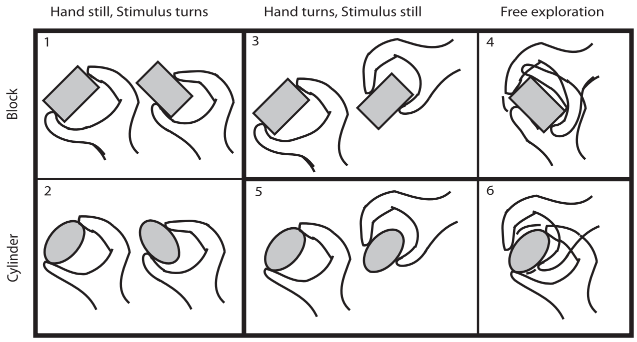

Fig. 1. Schematic illustration of the six conditions of the experiment. 1) Block is grasped with the fingertips statically between thumb and other fingers and then released. After the block is turned 90 degree by the experimenter, this is repeated. 2) Cylinder is grasped with the fingertips statically between thumb and other fingers and then released. After the cylinder is turned 90 degree by the experimenter, this is repeated. 3) Block is grasped statically between thumb and other fingers and then released. After the hand is turned 90 degree around the block, this is repeated. 4) Block is grasped with the whole hand, after which the subject freely explores the stimulus. 5) Cylinder is grasped statically between thumb and other fingers and then released. After the hand is turned 90 degree around the cylinder, this is repeated. 6) Cylinder is grasped with the fingertips, after which the subject freely explores the stimulus.

condition, there is only the information about the aspect ratio available. In the second condition, there is both local curvature information and information about the aspect ratio available to the observers. The third condition has similar information as the first condition, but now movement of the hand is included. In the fourth condition, there is both information about the aspect ratio as well as information obtained by freely exploring the block, for instance, feeling the length of the sides by sliding the finger over it. Therefore, movement of the hand is included and the edges are also felt. In the fifth condition, there is information about the aspect ratio and the local curvature available, while movement is present. Finally, in the sixth condition, change in curvature information is added to the information available in condition 5. The aspect ratio of the cross sections of the elliptical cylinders and the rectangular blocks varied from almost circular or square to more elongated or rectangular, so that a threshold could be determined.

By comparing conditions 1 and 2, the effect of curvature can be investigated. In both conditions, the exploration procedure is the same. The length of the long and short axes of the cylinder are equal to the long and short axes of the block, which means that the aspect ratios of the cylinders and the blocks are equal. The only difference is the presence of curvature in the cylinder. The curvature on the tip of the long axis of the ellipse is higher than the curvature on the short axis. Subjects could also determine the orientation by comparing these curvatures. From Van der Horst and Kappers [11] it can be deduced that when curvature is present, subjects will be able to determine the orientation for lower aspect ratios. The question is, whether this effect will be as large as found in Van der Horst and Kappers. In their experiment, the lower thresholds found for cylinders could be explained by the curvature, but in addition the effect of edges in the blocks could have increased the thresholds for blocks, making the difference bigger than can be explained by just adding curvature.

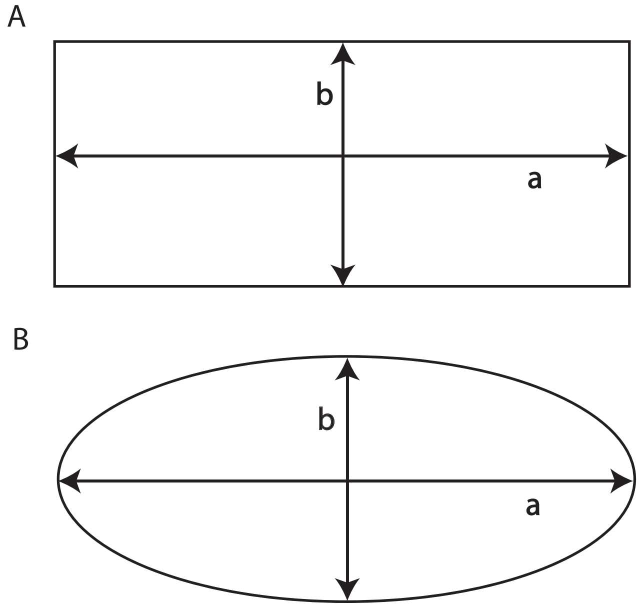

Fig. 2. Schematic illustration of a rectangular cross section of a block (A) and an elliptical cross section of a cylinder (B) with long axis a and short axis b.

