Haptic perception of curved shapes

ISBN: 978-90-393-4869-7

Haptic perception of curved shapes

Haptische waarneming van gekromde vormen
(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht
op gezag van de rector magnificus, prof.dr. J.C. Stoof,
ingevolge het besluit van het college van promoties
in het openbaar te verdedigen

op maandag 8 september 2008 des middags te 4.15 uur

door

Bernard Johannes van der Horst
geboren op 21 februari 1979 te Gorssel

Promotor: Prof. Dr. A.M.L. Kappers

The research described in this thesis was supported by a grant from the Netherlands Organisation for Scientific Research (NWO)

Contents

1 Introduction

In order to grasp and manipulate objects with our hands, we need accurate and constantly updated information about the shape and changes in the shape of objects that we employ. The sensitivity of the fingers for shape is indispensable in providing this information. In this thesis, the ability to use the hand in the perception of object shape is investigated.

1.1 Haptic exploration

Haptics refers to the perceptual aspect of human hand functioning. The haptic sense is characterized by the variety of ways in which the hand can be used to acquire information from an object. One distinction that can be made is between active and passive touch. Active touch means that the contact is controlled by the observer; passive touch is equivalent to being touched, which does not require control (Loomis and Lederman 1986; Chapman 1993). Another distinction that can be made is between dynamic and static touch. Dynamic touch is characterized by movement contact between the observer and the object. In general, the movement is executed by the observer on the object, but the reverse scenario is also possible. In static touch, the contact between observer and object is motionless. A special aspect of the haptic sense is the variety of body parts that are involved. Touching can be done with the tip of a single finger, with the whole finger, or with the complete hand; either the palmar or dorsal side can be used; fingers within the hands can be combined, or both hands can be used. Lederman and Klatzky (1987) proposed that the manner of exploration depends on the class of information that the observer attempts to achieve.

1.2 Haptic perception of object shape

Klatzky et al. (1985) and Lederman and Klatzky (2004) have studied the ability to identify common objects, like kitchen supplies, when only the hands are used. They showed that humans are fast and accurate when they are free in their manner of exploration, but performance decreases when the exploration is constrained.

Recognition of objects can be based on combining information about several properties, such as size, shape, temperature, compressibility, roughness, and weight. The role of shape information in object recognition can be studied by creating objects that differ in shape but are made from the same material. Newell et al. (2001) created non-familiar objects from LEGO bricks; Norman et al. (2004) made solid copies of bell peppers; Cooke et al. (2007) produced a set of non-familiar 3D objects that not only varied systematically in shape but also in texture. These objects were especially designed to compare performance in haptic object recognition to visual or cross-modal object recognition. They are less sufficient for studying haptic shape perception in a systematic way, since the objects that are used have quite complex shapes.

A more systematic manner in which to study the haptic perception of object shape is by using stimuli that can easily be described by geometry. Lakatos and Marks (1999) used polyhedrons and polyhedrons with local deformations to study similarity judgments. They found that these judgments were primarily based on local object features, but the global shape was weighted more heavily with an increase in exploration time. Roland and Mortensen (1987) studied the discrimination performance of objects like ellipsoids, spheres, and parallelepipeda that slightly differed in size. They found a high performance for the ellipsoids, which are characterized by differences in local curvature.

Instead of concentrating on the shape perception of complete objects, the perception of local shape can be investigated. At a local level, the shape of a smooth object can be described by the curvature, which is defined as the reciprocal of the radius of either a circle or a sphere. One way to investigate the perception of curvature information is by using a range of stimuli with well-defined curvature profiles that differ only slightly. Discrimination experiments can be performed to establish how much the shapes should differ in order to be distinguishable.

As mentioned, many exploration modes can be used to acquire object information by touch. The manner of exploration might determine how sensitive humans are in perceiving shape information. Moreover, the conversion from physical shape to mental percept might depend on the means by which the information is obtained. For example, two object surfaces with an identical shape profile might be judged differently when compared with the left and right hand. Or, to give another example, the perception of the curvature of a surface might depend on what we have touched before.

The studies that are presented in this thesis report the findings of several psychophysical experiments on the haptic perception of shape information. These experiments were conducted to establish how the haptic perception of shape depends on the exploration mode. The purpose was to obtain a better understanding of the capabilities of humans in using their haptic sense and to provide greater insight into the representations underlying haptic perception. In the following sections, the topics of the different chapters are introduced by providing a synopsis of the literature on haptic shape perception.

1.3 Haptic curvature discrimination

Several studies have been conducted to investigate the human ability to perceive curvature by touch. Davidson (1972) let subjects judge whether weakly curved strokes felt convex, flat, or concave. The exploratory procedures that the subjects applied were then analysed. In most cases, the surfaces were touched by sweeping one, two, or several fingers along the contour. In some cases, the stimulus was touched by a static contact with several fingers. Performance was best when back and forth movements with several fingers were made. Gordon and Morison (1982) measured discrimination thresholds when curved surfaces were touched dynamically with the tip of the index finger. Their findings indicated that the slope difference over the stimulus surface was the effective parameter on which the judgment of curvature was based.

Curvature perception in static touch was investigated by Goodwin et al. (1991). They applied spherically curved stimuli on a single fingerpad and found that a shape with a curvature of about 5 m^{-1} could be distinguished from a flat surface at a 75% correct level. Pont et al. (1997) established the ability to perceive the shape of curved strips that were statically touched with different parts of the hand. They found that performance increased with contact length. Their findings suggest that the magnitude of the threshold was primarily determined by the total slope difference over the stimulus surface, which is in accordance with the results of Gordon and Morison (1982). However, their supposition was based on dynamic touch. Extensive experiments on dynamic touch were performed in later studies by Pont et al. (1998, 1999). These studies confirmed that the slope difference is the main geometrical parameter on which curvature perception is based in static as well as in dynamic touch. Further validation was provided by Louw et al. (2000, 2002a), who studied detection and discrimination of Gaussian-shaped stimuli. They found that thresholds increased with a power of 1.3 with the width of the shape, which indicates that the threshold is mainly determined by the slope but also in part by the curvature of the shape.

In most of these studies, only a single finger was used to touch the stimuli. Moreover, the stimuli that had to be compared were touched sequentially by the same finger. Other studies have been performed in which the whole hand was used to perceive curvature. Discrimination performance was better when the stimuli were touched by successive unimanual exploration than by simultaneous bimanual exploration (Kappers et al. 1994; Kappers and Koenderink 1996). Moreover, idiosyncratic biases were found in dynamic bimanual curvature discrimination tasks (Kappers et al. 1994; Kappers and Koenderink 1996; Sanders and Kappers 2006). A bias represents a systematic curvature difference between two shapes that are touched with different hands but are perceived to be similar.

The preceding overview shows that several studies have been conducted on dynamic curvature discrimination with the single finger of the preferred hand, but neither the ability to perceive curvature with other fingers nor the ability to compare curvature when different fingers are applied on different shapes have been investigated. Curvature discrimination studies in which the whole hand was used suggest that performance may depend on the finger that is used and the manner in which the finger is employed.

In Chapter 2, we investigate how the ability to perceive curvature by dynamic touch with the fingers depends on several exploration variables. One way of comparing the curvature of two surfaces is by subsequently touching both surfaces with the same finger, as in previous studies. We tested whether sensitivity depended on the finger that was used for this task. Another manner to compare the curvature of two surfaces is by using different fingers for each surface. In that case, sensitivity to perform this task may deviate from the situations in which only a single finger is used, and biases may occur. In both the one- and two-finger conditions, the stimuli were explored sequentially. However, in the bimanual conditions of the previously discussed whole-hand discrimination experiments, the stimuli were generally touched simultaneously (Kappers et al. 1994; Kappers and Koenderink 1996; Sanders and Kappers 2006), which seems a natural way for comparing two entities. We wondered whether the ability to discriminate curvature was affected by sequential or simultaneous exploration and tested this for the bimanual discrimination with the index fingers.

The experiments that are described in Chapter 2 were all performed on convex shapes. Convex is defined as outward pointing, whereas concave is defined as inward pointing. Several studies have shown that shape discrimination performance is similar for convex and concave shapes (Goodwin et al. 1991; Kappers and Koenderink 1996; Pont et al. 1997; Louw et al. 2000, 2002a). In all these studies, a comparison between congruent shapes had to be made; that is, a convex shape had to be discriminated from another convex shape, or a concave shape had to be distinguished from another concave shape. However, no comparison between the curvature of a convex shape and the curvature of its concave counterpart was made. In Chapter 3, we investigate the performance for the discrimination of these opponent shapes and compare the results to the performance for congruent shapes, as were studied in chapter 2. Experiments were conducted for both unimanual one-finger conditions and bimanual two-finger conditions.

In the experiments described in Chapters 2 and 3, the stimuli that were used are surface parts with a constant curvature. In Chapter 4, we transition to using complete objects as our stimuli. We wondered how the ability to perceive curvature could be used when subjects had to distinguish between the shapes of full objects. An experiment was performed in which elliptical cylinders had to be distinguished from circular cylinders. For comparison, rectangular cuboids had to be distinguished from square cuboids. The finding of a better performance for the elliptical stimuli would indicate that curvature information could be used in an appropriate manner.