By comparing conditions 3 and 4, the effect of the edges can be determined. One could expect that when subjects are asked to explore the block freely as in condition 4, they would be able to determine the orientation of the block correctly for smaller aspect ratios, because they can feel more information, such as the length of the sides, which could also be perceived by sliding the fingers along the total length of the side. On the other hand, one could expect that by avoiding the edges in the exploration of the block, the disrupting influence of the edges is eliminated, leading to lower thresholds. The result of these two conditions has been previously reported [12] and will be discussed together with the results of the other conditions.

Finally, by comparing conditions 5 and 6, the effect of the continuous change in curvature can be measured. In condition 5, the subject grasps two opposing sides statically, thus feeling only the curvature and a small part of the change in curvature at the tips, while in condition 6 the continuous change in curvature is also felt. From research done by Pont et al. [9], it is known that the change in attitude is the most important feature in curvature perception. By dynamically feeling the attitude change along the surface of the cylinder, one could expect a better performance than statically feeling the curvature in two different places on the surface. On the other hand, the difference in curvature is maximal between the long and the short axes. By skipping the surface in between, one can directly compare these extremes.

2 Method

2.1 Subjects

Eleven paid subjects (mean age 21 ± 3 years, 6 male) participated in the experiment. The result of one of these subjects was not included, since this subject employed a strategy which was not based on grasping during the experiments using blocks. One subject was strongly left-handed, one subject was moderately right-handed, all other subjects were strongly right-handed according to Coren's test [13]. All subjects used their dominant hand for the experiment. All subjects were naive as to the purpose of the experiment and gave their informed consent. None of the subjects reported any known hand deficits.

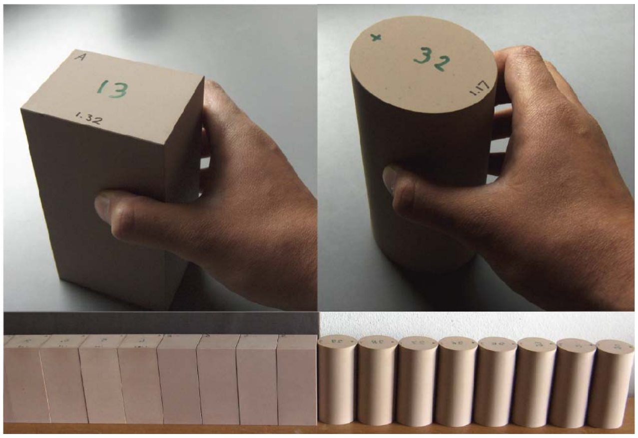

Fig. 3. Set of stimuli used.

2.2 Stimuli

Blocks with a rectangular cross section and cylinders with an elliptical cross section were used as stimuli. The stimuli were made of a compound of polyurethane foam and artificial resin (Cibatool BM 5460) and manufactured on a computer controlled milling machine. They were similar to the stimuli used by Van der Horst and Kappers [11], but of slightly different dimensions. The height was 150 mm. The areas of the cross sections of the rectangles were $4{,}900\ \mathrm{mm}^2$. The lengths of the axes of the cylinders were chosen to be equal to those of the rectangles. In this way, the distance between the fingers on a cylinder are equal to the distance on a block and a direct comparison is possible. The stimuli are defined in terms of the aspect ratio of the horizontal cross section (α), which is defined as the quotient of the longest axis (a), and the shortest axis (b) as depicted in Fig. 2.

For the first five conditions, test stimuli with aspect ratios of 1.004, 1.006, 1.010, 1.016, 1.020, 1.04, 1.06, and 1.08 were used. For the final condition, where the subjects explored blocks freely, test stimuli with aspect ratios of 1.006, 1.010, 1.020, 1.04, 1.06, 1.08, 1.1, and 1.13 were used. The ranges of the test stimuli were based on pilot experiments. An image of the stimuli used can be seen in Fig. 3.

2.3 Procedure

The subjects were seated behind a curtain which prevented them from seeing the experimenter and the stimuli. The stimulus was placed on the table behind the curtain, in such a way that the subject could comfortably reach around the stimulus. The subjects had to indicate from a drawing, one for blocks and one for cylinders as shown in Fig. 4, in which orientation they felt the stimulus was standing behind the curtain. This drawing was located in front of the curtain. After they indicated the orientation, the experimenter recorded their answer. The subjects received no feedback on the correctness of their answer.

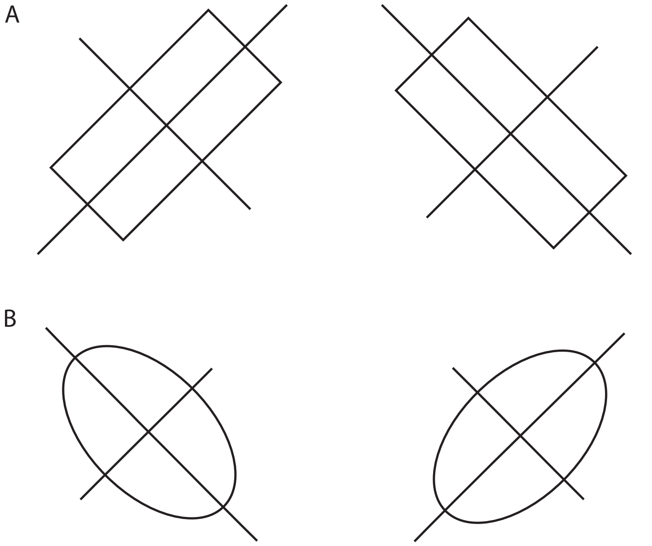

Fig. 4. Visual depiction of the two orientations, from which the subjects had to choose. The image of two rectangles (A) was used when the stimuli presented were blocks. The image of two ellipses (B) was used when the stimuli presented were cylinders.

On the drawing, the top view of two blocks or two cylinders was depicted. For half the subjects the left stimulus had the longest axis from the bottom left to the top right, while the right stimulus was rotated 90 degree. For the other half this was the other way around. The subjects were asked to indicate whether the block or cylinder they felt was oriented in the same direction as either the left or the right stimulus on the drawing. For the first and second conditions, the cylinder or block was turned by the experimenter after the subject had felt the stimulus and let go, but the position of the hand of the subject remained in place. The subjects were instructed to indicate what orientation they felt the stimulus was in, when it was in the final position.

During a trial the subjects put their dominant hand under the curtain and felt the stimulus. During exploration, the experimenter held the block or cylinder in position by holding it at the top. In the first condition, subjects held their hand open and steady in one place, while the experimenter placed a block between the thumb and other four fingers. The subject felt the stimulus statically with the fingertips. After the observer released the stimulus, the experimenter turned the stimulus 90 degree. Then, the subject felt the stimulus again in a similar manner. The second condition was similar to the first, but instead of a block, the subjects had to feel a cylinder. In the third condition, the subjects were asked to grab two opposing sides of a block between their thumb and the other four fingers, making sure not to come into contact with the edges. They then let go and turned their hand around the stimulus without touching it, to grab the other two opposing sides in a similar manner. In the fourth condition, the subjects grasped a block and were left free to explore the block as they wished. In the fifth condition, the subjects were asked to grab two opposing sides of the cylinder between their thumb and the other four fingers. They then let go and turned their hand around the stimulus without touching it, to grab the other two opposing sides in a similar manner. This condition is similar to condition 3, but now with a cylinder. In the sixth condition, they were asked to grab a cylinder between the fingertips of their thumb and four other fingers and could explore the surface however they wanted. A schematic drawing of the hand positions is given in Fig. 1.