1.4 Haptic curvature representation

All studies referred to in the previous section used a psychophysical approach to establish the ability to perceive curvature. A different way to study the perception of shape information is by using a neurophysiological approach. Neurophysiological studies attempt to correlate activation in the nervous system to the impression of the shape of an object on the skin. Four types of mechanoreceptive afferents innervate the human skin. These cutaneous receptor units are classified on basis of adaptation properties and on basis of receptive-field properties. Slowly adapting units respond with a sustained discharge to stimulus information; fast adapting units respond only at the onset and removal of a stimulus. Type I units have small receptive fields, while type II units have large receptive fields (see e.g., Johansson and Vallbo 1983; Johnson 2001).

Goodwin et al. (1997) and Jenmalm et al. (2003) have investigated how these different afferents respond to curvature information. They applied spherically curved stimuli to a single fingerpad and measured the responses of several units. It was found that the responses of slowly adapting type I receptors (SAI) and fast adapting type I receptors (FAI) were correlated with the curvature of the stimuli. However, as Goodwin and Wheat (2004) argued, shape information cannot be deduced from the response of an individual mechanoreceptor, only from the response profile of a whole population of receptors. Technically, it is impossible to measure the response of a whole population at the same time, although it remains possible to build models of the population on the basis of individual responses.

Neurophysiological methods are useful for obtaining detailed information about the processing of shape information but are limited in providing a complete picture of the representation of shape information. A psychophysical approach that can be used to achieve more insight into the representation underlying shape perception is studying curvature aftereffects. A curvature aftereffect is the phenomenon whereby a flat surface feels concave (convex) following the prolonged adaptation to a convex (concave) surface. In general, aftereffects occur for several properties that are perceived by the senses. The study of aftereffects is attractive, because it enables a connection between perceptual phenomena and neural processes.

The existence of a curvature aftereffect in dynamic touch was reported by Gibson (1933). Vogels et al. (1996, 1997, 2001) demonstrated the occurrence of an aftereffect in static touch, when the whole hand was applied on spherically curved surfaces. In Chapters 5 and 6, we study the aftereffect for single-finger static and dynamic touch to investigate how the representation of curvature information depends on the exploration mode. Pont et al. (1999) showed that similar curvature discrimination thresholds were found for static and dynamic touch. However, a finding of similar thresholds does not entail that similar processes are involved in the representation of curvature by static or dynamic touch.

In chapter 5, we establish the occurrence of an aftereffect when spherically curved surfaces are touched by a single finger and investigate whether this effect transfers between fingers of the same or different hands. Transfer means that adaptation with one finger induces an aftereffect in another finger. In Chapter 6, we study the occurrence and intermanual transfer of a curvature aftereffect in dynamic touch.

2 Curvature discrimination in various finger conditions

Van der Horst BJ, Kappers AML (2007) Exp Brain Res 177:304-311

Abstract The ability of humans to discriminate curvature was investigated for different finger conditions. The experiments were conducted in which subjects explored cylindrically curved stimuli by touch. Using a 2-alternative forced–choice procedure, discrimination thresholds and biases were measured for several conditions. In 1-finger conditions, reference and test stimulus were explored with the same finger, whereas in 2-finger conditions these stimuli were felt with different fingers. Similar thresholds were obtained for the 1-finger conditions, in which either the preferred or the non-preferred index finger or the thumb was employed. However, significantly higher thresholds were found for the conditions in which subjects used two fingers, either of the same hand or of different hands. Interestingly, even higher thresholds were obtained for a 2-finger condition in which subjects explored the stimuli simultaneously instead of sequentially. In addition, subject-dependent biases were found in the 2-finger conditions. We conclude that the number of fingers and the mode of exploration have a considerable effect on performance in a haptic task such as curvature discrimination.

2.1 Introduction

Humans can use their haptic sense in various manners to gather information about objects in the world around them. Generally the hands, and more specifically the fingers, are very important for obtaining information about properties, such as the texture and temperature, and the size and shape of an object. Depending on the substance, structure, or function of an object, humans use their hands and fingers in different fashions to obtain the information they want (see, for example, Lederman and Klatzky 1987). Quite some research has been done to study humans' abilities to haptically perceive object properties like edges, angles and curvature. Most studies have concentrated on how subjects perceive these properties when only a single finger is used (unimanual conditions). In natural situations, however, often different fingers and combinations of fingers are used when object properties are discriminated. To obtain an improved understanding of the haptic system, it is required to study how the performance of humans depends on the fashion in which the haptic sense is used in exploring shapes or shape properties like curvature.

Discrimination experiments in unimanual conditions have demonstrated that the effective stimulus for discriminating curvature is the attitude difference, the total change of local surface attitude (slope) over the stimulus surface (Gordon and Morison 1982; Pont et al. 1997, 1999). Moreover, Louw et al. (2000, 2002a) showed that, over a range of three decades, the discrimination threshold of Gaussian-shaped stimuli increased with a power of 1.3 with increasing stimulus width, confirming the earlier results that the attitude difference over a curved surface is an important parameter. Based on previous research, we expected that the curvature discrimination with the index finger would be based on differences in local attitude. It was of particular interest to see whether discrimination with only the thumb would give similar results.

Jansson and Monaci (2004) showed that using more fingers, instead of a single finger, improves performance in object identification tasks. However, discrimination experiments in which different fingers of the same hand were used (intramanual conditions) were only performed by Nefs et al. (2005), who studied grating discrimination. In the present study, we included a condition in which a subject had to discriminate a curved stimulus, explored with the index finger, from a curved stimulus, explored with the thumb.

It seems to depend on the nature of the task whether humans perform better in a unimanual (Kappers et al. 1994; Kappers and Koenderink 1996; Nefs et al. 2005) or in a bimanual condition (Ballesteros et al. 1997; Russier 1999). Besides, in the discrimination experiments on bimanual hand-sized curved surfaces, subject-dependent (idiosyncratic) biases were found (Kappers et al. 1994; Kappers and Koenderink 1996; Sanders and Kappers 2006). Although it seems more natural to use fingers of both hands to compare curvature, we cannot predict in advance whether subjects perform better when they use either one or two index fingers in discriminating curvature. With regard to the bimanual conditions, an interesting issue arises. In the experiments mentioned earlier, subjects explored the stimuli either sequentially or simultaneously. Although Weber (1834) already found that temperature and weight are easier discriminated when the hands are used sequentially instead of simultaneously, there has not been any further systematic inquiry into the differences between these modes of exploration in haptic tasks. Therefore, we designed an experiment in which sequential and simultaneous exploration was compared directly.

The aim of the present study was to examine how the ability to discriminate the object property curvature depends on the fingers and the combinations of fingers which are employed and the mode in which these fingers explore. More specifically, we investigated whether the discrimination performance depends on hand preference or on which finger is used (index finger or thumb). Furthermore, these unimanual conditions were compared to conditions in which two of those fingers were employed in the same condition, i.e. an intramanual and a bimanual condition. Finally, we determined whether performance is different when curvature is explored simultaneously or sequentially.

2.2 Experiment 1

2.2.1 Method

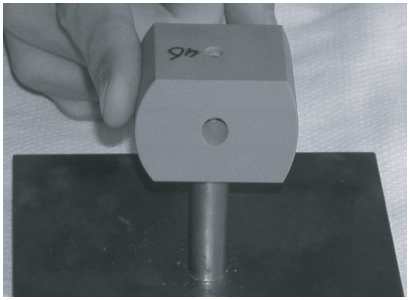
Subjects

Eight subjects (five male and three female, mean age 23 years) participated in both experiments. They were paid for their efforts and were naive with respect to the purpose of the experiment. A standard questionnaire established that six subjects were strongly right-handed, one was moderately right-handed and one was strongly left-handed (Coren 1993).

Stimuli

The stimuli were produced from small rectangular blocks made of a synthetic material, a compound of polyurethane foam and artificial resin (Cibatool BM 5460). A computer-controlled milling machine was used to make well-defined cylindrically curved surfaces on two opposite sides of a block. One curved side of each block, the reference stimulus, had a curvature equal to 33 m^{-1} (curvature is defined as the reciprocal of the radius of a cylinder). The curvature of the opposite side, the test stimulus, differed for each block and varied from 20 to 46 m^{-1} in steps of 1 m^{-1}. In addition, eight test stimuli were made with curvatures differing by ±0.3, 0.7, 1.3, and 1.7 m^{-1} from the reference stimulus. So a total number of 35 test stimuli were obtained. Fig. 2.1a illustrates a block that was shaped to present a reference stimulus and a test stimulus. The curvatures of the stimuli were consistently oriented as depicted in Fig. 2.1b.

a)



b)

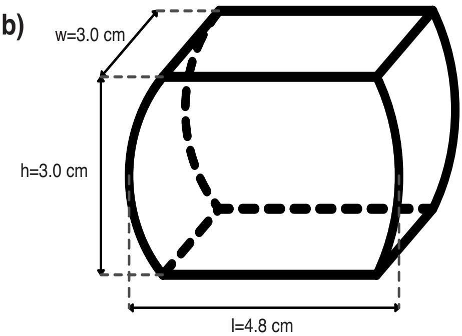


Fig. 2.1 a) Photograph of a block containing a reference and a test stimulus. A block was placed on a stand, which was placed on a table in front of the subject. The curved surfaces were always oriented with respect to the table as shown in the picture. A stimulus was explored as indicated. **b)** Schematic drawing of a block, for which the sizes are given. For each block, the curvature of the reference stimulus (the stimulus on the right of the drawing) was 33 m^{-1}. The illustrated test stimulus has a curvature of 46 m^{-1}, the highest curvature in the range from 20 to 46 m^{-1}.

Conditions

Five conditions were studied. In the 2-finger conditions, subjects used either the index finger and thumb of the preferred hand (A) or both the index fingers (B). In the 1-finger conditions, either the index finger of the preferred hand (C), the thumb of the preferred hand (D), or the index finger of the non-preferred hand (E) was used.

Setup

Subjects sat behind a table while their arms rested freely on the table. A curtain prevented them from seeing the stimuli. A block was placed on a stand (as depicted in Fig. 2.1a), which stood about 50 cm in front of the subject. In conditions B, C and E, the length direction of the block was perpendicular to the midsagittal plane. In conditions A and D, the blocks were slightly rotated (between 0 and 45°) to guarantee that subjects were able to explore the stimuli comfortably.

Subjects felt the stimulus, by passing the distal phalanx of a finger up and down over the stimulus surface. The axis of the finger was oriented perpendicular to the curvature, as done previously (Pont et al. 1999; Louw et al. 2000). They were asked to avoid systematic exploration of the edges of the stimulus surface, and the experimenter verified this. Subjects were instructed to explore the stimuli sequentially, although no delay was specified. The block remained in the same position in the 2-finger conditions, whereas it was turned 180°, between succeeding explorations of the 1-finger conditions.

Procedure

The discrimination experiments were conducted by means of a two-alternative forced-choice (2AFC) procedure: in each trial, a subject had to indicate which of the two presented stimuli felt more curved. No restrictions were imposed on the exploration time, the inter-stimulus interval, or the number of explorations of each stimulus. The subjects were not told that the reference stimulus occurred in all trials. They did not receive feedback on their performance.

Prior to the real experiments, we conducted some test trials in different conditions to obtain a rough estimate of a subject's threshold and possible bias. On the basis of these tests, an optimal stimulus set was chosen per subject-condition combination. In each condition, ten values of curvature difference were used, consisting of test stimuli with curvature values above and below the estimated threshold value (see Fig. 2.2 for some representative examples of stimulus sets). The order of presenting the reference stimulus and the test stimulus was counterbalanced for all conditions.

The experiment was performed in a pseudo random order. Each of the conditions consisted of 140 trials, which were divided into seven blocks of 20 trials. Each block contained ten values of curvature difference for both positions of the reference stimulus in random order. The first blocks of each condition were measured in a random order, followed by the second blocks of each condition, and so on. A number of complete blocks were measured in sessions of 1 h a day. It took a total number of 5–7 h per subject to complete the whole experiment.

Analysis

For each subject and condition, we calculated for all ten values of curvature difference the percentage of times the subject had responded that the stimulus on the index finger of the preferred hand (in the case of the 2-finger conditions) or first explored stimulus (in the case of the 1-finger conditions) felt more curved. A cumulative Gaussian distribution g as function of the curvature difference x was fitted to the data, using:

$$g(x) = \tfrac{1}{2}\left(1 + \mathrm{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right)\cdot 100\%.$$

Examples of these fits for the 2- and 1-finger conditions are given in Fig. 2.2. We used σ as a measure of the discrimination threshold. It is an important parameter because it indicates how sensitive subjects are in perceiving curvature differences in a certain condition. The μ is the shift or bias in the psychometric curve. It represents the curvature difference between two stimuli which were on an average judged equal. Such a bias could occur in a 2-finger condition, when a subject

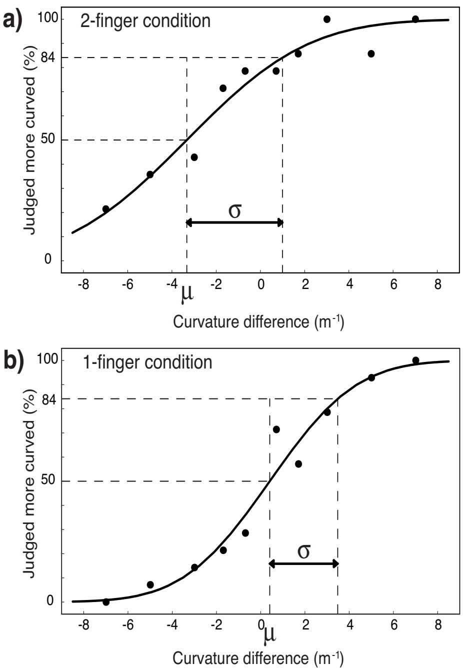


Fig. 2.2 a) Example of a psychometric function, fitted to a data set in a 2-finger condition. A data point represents, for a certain curvature difference, the percentage of times the subject judged the stimulus on his preferred index finger to be more curved than the stimulus on his other finger. The 50% point on the psychometric curve is indicated by a curvature difference μ. The discrimination threshold is represented by σ. **b)** Example of a psychometric curve in a 1-finger condition. Curvature difference is defined as the difference in curvature between the first and second explored stimulus. Again σ and μ are used as fit parameters, although the value of the latter is generally close to zero.

systematically underestimated the curvature on one finger with respect to the curvature on the other finger. A bias could not arise in a 1-finger condition.

The effect of condition on threshold was analysed by an ANOVA using a repeated measures design. Subsequently, conditions were pairwise compared. To correct for multiple comparisons, the p values were multiplied by the total number of possible comparisons (Bonferroni adjustment). In order to obtain an estimate of the confidence interval of the biases, a parametric bootstrap was used (see Wichmann and Hill 2001b for a general background on this technique). The level of significance was set at 0.05 for all statistical tests.

2.2.2 Results

Fig. 2.3a shows the mean values obtained for the threshold σ. The error bars indicate the standard errors of the mean for each condition without any correction for the variability in the mean thresholds for subjects. The ANOVA revealed a significant main effect of condition ($F_{4,28} = 8.7$, $p < 0.001$). Significantly higher thresholds were found for the 2-finger conditions compared to the related 1-finger conditions: A versus C and D ($p = 0.010$ and $p = 0.028$, respectively); B versus C and E ($p = 0.015$ and $p = 0.029$, respectively). No significant differences were obtained for comparisons of the various 1-finger conditions (C, D and E) and for a comparison of the 2-finger conditions (A and B).

Bias values μ were either positive or negative. In the 2-finger conditions, high values were found (significant in 9 out of 16 cases), which varied from subject to subject. Only low values were obtained in the 1-finger condition (with one exception, not significant). The means and the standard errors of the mean for the absolute values of the biases are: 2.3 ± 0.6 m^{-1}, 1.5 ± 0.7 m^{-1}, 0.33 ± 0.05 m^{-1}, 0.32 ± 0.07 m^{-1}, 0.44 ± 0.16 m^{-1}, for conditions A–E, respectively.

2.2.3 Control experiment

As aforementioned in the Method section, the block containing the stimuli remained in the same position in the 2-finger conditions, whereas it had to be rotated between consecutive explorations of the 1-finger conditions. As a consequence, subjects could transfer faster from the reference stimulus to the test stimulus in the former conditions in comparison to the latter. This difference in delay might have caused the difference in threshold between the 2-finger conditions and the 1-finger conditions. To exclude this possibility, an additional experiment was conducted without systematic differences in time lag.

The discrimination experiments were performed in a 1-finger condition (index finger of the preferred hand) and a 2-finger condition (two index fingers). Test and reference stimulus were on different blocks, so the experimenter had to substitute the stimulus between each exploration. The resulting inter-stimulus interval was about 3 s for both conditions. Five subjects (three male and two female; mean age 23 years; all strongly right-

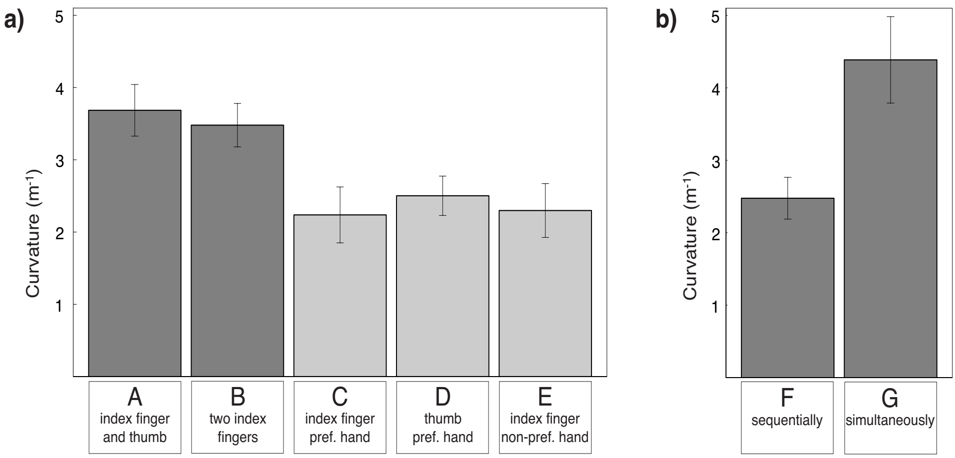


Fig. 2.3 a) Mean threshold for eight subjects in five different conditions. Condition *A*: index finger and thumb of the preferred hand; *B*: index fingers of both hands; *C*: index finger of the preferred hand; *D*: thumb of the preferred hand; *E*: index finger of the non-preferred hand. The indicated error bars are the standard error in the mean for each condition. N.B. In the error bars, no correction for general differences in sensitivity between subjects is taken into account. **b)** Mean thresholds for the same eight subjects in two different conditions. In both conditions subjects used two index fingers. In *F* the stimuli were explored sequentially and in *G* they were felt simultaneously.

handed) participated in this experiment. Blocks of each condition were measured alternately. The experiment took 2–3 h per subject.