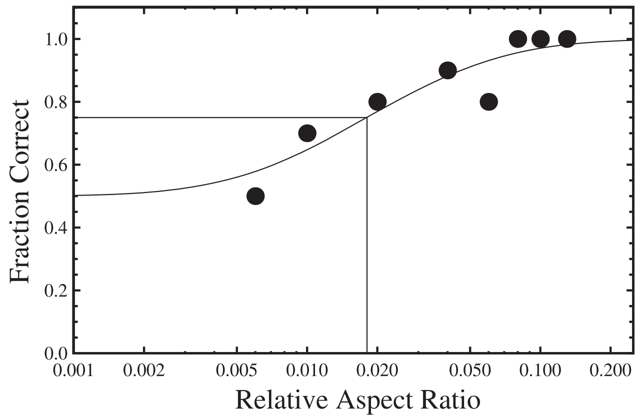

Fig. 5. Example of a psychometric curve for condition 4 (Block, free exploration) of one subject. The response is plotted against the relative aspect ratio, which is defined as the aspect ratio minus 1. Note that a logarithmic scale is used. A psychometric function was fitted to the data. The detection threshold is defined as the relative aspect ratio value for which the psychometric function equals 0.75.

Each condition consisted of 80 trials. Each stimulus was presented five times in both orientations, giving 10 trials per stimulus. The stimuli were presented successively in a random sequence. The order in which the conditions were measured was counterbalanced across subjects using a balanced Latin square design for the first six subjects [14]. For the next four subjects, another Latin square was constructed with the columns shifted one to the right and the bottom two rows left out. With this design the conditions were as counterbalanced as possible. Each session with two conditions took 40-80 min.

2.4 Analysis

The fraction of correct responses was plotted against the relative aspect ratio $(\alpha - 1)$ on a logarithmic scale. To the fraction of correct judgments, a psychometric function of the form

$$g(x) = \frac{1}{4}\mathrm{erf}\left(\frac{{}^{10}\log\left(\frac{x}{\mu}\right)}{\sqrt{2}\sigma}\right) + \frac{3}{4}, \qquad (1)$$

was fitted. Here, erf is the cumulative Gaussian distribution, μ is the relative aspect ratio of the 75 percent point (the point halfway between chance level and 100 percent correct) and σ is a parameter that describes the steepness of the curve. This function, described in Bergmann Tiest and Kappers [15], was chosen to enable an analysis that assumes that performance is at chance level when the relative aspect ratio reaches zero. Furthermore, this function is antisymmetric on a logarithmic scale. The relative aspect ratio where the function equals 0.75 was taken as the detection threshold. An example of condition 4 for one subject is shown in Fig. 5.

As the magnitude of the discrimination thresholds differ from person to person, the results were normalized by