The resulting mean values for the threshold σ are 4.2 ± 0.5 m^{-1} for the 2-finger condition and 3.3 ± 0.8 m^{-1} for the 1-finger condition. This difference was significant, according to a one-tailed paired t test (t = 2.2, p = 0.045). In conclusion, we can reject the hypothesis that a difference in time lag had caused the difference in performance between the 2-finger conditions and the 1-finger conditions.

2.2.4 Quantitative comparison with the literature

Previously, curvature discrimination experiments have been conducted in which a single finger was used. However, a direct comparison of the threshold values we found with those reported in the literature is not possible, because the range of curvatures that were used lies outside the range of our experiment. Nevertheless, Louw et al. (2000, 2002a) demonstrated that the curved surfaces can consistently be discriminated over a large stimulus range. Furthermore, Pont et al. (1997, 1998, 1999) showed that subjects mainly compare the slope differences over the stimuli they perceive. Thresholds expressed in slope differences were 3.4° and 4.1° for the results reported by Gordon and Morison (1982) and were between 3.3° and 5.3° for their own results (Pont et al. 1999). For the different 1-finger conditions (C–E), we converted the mean thresholds to slope differences, obtaining 4.5°, 5.0° and 4.6°, respectively. These values are rather similar to the earlier found slope differences.

The slope difference appears to be useful in comparing results of curvature discrimination experiments. Unfortunately, no comparison could be made with the results of Provancher et al. (2005), who conducted discrimination experiments in a similar range of curvatures as we did, but did not report the contact length that subjects made with the stimuli. A rather different experiment was performed by Henriques and Soechting (2003), who let subjects discriminate curvature by moving the handle of a robot arm along a virtual wall. A conversion of their thresholds to slope difference values gives 12° and 15°. This suggests that discrimination performance of real, curved surfaces with a single finger may be better than that of virtual, curved walls by manipulating the handle of a robot arm.

2.3 Experiment 2

In each condition of the first experiment, subjects explored the stimuli sequentially. The second experiment was developed to investigate whether there is a difference in discrimination performance between sequentially and simultaneously explored stimuli.

2.3.1 Method

The eight subjects of the first experiment also participated in the second experiment. The second experiment was conducted after completing the first. Condition F was identical to condition B of the first experiment. In condition G, subjects also used both index fingers, but they were instructed to pass their fingers simultaneously instead of sequentially over both the test and the reference stimulus. Discrimination experiments were performed, in which the same procedure was used as in the 2-finger conditions of the first experiment. Blocks of 20 trials of conditions G and F were measured alternately. Each subject took 1–2 h to complete the experiment.

2.3.2 Results

Mean threshold values are shown in Fig. 2.3b. The difference between the condition in which subjects used their index finger sequentially (F) and the condition in which they used them simultaneously (G) was significant (t = –4.5, p = 0.003). Subject-dependent biases were found in both conditions. In 11 out of 16 cases, these biases were significant.

2.3.3 Control experiment

Condition B of the first experiment and condition F of the second experiment were identical with respect to the task subjects had to perform. However, the mean thresholds were lower for F than for B: 2.5 ± 0.3 m^{-1} and 3.5 ± 0.3 m^{-1}, respectively (t = 5.1, p = 0.001). The difference we found in the second experiment between sequential exploration and simultaneous exploration might be due to the experience of subjects with the sequential condition. To discount this possibility, we replicated the second experiment with five new subjects (three male and two female; mean age 22 years; all strongly right-handed). The resulting mean values for the threshold are 4.1 ± 0.4 m^{-1} for the sequential condition and 8.7 ± 1.6 m^{-1} for the simultaneous condition, which is significant (t = 3.5, p = 0.013). Although experience might have influenced the results of the second experiment, it has not caused the difference in performance between sequential and simultaneous exploration. Although experience might have influenced the results of the second experiment (lower thresholds with repetition), the difference in performance between sequential and simultaneous exploration is, itself, an independent and robust finding.

2.4 Discussion

The discrimination experiments reported in this study revealed clear results. Similar thresholds were found for the various 1-finger conditions; the thresholds in both 2-finger conditions were also comparable. However, the thresholds obtained when two fingers were employed were significantly higher than those measured in the 1-finger conditions. Even higher thresholds were obtained when curvature was discriminated simultaneously instead of sequentially. In addition, subject-dependent biases were found in the 2-finger conditions. These biases strengthen the conclusion that the ability of humans to distinguish two physically different curvatures is better when one finger is used instead of two.

How can we understand the similar results for the 1-finger conditions? The similar ability of the two index fingers is in agreement with other haptic tasks in which one hand or a single finger was used (Kappers et al. 1994; Kappers and Koenderink 1996; Ballesteros et al. 1997; Russier 1999; Nefs et al. 2005). Perhaps more surprising is the similarity of the discrimination threshold for the index finger and the thumb, because they differ, for example, in number and size of the phalanges. On the other hand, similar results for both fingers were also found in the classical two-point threshold measurement (Weinstein 1968) and in grating orientation discrimination (Sathian and Zangaladze 1996). The latter results indicate a comparability in spatial acuity and thus of SAI afferents (Van Boven and Johnson 1994; Johnson et al. 2000; Johnson 2001), the afferents that are also important in the perception of curvature (Goodwin et al. 1991, 1995, 1997; Wheat et al. 1995). The similar performances with the thumb and the index finger are consistent with similar densities of innervation in the two digits, as indicated by Sathian and Zangaladze (1996).

While the index finger and thumb, separately, were equally good at discriminating curvature, significantly higher thresholds were obtained when subjects had to compare a curved surface presented to the index finger with one presented to the thumb. The higher thresholds obtained in the 2-finger condition of the curvature discrimination experiment may perhaps be due to the inability of subjects to spread their attention effectively across two stimuli explored with different fingers of the same hand. Experiments by Evans and Craig (1991) and Evans et al. (1992) showed that subjects have difficulty in focusing their attention on a stimulated finger, while another finger is being stimulated at the same time or is stimulated a short time later (response-competition). While in these experiments it did not matter whether the other finger was adjacent or not, other studies have shown that specifically neighbouring fingers influenced each other (Schweizer et al. 2000; Harris et al. 2001). Concerning the intramanual condition we studied, we can imagine that the representations of the stimuli presented to the index finger and the thumb interfered with each other in some way. Possibly, the obtained subject-dependent biases are also related to this interference.

Discriminating curvature is harder in a bimanual condition than in a unimanual condition, and in the bimanual condition it matters whether stimuli are explored simultaneously or sequentially. As mentioned in the Introduction, the nature of the task might determine whether subjects perform better in a unimanual or in a bimanual condition; no research has been done into the difference between sequential and simultaneous exploration. Decreased performance in a bimanual condition may stem from a degradation of the neural signal during interhemispheric relay (Charron et al. 1996; Bradshaw et al. 1998), although it cannot be ruled out that the interhemispheric processes are also involved in tasks in which only one hand is used (Schnitzler et al. 1995; Nefs et al. 2005). Just as in the intramanual case, interference between the percept of different fingers has been reported for bimanual conditions: A response-competition effect was found (Evans et al. 1992), and fingers of opposite hands influenced each other, in the same manner as occurred to neighbouring fingers of a single hand (Braun et al. 2005; Harris et al. 2001). Interestingly, the effects reported by Evans et al. (1992) and Braun et al. (2005) diminished when the time between the stimulation of both fingers increased. A change of result in time has also been shown in other haptic tasks (Vogels et al. 1996; Zuidhoek et al. 2003; Voisin et al. 2005). The time factor might perhaps explain why the performance of subjects improved when they had to discriminate two curvatures sequentially instead of simultaneously. The difference in threshold between the 2-finger conditions and the 1-finger conditions, on the other hand, cannot be explained by the factor of time because the difference persisted when the delay between explorations was controlled.

In conclusion, this study showed that the performance of humans in a haptic task like curvature discrimination clearly depends on the number of fingers and the mode of exploration. This kind of information should be taken into account in, for example, the design of haptic devices. It might also be relevant to surgeons who have to palpate the human or animal body but are deprived of visual information.