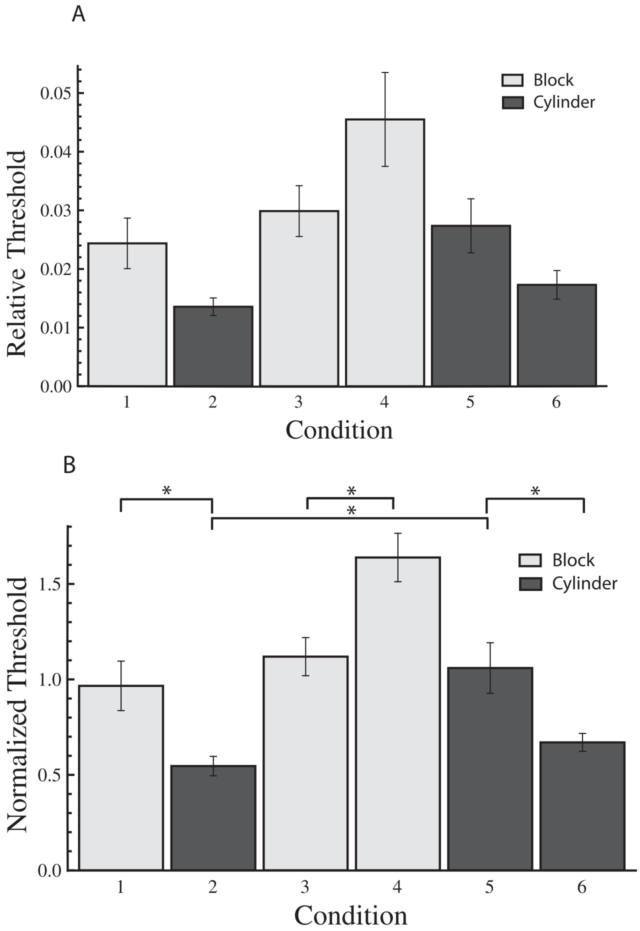

Fig. 6. Mean detection threshold results (A) and normalized mean detection threshold results (B) of 10 subjects in the six conditions. The error bars represent standard errors. The asterisks indicate significant differences ($p < 0.05$) tested by a two-tailed paired t-tests. To investigate the effect of curvature, edges and change in curvature the t-tests were performed on conditions 1 and 2, conditions 3 and 4, conditions 5 and 6, and conditions 2 and 5, respectively.

dividing by the average threshold per person. This way, the relative influence of the different features could be determined from the average normalized thresholds. A two by three ANOVA was performed to investigate if there was a significant difference in the performance due to shape and exploration. To investigate the influence of curvature, edges and change in curvature, we compared the conditions as depicted in Fig. 1 by performing t-tests on conditions 1 and 2, conditions 3 and 4, and conditions 5 and 6, respectively. Finally, to investigate the influence of moving the hand around the cylinder we performed a t-test between conditions 2 and 5 and corrected for the multiple paired t-tests by employing the Holm-Bonferroni method.

3 Results

3.1 Thresholds

Fig. 6 shows the mean detection thresholds for 10 subjects in six conditions and the thresholds normalized per person. A two (shape) by three (exploration) repeated measures ANOVA was performed on the normalized thresholds. Both shape ($F(1,9) = 38, p = 0.00016$) and exploration ($F(2,18) = 6.5, p = 0.0075$) had a significant effect on detecting the orientation. The thresholds for cylinders, as can be seen in Fig. 6, were significantly lower than thresholds for the blocks. Furthermore, the way of exploration had an influence on the thresholds obtained. The interaction between shape and exploration was also significant ($F(2,18) = 7.5, p = 0.0043$): there is hardly any difference for the exploration "stimulus still, hand turned" between conditions 3 (block) and 5 (cylinder), a moderate difference for the exploration "stimulus turned, hand still" between the first two conditions, and a big difference for the exploration "free exploration" between conditions 4 (block) and 6 (cylinder). To further investigate the significant effects found in the ANOVA, we performed a number of t-tests as described in the methods section. Condition 1 (block, stimulus turned, hand still) differed significantly ($t = 3.5, p = 0.0069$) from condition 2 (cylinder, stimulus turned, hand still). The difference between conditions 3 (block, stimulus still, hand turned) and 4 (block, free exploration) was significant ($t = 3.3, p = 0.0088$). The difference between conditions 5 (cylinder, stimulus still, hand turned) and 6 (cylinder, free exploration) was significant ($t = 2.4, p = 0.039$). Finally, also the difference between conditions 2 (cylinder, stimulus turned, hand still) and 5 (cylinder, stimulus still, hand turned) was significant ($t = 3.5, p = 0.0073$).

4 Discussion

By comparing the performance in condition 1 to condition 2 the effect of curvature can be determined. In condition 2, subjects felt two opposing sides of a cylinder with an elliptical cross section, whereas in condition 1, they did the same for a block with a rectangular cross section. The threshold for determining the orientation decreased by 43 percent when local curvature information was added. As the local curvature at the long axis is higher than the local curvature on the short axis, there is extra information available to the subject. This extra information is incorporated effectively to help in determining the global orientation of the stimulus.

By comparing conditions 5 and 6, one can see that also here the local properties improve the performance. In condition 5, subjects were asked to feel the surface at the long and short axes of a cylinder statically between their fingertips, whereas in condition 6, they could dynamically explore the whole area between the four points. Thus, in addition to curvature, subjects were also presented with the change in curvature. In this case the threshold decreased by 37 percent. As curvature change is dependent on the curvature, and this in turn is dependent on the orientation of the short and long axis, change in curvature is extra information for determining the orientation. This extra information is incorporated effectively.

When one compares conditions 3 and 4, it is clear that local features do not always increase sensitivity. In condition 3, subjects were asked to feel the surface at the long and short axes of a block statically between their fingertips, while avoiding the edges, whereas in condition 4 they were free to explore the block with their whole hand. There is extra information due to the free exploration available in condition 4 compared to condition 3. However, in addition, edges are felt. When information from free exploration and edges was included, the threshold increased by 46 percent.

Even though one would expect that when the subject is free to explore the object, the subject would be able to choose the optimal way and would have a lower threshold for determining the orientation, it appears that the edges disrupt the perception in such a way that the subject is less sensitive to the global orientation than without the extra local information.

Another interesting comparison is the difference between the performance on the cylinders compared to the performance on the blocks. In general, the thresholds for cylinders are lower than the thresholds for the blocks, independent of the exploratory procedure used. This result was also found in Van der Horst and Kappers [11] for cylinders and blocks and in Roland and Mortensen [10] for ellipsoids and cuboids. This is not surprising, as the cylinder and the ellipsoid always have the additional feature of curvature, as well as the feature of aspect ratio. The only condition for which there was no clear difference between the block and the cylinder was when the subjects were asked to move their hand around the stimulus. This could be caused by the added complexity of turning the hand 90 degree around a cylinder. This task does not require as much precision around a block, as the surfaces are the same across the entire length of a side.

The explanation of added complexity of turning the hand 90 degree around a cylinder is supported by the significantly lower thresholds for condition 2 than for condition 5. When the cylinder is turned, all the subjects were required to do was to open and close their hand. The positioning at the tips of the axes was done by the experimenter by turning the cylinder correctly whereas in condition 5 the subjects were asked to move their hands 90 degree to grasp the tips of the axes, making the task more difficult which resulted in higher thresholds.

The question arises, how do the studies on local properties such as curvature, change in curvature, and length perception, compare to the results we found when these local features are used in perception of a global property. This is explored further in the next sections.

4.1 Aspect Ratio

The influence of the aspect ratio can be compared to studies that investigated length discrimination by grasping objects between the thumb and the index finger or the other fingers, the so-called finger span method. The aspect ratio can be seen as the ratio between the lengths of the two perpendicular axes. The effect of the aspect ratio can be most directly seen in the conditions 1, 3, and 4 (the conditions involving the blocks), as these conditions give the subjects no curvature information, but only the aspect ratio information. The relative aspect ratio can be expressed in terms of the difference between the long axis and the short axis:

$$\alpha - 1 = \frac{L + \Delta L}{L} - 1 = \frac{\Delta L}{L}, \tag{2}$$

where $L + \Delta L$ represents the long axis that can still be discriminated from the short axis L. The right side of this equation is a Weber fraction. This way we can compare the Weber fractions found in the literature for length discrimination with our results for the threshold of the relative aspect ratio.