3 Haptic curvature comparison of convex and concave shapes

Van der Horst BJ, Kappers AML (2008) Perception (in press)

Abstract A sculpture and the mould in which it was formed are typical examples of objects with an identical, but opponent surface shape: each convex (i.e. outward pointing) surface part of a sculpture has a concave counterpart in the mould. The question arises whether the object features of opponent shapes can be compared by touch. Therefore, we investigated whether human observers were able to discriminate the curvatures of convex and concave shapes, irrespective of whether the shape was convex or concave. Using a 2-AFC procedure, subjects had to compare the curvature of a convex shape to the curvature of a concave shape. In addition, results were also obtained for congruent shapes, when the curvature of either only convex shapes or only concave shapes had to be compared. Psychometric curves were fitted to the data to obtain threshold and bias results. When subjects explored the stimuli with a single index finger, significantly higher thresholds were obtained for the opponent shapes than for the congruent shapes. However, when the stimuli were touched by two index fingers, one finger per surface, we found similar thresholds. Systematic biases were found when the curvature of opponent shapes was compared: the curvature of a more curved convex surface was judged equal to the curvature of a less curved concave surface. We conclude that human observers had the ability to compare the curvature of shapes with an opposite direction, but that their performance decreased when they sensed the opponent surfaces with the same finger. Moreover, they systematically underestimated the curvature of convex shapes compared to the curvature of concave shapes.

3.1 Introduction

A sculpture and the mould from which it was produced are typical examples of objects with an identical, but opposite shape. In contrast to the haptic system, the visual system is not always able to distinguish between identical shapes with an opposite direction (for example, the hollow face illusion). The special property of the haptic system is that it has direct access to objects. Obviously, subjects are able to discriminate a convex shape from its concave counterpart by touch. However, it is not yet known whether subjects are able to compare the properties of opposite shapes. Until now, studies in haptic shape perception have concentrated on the ability of human observers to compare the properties of similar objects, orientated in the same direction. Inspired by what is known from these studies, we wondered whether human observers are also able to compare the properties of object surfaces with an opposite shape.

The surface of a sculpture, or any smooth object, can be described locally by a single parameter, the curvature. The stimuli we used in this study were circularly curved cylinder parts, each part having a constant curvature value over the stimulus surface. Convex as well as concave shapes were used. By definition, a convex shape curves outwards, whereas a concave shape curves inwards. A convex and a concave surface with an identical curvature fit into each other like a sculpture and its mould (see Fig 3.1). In the experiments we performed in this study, a distinction was made between congruent modes and opponent modes. In a congruent mode, either two convex stimuli, or two concave stimuli were presented to a subject, whereas in an opponent mode, both a convex and a concave shape were presented.

The haptic perception of convex and concave shapes has been the subject of several studies. Experiments in which subjects had to distinguish a curved surface from a flat one (detection experiments) revealed no difference in detection threshold for convex and concave shapes, either when spherically curved surfaces were applied to the finger pad (Goodwin et al. 1991), or when subjects had to move their finger over zeroth or second order Gaussian shaped surfaces (Louw et al. 2000, 2002a). Similar thresholds for convex and concave stimuli were also found in experiments in which subjects had to indicate which of the two stimuli presented felt more curved (discrimination experiments). This was found both in conditions where cylindrically curved, hand-sized surfaces were actively explored (Kappers and Koenderink 1996), as in conditions where circularly curved strips were felt passively (Pont et al. 1997). The curvatures used in these experiments were between –5.7 m^{-1} and +5.7 m^{-1} and between –1.8 m^{-1} and +1.8 m^{-1}, respectively.

The finding that thresholds were

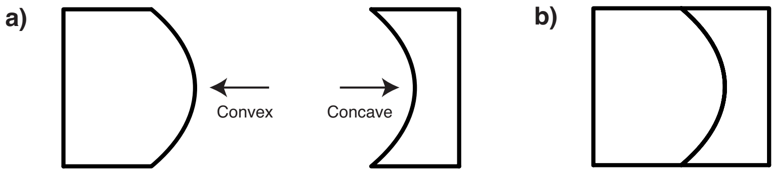


Fig. 3.1 a) Illustrations of a convex and a concave shape. **b)** A convex and a concave shape with the same curvature fit into each other like a sculpture and its mould.

similar for convex and concave shapes might be understood by the fact that the slope difference over the stimulus is a good first approximation for the effective stimulus for the discrimination of curvature (Gordon and Morison 1982; Pont et al. 1997, 1999). This concept is supported by a neurophysiological study by LaMotte and Srinivasan (1996). Extensive studies on curved surfaces by Louw et al. (2002a, 2002b) confirmed that subjects were particularly sensitive to the slope difference of the stimulus, but that the curvature of the stimulus was also of significant importance. Since a convex shape and its concave counterpart can be characterised by an identical slope difference and an identical curvature, it follows that their discrimination thresholds are the same. In the results reviewed so far, subjects had to compare the properties of convex surfaces to those of other convex surfaces, or the properties of concave surfaces to those of other concave surfaces. Asking subjects to compare the properties of a convex surface to the properties of a concave surface is quite a different matter. Specifically, subjects can be asked which of two surfaces presented feels the more curved. When subjects are able to perform this task by comparing the absolute values of the slope differences and curvatures of the stimuli directly, they will encounter thresholds similar to those they encounter when they have to compare convex (concave) shapes to other convex (concave) shapes. However, if the direction of the surface with respect to the external space or with respect to the finger influences their sensation, subjects might not be able to perform the task with the same facility. An additional research question is how subjects perform in this task when they use two hands. Van der Horst and Kappers (2007) studied the discrimination performance of convex shapes in a unimanual and in a bimanual mode, and found a higher threshold in the latter case. As can be seen in Fig. 3.2, in unimanual modes, congruent shapes are orientated in the same direction with respect to the external space, whereas opponent shapes are orientated oppositely. In contrast, in bimanual modes, congruent shapes can be oriented oppositely, whereas opponent shapes have the same direction with respect to the external space.

The aim of this paper is to explore how human observers haptically

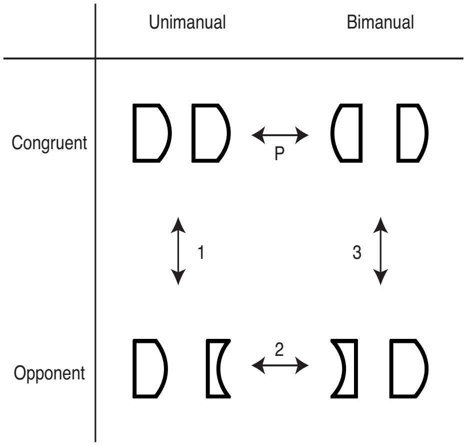


Fig. 3.2 Scheme of the experiments conducted in this study. The numbers refer to the experiments. **1**. Curvature discrimination performance was studied for congruent modes and opponent modes in a unimanual condition. The experiment was conducted for strongly curved stimuli and for weakly curved stimuli. **2**. Curvature discrimination performance was compared for a unimanual mode and bimanual modes. Opponently curved shapes were used. A similar experiment has already been conducted by Van der Horst and Kappers (2007) for congruent shapes (**P**). **3**. Comparison of curvature discrimination performance for congruent shapes and opponent shapes in a bimanual condition.

discriminate object surfaces that are described by the same physical curvature but vary in the orientation with respect to the fingers and with respect to external space. We investigated this in a series of experiments. We were interested in what respect the perception of opponent shapes differs from the perception of congruent shapes and why this difference occurs. We studied the influence of factors such as the degree of the curvature of the surfaces, the orientation of the stimuli with respect to the finger and to the external space, and the use of one hand or two hands. An overview of the experiments is given in Fig. 3.2.

3.2 Experiment 1

In the first experiment, we studied whether subjects can discriminate the curvature of opponent shapes with the same precision as they can discriminate the curvature of congruent shapes. Two parameters can be distinguished: the sensitivity of a subject (discrimination thresholds) and the point of subjective equality (bias). One would expect similar thresholds for the opponent mode and the congruent modes, since the slope difference and the curvature are the important cues in the curvature discrimination of congruent shapes. However, were a higher threshold to be found in the opponent mode this would indicate that not only the slope difference and curvature, but also the direction of the curved surface are important in shape perception. The second parameter, the bias, represents the curvature difference between two stimuli which were on average judged to be equal.

The experiments in this study were primarily performed with strongly curved surfaces (the curvatures used are similar to the curvature of a coffee cup). However, we decided to measure in addition the performance for weakly curved stimuli (the curvature of weakly curved stimuli are similar to the curvature of a water butt). For weakly curved stimuli, we know already that the discrimination performance is similar for convex and concave stimuli (Goodwin et al. 1991; Kappers and Koenderink 1996; Pont et al. 1997, Louw et al. 2000). When the slope difference and curvature are the only cues that subjects use, no differences between the congruent modes of the strongly curved stimuli are to be expected. However, since the index finger itself has a convex shape, the contact area of the finger with a concave surface is larger than the contact area of the finger with a convex surface, and, what is more, a shorter movement suffices to explore the whole stimulus surface. These differences in contact area and scanning length are probably negligible for long, weakly curved stimuli, but not for short, strongly curved stimuli. We hypothesize that, when strongly curved stimuli are used, a concave stimulus induces a stronger sense of curvature than a convex stimulus, although their physical curvature is identical. As a first consequence, lower thresholds might be obtained in the concave-concave mode than in the convex-convex mode, whereas similar thresholds are obtained for the weakly curved stimuli. Secondly, a systematic bias should occur when subjects have to compare the curvature of two strongly curved opponent shapes, but no systematic bias should occur when the weakly curved stimuli are used.