In a few studies, the just noticeable difference (JND) was reported with respect to a reference stimulus. These JNDs were determined by use of the finger span method. In this method, the subjects were asked to feel the distance between two plates by holding them between the thumb and the index finger. Unfortunately, the exact definitions on which the JNDs of these studies were based, were not always reported, so our comparison is done tentatively. A wide range of Weber fractions have been reported [16], [17], [18], [19], [20]. The length of the axes of our stimuli was around 70 mm. Weber fractions found around this reference length vary from 0.01 with a 50 mm reference length [16] to 0.03 with a reference length of 80 mm [18], [20]. Our results fall within this range, with the exception of the results of condition 4, where edges are also felt. It is important to note that in our experiment the stimulus was explored with all fingers of the hand and not with only the thumb and index finger. When all the fingers were opposing the thumb, the distance between each of the fingers and the thumb was different. As our results fall within the range reported in previous studies, the different distances do not seem to influence the overall perception.

In Berryman et al. [21] the contribution from proprioceptive and cutaneous receptors was disentangled by anesthetizing the fingers. The subjects were asked to estimate the size of stimuli by the finger span method in both anesthetized and normal conditions. They found that proprioceptive information alone provides only a rough estimate of object size. The influence of cutaneous input is also apparent in the comparison between blocks and cylinders in this experiment. Curvature in static touch is perceived by cutaneous receptors, while distance between the fingers is felt by proprioceptive receptors. As we found a lower threshold for condition 2 than for condition 1, one could argue that the extra information on curvature from the cutaneous receptors causes a lower threshold. However, it is not possible to disentangle cutaneous from proprioceptive cues completely, as was done in Berryman et al., because in the condition with the blocks there still is stimulation of cutaneous receptors.

4.2 Curvature

The influence of curvature can be related to previous findings on discrimination between curvatures. Curvature (k) is defined as $k = R^{-1}$, where R is the radius of a circle with the same curvature as the surface under consideration. Goodwin et al. [5] investigated discrimination of curvature in a static and passive condition for the index finger. In their experiments, they found that the discrimination threshold between a convex surface and a flat surface was $4.9\ \mathrm{m}^{-1}$ and that between two convex surfaces, a curvature of $144\ \mathrm{m}^{-1}$ could be distinguished from a curvature of $158\ \mathrm{m}^{-1}$, which is a $14\ \mathrm{m}^{-1}$ difference in curvature.

If one takes only curvature into account, one can calculate a threshold for orientation, that is based solely on the difference in curvature at the ends of the long and short axes. This can be done be rewriting the equation for an ellipse (3) and taking the second derivative (5) at the end of one of the axes

$$\frac{x^2}{(b/2)^2} + \frac{y^2}{(a/2)^2} = 1, \tag{3}$$

$$y = \pm(a/2)\sqrt{1 - \frac{x^2}{(b/2)^2}}, \quad (4)$$

$$\frac{d^2y}{dx^2} = \frac{(a/2)x^2}{(b/2)^4\left(1 - \frac{x^2}{(b/2)^2}\right)^{3/2}} + \frac{a/2}{(b/2)^2\sqrt{1 - \frac{x^2}{(b/2)^2}}}. \quad (5)$$

Here, a and b are the long and short axis, respectively. From (5) it follows that the curvature (second order derivative) at the tip of the long axis ($x = 0$) is:

$$k_a = \frac{2a}{b^2}, \quad (6)$$

and the curvature at the tip of the short axis can be calculated in a similar manner to be:

$$k_b = \frac{2b}{a^2}. \quad (7)$$

The difference between these two curvatures is what can be compared to the values found by Goodwin et al. [5].

In our experiments, thresholds for which the orientation of cylinders could be detected, ranged between 1.014 and 1.027. Using the fact that the product of the two axes always equals $4{,}900\ \mathrm{mm}^2$, one can calculate a and b. Substituting these values in (6) and (7) leads to a range of curvature thresholds of 1.19 to $2.28\ \mathrm{m}^{-1}$. There is a difference in the reference used by Goodwin et al. [5] and our experiment. In their experiment, the references were either a flat surface, which has a curvature of $0\ \mathrm{m}^{-1}$, or a surface with a curvature of $158\ \mathrm{m}^{-1}$. The curvatures in our experiment were around $28.6\ \mathrm{m}^{-1}$. Our findings for curvature are lower than both values found in Goodwin et al. [5], but the range of curvatures in which we did our experiment was different from their range. Furthermore, we must bear in mind that the tasks with which these thresholds for curvature discrimination were determined differ greatly. In Goodwin et al. [5], the subjects were passively presented with curved surfaces on the pad of the index finger. In our experiment, the subjects actively felt the curvature of two opposing sides of a cylinder and compared it to two other opposing sides.

Pont et al. [22] also reported curvature discrimination thresholds. They used stimuli from $-4\ \mathrm{m}^{-1}$ to $+4\ \mathrm{m}^{-1}$. Subjects were asked to feel the curvature with different combinations of three, two, or one finger on different positions on a curved surface. In a control experiment, curvature discrimination thresholds for the middle finger were found. These thresholds ranged from $8.3\ \mathrm{m}^{-1}$ to $14.5\ \mathrm{m}^{-1}$. These exceed the measuring range of their stimuli and thus were not well defined. Our result for curvature discrimination is lower than these results. Similar points of discussion can be made as in the comparison with the values found by Goodwin et al. [5], with the exception that in Pont et al. [22] subjects actively felt the curvature.

4.3 Change in Curvature

Unlike curvature itself, thresholds for change in curvature are much more difficult to determine. From our experiment, it is clear that feeling the change in curvature in addition to the local curvature, allows subjects to discriminate the orientation of a cylinder for lower aspect ratios than if change in curvature is not felt. This is probably due to feeling the continuous change of the curvature, which gives more information than feeling only two points.

4.4 Edges

Plaisier et al. [23] showed that edges and vertices are salient features in a haptic search task. In the search task they constructed, a target of one shape had to be detected among distractor items of a different shape. The shapes consisted of cubes, spheres, tetrahedrons, cylinders, and ellipsoids. The presence of edges helped in distinguishing cubes and tetrahedrons from spheres and ellipsoids. However, in our experiment the edges did not contribute to determining in which orientation the block was placed. As the edges contain no information regarding the orientation, one would not expect them to play a role in this experiment. When subjects are asked to explore the block freely, one would expect a better performance as more information, such as information from sliding the fingers along the sides, is added to the cues available. As our results show, this assumption is incorrect. The threshold increases with 46 percent, even with the added information from freely exploring the stimulus. The influence of this information and the edges cannot be directly disentangled in this setup, but the presence of edges can be said to raise the threshold with at least 46 percent. Therefore, it is clear that feeling edges has a big disruptive influence on the determination of the orientation of a block.

Other experiments, in which edges do not contribute, but could play a disruptive role, show similar effects. Van der Horst and Kappers [11] found that when humans are asked to distinguish blocks with a rectangular cross section from blocks with a square cross section, they are less accurate than when distinguishing cylinders with an elliptical cross section from ones with a circular cross section. Van der Horst and Kappers [11] used similar cylinders as those used in our experiment, but the blocks were chosen to have a circumference equal to the circumference of the cylinders. This means that the axes of the blocks they used were smaller than those used in our experiment, where the axes of the blocks were equal to the axes of the cylinders. Roland and Mortensen [10] found that when humans are asked to distinguish the more oblong object, they are more accurate in ellipsoids than in cuboids. Both studies concluded that the curvature is used in a reliable and efficient way. From our experiment, it can be seen that this conclusion is only a part of the explanation. The presence of the edges also plays a role in the increase in detection threshold for blocks.

5 Conclusion

This experiment shows that local features can be used effectively in determining global properties, but they can also cause the performance to deteriorate. With the current setup, we are able to quantify this influence for curvature and change in curvature and give a lower limit on the influence of the edges. Both curvature and change in curvature on the cylinder give extra information on the global shape and therefore increase the performance, whereas edges, as salient features, distort the perception of the overall shape, thereby decreasing the performance. The influence of local properties depends on whether they contribute information on the global shape or not. Salient features that do not contribute information on the global shape, distort the accuracy of the perception of the global shape.

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