3.2.1 Method

Subjects

Six subjects participated (three female and three male, mean age 25 years). They were paid for their efforts and they were naive with respect to the design of the experiment. A standard questionnaire established that all subjects were strongly right-handed (Coren 1993).

Stimuli

Convex and concave stimuli with a constant curvature were used. A distinction was made between strongly curved stimuli and weakly curved stimuli. The strongly curved stimuli were made of a compound of polyurethane foam and artificial resin (Cibatool BM 5460). The curvature of the test stimuli varied from ±20 to ±46 m^{-1}, in steps of 1 m^{-1}. The curvature values of the reference stimuli were ±33 m^{-1}. The convex stimuli were already used by Van der Horst and Kappers (2007). The weakly curved stimuli were made of PVC. The curvature of these test stimuli varied from ±0.2 to ±3.8 m^{-1}, in steps of 0.2 m^{-1}. The curvatures of the reference stimuli were ±2.0 m^{-1}. This stimulus set was already used by Pont et al. (1998, 1999). Schematic illustrations of the stimuli are given in Fig. 3.3a-d. Although the materials of the weakly and strongly curved stimuli were different, their surfaces were both very smooth. We presented the stimuli in the same orientation as in the previous studies.

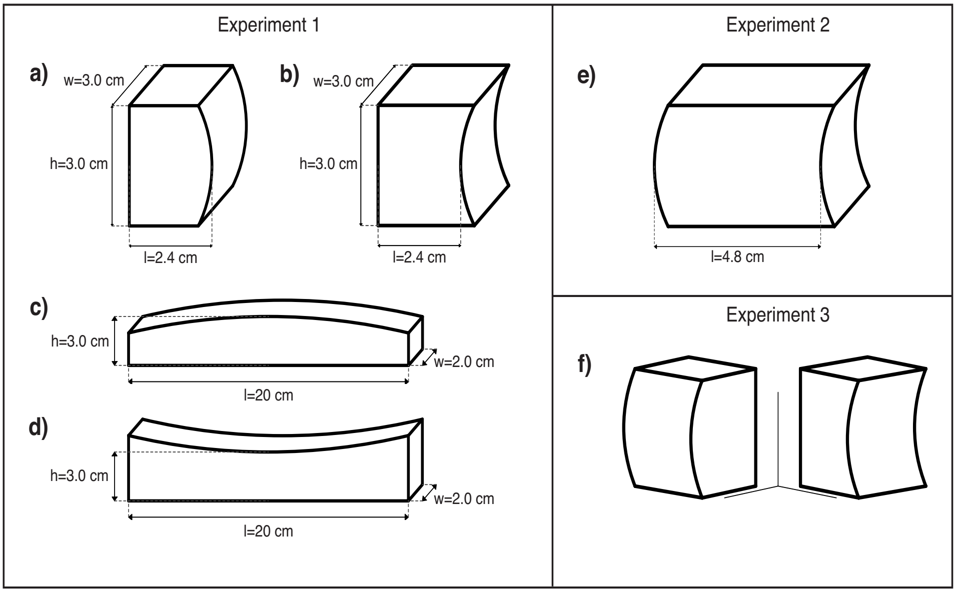


Fig. 3.3 Schematic drawings of the stimuli used in this study. First experiment: **a)** strongly curved convex stimulus, **b)** strongly curved concave stimulus, **c)** weakly curved convex stimulus, **d)** weakly curved concave stimulus. The sizes of the stimuli are given. Notice the difference in scale between the strongly curved stimuli and the weakly curved stimuli. The curvature of the strongly curved stimuli was 33 m^{-1}. The curvature of the weakly curved stimuli was 2.0 m^{-1}. The strongly curved stimuli were placed on a stand, 5 cm above the tabletop. The weakly curved stimuli were placed in a holder, directly on the table top. Subjects moved the tip of the index finger either upwards and downwards (strongly curved stimuli) or leftwards and rightwards (weakly curved stimuli) over the stimulus surface. Second experiment: **e)** example of a stimulus combination used for a bimanual condition. The surfaces were similar to the strongly curved surfaces of the first experiment. One index finger explored the convex surface, the other index finger explored the concave surface. Third experiment: **f)** example of a stimulus combination of two opponent shapes. The surfaces were similar to the strongly curved surfaces of the preceding experiments. The angle between the orientations of the stimuli is 90°. The horizontal distance between the middle parts of the two surfaces is 10 cm. Notice that the drawing depicts the backs of the stimuli. In this example, the convex surface was explored by the right index finger and the concave surface was explored by the left index finger.

Design and procedure

Six conditions were studied in a three (mode) x two (curvature) repeated measures design. In the opponent mode, convex shapes were compared to concave shapes; in the congruent modes, either convex or concave stimuli were used. All three modes were tested for both strongly curved stimuli and weakly curved stimuli.

Subjects were seated behind a curtain. Their forearm rested on a table. They put their right hand under the curtain to touch the stimuli without seeing them. The stimuli were presented in front of the subjects, 40 cm from the edge of the table. The strongly curved stimuli were placed on a stand; the weakly curved stimuli were placed in a holder on the table. Subjects explored the stimuli by passing the distal phalanx of their index finger to and fro over the stimulus surface. The axis of the finger was orientated perpendicular to the curvature.

Discrimination experiments were conducted by means of a two-alternative forced-choice (2AFC) procedure. In each trial, subjects had to indicate which of the two sequentially presented stimuli felt the more curved. No restrictions were imposed on the number of movements over the stimulus or on the number of alternations between the stimuli.[1] No feedback was provided to subjects regarding their performance.

In each condition, stimulus combinations of ten values of curvature difference were chosen, as specified below. Curvature difference is defined as the difference in the absolute curvature between either the convex and the concave stimulus (opponent mode) or the first and the second stimulus presented (congruent modes). In the opponent mode, we did not know in advance whether biases would occur, and, if they occurred we did not know whether they would differ between subjects. Hence, before beginning the actual experiment, we obtained an estimate of the bias level. We did this by performing a staircase experiment, with a simple up-down method (Treutwein 1995). Each trial in a sequence was determined by the outcome of the preceding trial in that sequence. Starting at two different curvature difference values, two sequences each consisting of 15 trials were randomly interleaved. The mean curvature difference value in the outcome of the last eight trials of both sequences was taken as the estimated bias level. The stimuli were chosen around this estimated bias level. This level was restricted to ± 4 m^{-1} for the strongly curved stimuli and to ± 0.4 m^{-1} for the weakly curved stimuli. In contrast to our expectations for the opponent mode, we did not expect biases to occur in the congruent modes. Therefore, the stimuli were chosen symmetrically around a zero level of curvature difference. The curvature difference of the stimuli with respect to the estimated bias level was $\pm$ 1, 3, 5, 7, 9 m^{-1}, for the strongly curved stimuli, and $\pm$ 0.2, 0.4, 0.6, 1.0, 1.4 m^{-1}, for the weakly curved stimuli, respectively.

Each condition consisted of 120 trials (10 curvature difference values x 12 repetitions), which were presented in a pseudorandom order: groups of all possible stimulus combinations were each randomised and presented successively. In one session, only a single condition was measured. Half of the subjects first performed the conditions with the strongly curved stimuli, whereas the other subjects started with the weakly curved stimuli. The order in which the modes were executed

[1] Extensive pilot experiments showed that the enforcement of restrictions resulted in a wider variance between subjects.

was counterbalanced among subjects. It took about six hours per subject to complete the whole experiment.

Analysis

For each subject-condition combination, the fraction of responses was expressed versus the curvature difference. Psychometric functions (cumulative Gaussians) were fitted to these data using a maximum-likelihood procedure. Examples of data sets and the accompanying psychometric functions are given in Fig. 3.4. The psychometric function is characterised by the threshold σ and the bias μ. The bias is the point of subjective equality. A positive bias value in the opponent mode means that the curvature of a more convex surface is on average judged to be equal to the curvature of a less concave surface. The threshold is defined as the curvature difference between the 84%-point and the bias level (50%-point). In order to establish the goodness of fit for each individual fitted curve, we used the method described by Wichmann and Hill (2001a). The deviance of the measured data set from the fitted curve is determined and compared to a distribution of deviances of 10,000 simulated datasets, obtained by a parametric bootstrap technique. The goodness of fit is poor when the deviance of the measured data set is higher than the 0.975 point of the percentile confidence interval of the distribution of deviances. The parametric bootstrap method was also used to obtain an estimate of the confidence level of each individual threshold and bias level (see Wichmann and Hill 2001b).

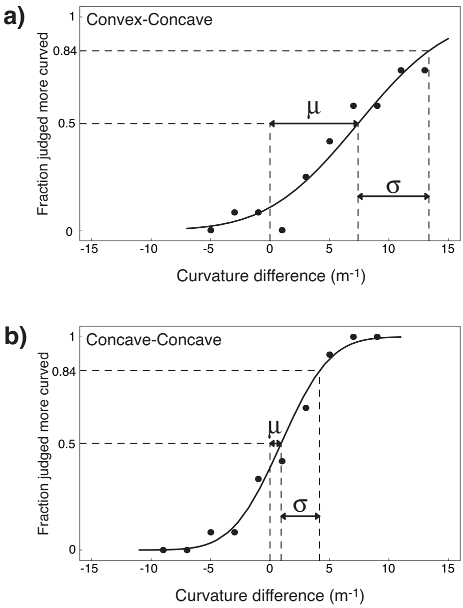


Fig. 3.4 Examples of psychometric curves for strongly curved stimuli in the opponent mode (convex-concave conditions) and the congruent mode (concave-concave conditions). Curvature difference is defined as the difference in the absolute curvature of either the convex and the concave stimulus (opponent mode) or the first and the second stimulus presented (congruent mode). The discrimination threshold is represented by σ; it is a measure of the sensitivity of subjects. The bias is represented by μ; it is the difference in the curvature of two stimuli that were judged to the equally curved. Biases occurred in the opponent modes, but were near zero in the congruent modes.

Results

Fig. 3.5a and 3.5b show the mean threshold values, for all conditions.

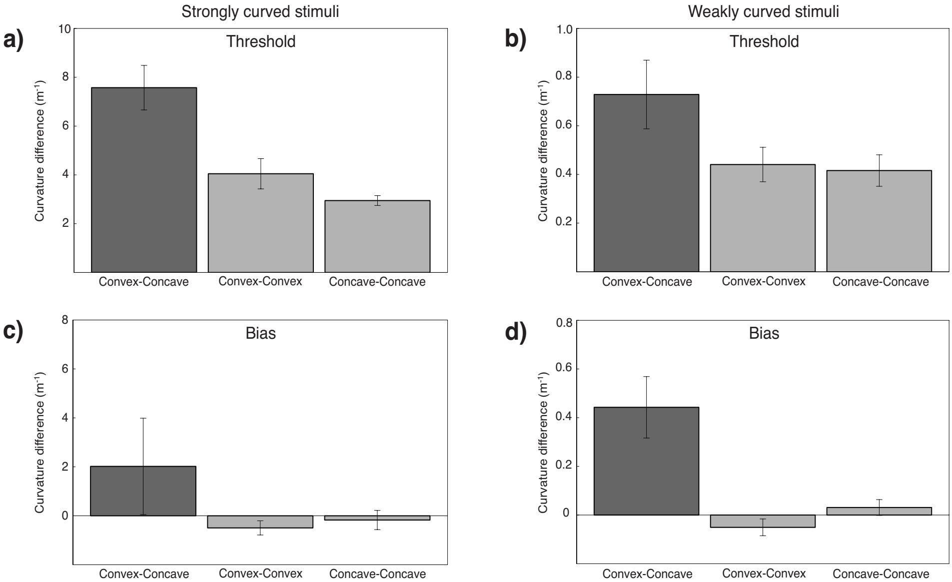


Fig. 3.5 Results of experiment 1. Each bar represents the mean value for six subjects in the specific condition. Note the difference in scale between the strongly curved stimuli (**a** and **c**) and the weakly curved stimuli (**b** and **d**). The error bars indicated are the standard error in the mean for each condition.

The error bars indicate the standard error for each condition without any correction for the variability in the mean thresholds for subjects. The thresholds were higher for the opponent modes than for the corresponding congruent modes; the thresholds for the congruent modes were comparable. The significance of the results was tested by a three (mode) x two (curvature) ANOVA with a repeated measures design. First, a significant main effect was found for mode ($F_{2,10}$ = 20.3, $p < 0.001$). As a further analysis we performed a planned comparison between, on the one hand, the opponent mode, and, on the other hand, the congruent modes. The contrast of the opponent mode versus the congruent modes was significant ($F_{1,5} = 27.6$, $p = 0.003$), but the contrast between the congruent modes (convex-convex versus concave-concave) was not significant ($F_{1,5} = 3.2$, $p = 0.1$). When repeated measures ANOVAs were performed for the two curvature regimes separately, the results were in accordance with the former analysis: the main effect was significant for the strongly curved stimuli ($F_{2,10} = 21.5$, $p < 0.001$) and the weakly curved stimuli ($F_{2,10}$ = 5.2, $p = 0.028$); the contrasts between the opponent mode and the congruent modes were also significant ($F_{1,5} = 30.0$, $p = 0.003$ and $F_{1,5} = 7.2$, $p = 0.043$, respectively), but no significant difference was found between the congruent modes ($F_{1,5} = 3.5$, $p = 0.1$, $F_{1,5} = 0.09$,

p = 0.8, respectively). Second, a main effect of curvature was found ($F_{1,5}$ = 99.8, p < 0.001). This reflects the fact that the thresholds were higher for the strongly curved stimuli than for the weakly curved stimuli. Third, the interaction of mode and curvature appeared to be significant ($F_{2,10}$ = 22.4, p < 0.001). This might, however, be ascribed to the effect of curvature, since no interaction effect was found when the ANOVA was performed on normalised data ($F_{2,10}$ = 2.9, p = 0.1).

The results for the biases are shown in Fig. 3.5c and 3.5d. The biases were on average positive for the opponent modes and near zero for the congruent modes. In the opponent modes, strong differences were found between subjects, as the error bars manifest. A t-test performed on each separate condition showed only a significant difference from zero for the convex-concave mode of the weakly curved stimuli (t_5 = 3.5, p = 0.017). We also looked at the significance of individual biases for all subjects in each condition, by comparing a bias value to an estimate of the confidence level. In the opponent mode, the bias was significant for four out of six subjects when the strongly curved stimuli were used and for five subjects when the weakly curved stimuli were used. For the congruent stimuli, only one significant bias was found in each condition.

The goodness of fit was tested for all 36 curves. With only one exception, all fitted curves were judged to be good. So we can be confident that our data are well described by the fits of the psychometric curves.

3.2.2 Discussion

This experiment revealed that discriminating the curvature of a convex from a concave shape is more difficult than discriminating the curvature of either a convex from a convex or a concave from a concave shape. No differences were found between the convex-convex mode and the concave-concave mode.

The threshold results for the convex-convex conditions can quantitatively be compared with the results of previous studies. First, the results for the weakly curved stimuli reproduced those of Pont et al. (1999), who found threshold values of 0.4 m^{-1}. Second, the results for the strongly curved stimuli were comparable to those of Van der Horst and Kappers (2007), who obtained 2.3±0.4 m^{-1} and 3.3±0.8 m^{-1}, in different experiments. Finally, when the stimuli and thresholds are recalculated in stimulus widths and height differences, they were consistent with Louw et al. (2002b).

The similarity in the thresholds for the congruent modes was found not only for the weakly curved stimuli, but also for the strongly curved stimuli. The former is in agreement with previous research (Goodwin et al. 1991; Kappers and Koenderink 1996; Pont et al. 1997; Louw et al. 2000). For the latter, we had suggested that subjects would obtain a stronger sense of curvature from a concave surface than from a convex surface, but we did not find this effect in our data. The results for the congruent conditions confirm that the curvature discrimination of convex from convex and concave from concave shapes is based on the same cues, which we suppose to be mainly the slope difference between the stimuli, and, to a lesser extent, the curvature (Pont et al. 1997, 1999; Louw et al. 2002a, 2002b).

The higher thresholds obtained in the opponent mode compared to the congruent modes rule out the possibility that the discrimination of two opponent surfaces can simply be reduced to the cues important for the congruent modes, namely, the slope difference and the curvature. Moreover, strong biases were found, which were on average positive. A positive bias means that subjects systematically underestimated the curvature of a convex stimulus compared to the curvature of a concave stimulus. This is consistent with the hypothesis that subjects might have obtained a stronger sensation from a concave stimulus than from a convex stimulus, due to a difference in contact area of the finger with the stimuli and a difference in scanning length of the finger over the stimulus surface. Although this hypothesis was originally formulated for the strongly curved stimuli and not for the weakly curved stimuli, we found only a significant effect for the weakly curved stimuli. However, the size of the biases we found differed to a great extent between subjects. Still, differences in contact area and scanning length might have played a role, but are certainly not the only factors that contributed to the biases we found.

One might wonder whether the difference in orientation between the strongly curved stimuli and the weakly curved stimuli might have influenced our results. However, the striking similarity in the results of the strongly curved stimuli and the weakly curved stimuli is a strong indication that this is not the case. Moreover, Pont et al. (1998) already showed that the size of the threshold was not affected by the orientation of the stimuli with respect to the external space. Therefore, we have no reason to expect that the results depend on the horizontal or vertical orientation of the stimuli.

The higher thresholds obtained in the opponent mode compared to the congruent mode and the occurrence of biases in the opponent mode might be related to the fact that, in the opponent mode, subjects had to compare the curvature of surfaces with an opposite direction with respect to the finger and with respect to the external space. Oldfield and Philips (1983) observed that the perceived orientation of a raised letter that indented the skin of the finger depended on the orientation of the finger and the body with respect to the external space. They suggested that subjects do not process skin indentation directly, but map tactile impressions onto a system of external references. When subjects had to discriminate same-shaped and mirror-shaped stimuli, they achieved faster reaction times and higher accuracy with the former, irrespective of whether mental rotation was required (Dellantonio and Spagnolo 1990; Prather and Sathian 2002). We can imagine that the mental process of curvature comparison is more complex for opponent shapes than for congruent shapes. In a congruent condition, subjects might be able to reduce their sensation directly to a slope difference and a curvature difference, whereas, in an opponent condition, they have to perform mental alignment operations, such as mental rotation or mirroring, before they are able to compare the slope difference and the curvature difference. However, another possibility is that subjects have difficulty in distinguishing signals from opposite shapes, obtained with one and the same finger. The second and third experiment were developed to address these issues.

3.3 Experiment 2

In all conditions of the first experiment, subjects used a single finger to explore each stimulus pair. In the second experiment, we compared the mode in which subjects used a single finger (unimanual mode) to the mode in which subjects used two index fingers, one finger per stimulus (bimanual mode). Previously, Van der Horst and Kappers (2007) conducted a similar experiment involving congruent (convex) surfaces. They found higher thresholds in the bimanual condition than in the unimanual condition, the difference being attributed to the fact that in a bimanual condition, signals have to be assembled from different fingers.

In the current experiment, only opponent stimulus combinations were used. The results of Van der Horst and Kappers (2007) supported the expectation that higher thresholds might be found in the bimanual mode. However, an advantage in this mode might be that the opponent surfaces are not sensed by the same finger. Subjects might also benefit from the fact that, in the bimanual mode, the surfaces are parallel in the external space, as can be seen in Fig. 3.3e.

3.3.1 Method

Twelve, right-handed subjects (five female and seven male, mean age 23 years), who were not involved in the first experiment, participated. They were paid for their efforts and they were naive with respect to the design of the study. The strongly curved stimuli of the first experiment were used. Three conditions were studied: one unimanual condition and two bimanual conditions. The unimanual condition was identical to the opponent condition of the first experiment: a convex and a concave stimulus were presented successively to the right index finger. In the bimanual conditions, the convex surface was presented to the index finger of the right hand and the concave surface was presented to the index finger of the left hand, or vice versa. Fig. 3.3e shows a stimulus in a bimanual condition. The distance between the middle points of the left and right surfaces was 4.8 cm. The procedure was similar to that of the first experiment. No restrictions were imposed on the exploration time or on the number of explorations of each stimulus, but they were not allowed to explore two stimuli simultaneously. The number of trials and the stimulus choice procedure were identical to the opponent condition of the strongly curved stimuli in the first experiment. For each subject, the first session was devoted to obtaining an estimate of the bias level in each condition. In the subsequent three sessions, the actual experiment was performed in which the data for the psychometric curves were obtained. The order in which subjects completed the experiment was counterbalanced. Each subject took three to four hours to complete the whole experiment.

3.3.2 Results

The results are shown in Fig. 3.6. On average, a slightly higher threshold value was found in the unimanual condition compared to the bimanual conditions. However, the ANOVA with a repeated measures design showed no significant main effect ($F_{1.3,13.7} = 3.4$, $p = 0.08$, $\varepsilon = 0.625$). The degrees of freedom were corrected by a Greenhouse-Geiser ε-correction.

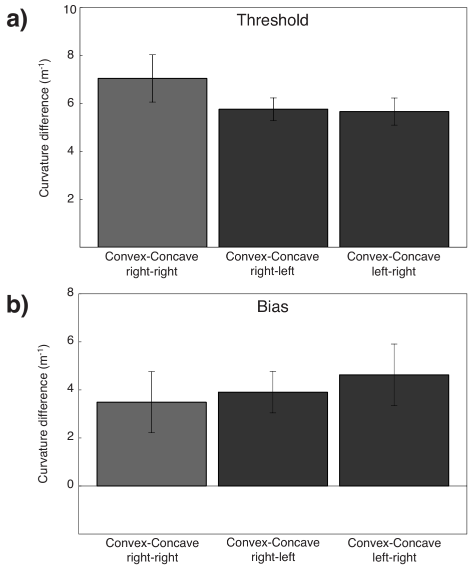


Fig. 3.6 Results of experiment 2. Each bar represents the mean value for 12 subjects in the specific condition.

The biases were on average positive. In each condition, a significant deviation from zero was found, as *t*-tests confirmed ($t_{11} = 2.7$, $p = 0.019$ for the unimanual condition and $t_{11} = 4.5$, $p = 0.001$ and $t_{11} = 3.6$, $p = 0.004$ for the two bimanual conditions, respectively).

Each individual psychometric curve was judged to be good, according to the goodness of fit test.

3.3.3 Discussion

Unlike the results of Van der Horst and Kappers (2007), who found an increase in threshold from the unimanual condition to the bimanual condition, the current experiment showed no increase in threshold from the unimanual to the bimanual mode. Nevertheless, in the previous study congruent stimuli were used, whereas in this experiment we used opponent stimuli. Apparently, the disadvantage of a bimanual comparison (assemblage of signals from different fingers) compared to a unimanual comparison, was countered by some advantageous factors, such as the parallelity of the surfaces in the external space, or the fact that the fingers did not have to alternate between a convex and a concave surface. To study this more thoroughly, a third experiment was performed.

No differences in threshold were found between the two bimanual conditions. This is in agreement with previous results, i.e., no differences were found in the ability to discriminate the curvature of only convex surfaces or concave surfaces (first experiment) or the ability to discriminate curvature with only the right index finger or the left index finger (Van der Horst and Kappers 2007).

Significant, positive biases were found in each condition. Although the size of the bias varied again from subject to subject, the mean bias was clearly positive.

3.4 Experiment 3

In the third experiment, subjects bimanually discriminated the curvature in two modes, one with opponent shapes, the other with congruent shapes. To rule out any advantage of the orientation of the stimuli in external space, we placed the stimuli at perpendicular orientations (see Fig. 3.3f). If the orientation of the surfaces is important and subjects have more difficulty in comparing the curvature of opponent shapes than that of congruent shapes, a higher threshold might be expected for the former comparison. Otherwise, results might be similar.

3.4.1 Method

Six, paid, right-handed subjects (five female and one male, mean age 23 years) participated.[2] They were naive with respect to the design of the experiment and were not involved in the previous experiments. The strongly curved stimuli were used. Two bimanual conditions were studied. In one condition, a convex surface was explored by the right index finger and a concave surface was explored by the left index finger. In the other condition, only convex surfaces were used for both index fingers. The stimuli were placed 40 cm from the edge of the table. The distance between the middle points of the left and right surfaces was 10 cm. The angle between the imaginary normals at the middle points was 90°. Fig. 3.3f shows an example of the stimuli for the opponent

[2] We had to exclude another subject (male, 59 yr) from the experiment. For this subject, the preliminary experiment conducted to obtain an estimate of the bias revealed a bias that was far outside our measurement range.

mode. The procedure, the number of trials, and the stimulus choice were similar to the procedure followed in previous experiments. The measurement of a single condition (estimate of the bias and the actual experiment) was performed in a single session. The order in which subjects completed the experiment was counterbalanced. Each subject took about two hours to complete the whole experiment.

3.4.2 Results

Fig. 3.7 shows the results. The results for the thresholds were similar. A two-tailed t-test confirmed that there was no significant effect ($t_5 = 0.28$, $p = 0.8$). The biases were on average positive, but, for each condition, did not differ significantly from zero ($t_5 = 2.2$, $p = 0.084$ for the opponent condition and $t_5 = 2.3$, $p = 0.068$ for the congruent condition). However, significant biases were found for individual subject-condition combinations (five for the opponent condition and three for the congruent condition). The assessment of the goodness of fit test showed that each individual psychometric curve was judged to be good.

As an additional analysis, we performed a comparison between, on the one hand, the threshold results of this experiment and, on the other hand, the results of two conditions of the first experiment, namely, the opponent condition and the convex-convex condition of the strongly curved stimuli. A 2*2 ANOVA was conducted with shape (opponent vs. congruent) as a within-subjects factor and hands (unimanual vs. bimanual) as a between-subjects factor. A significant main effect was found for shape ($F_{1,10} = 8.7$, $p = 0.015$) and for the interaction between shape and hands ($F_{1,10} = 21.3$, $p = 0.007$), but not for hands ($F_{1,10} = 1.5$, $p = 0.3$).

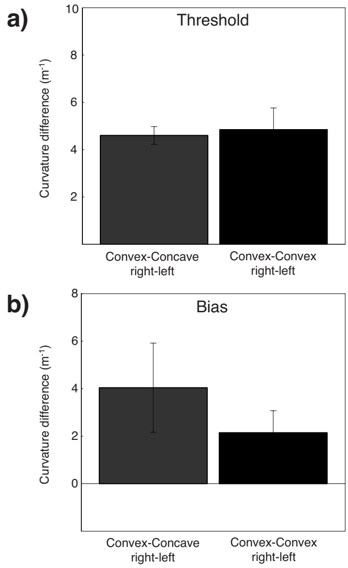


Fig. 3.7 Results of experiment 3. Each bar represents the mean value for six subjects in the specific condition.

3.4.3 Discussion

This experiment showed clearly that the curvature discrimination performance in a bimanual situation did not depend on whether congruent shapes or opponent shapes were used. The significant interaction between shape and hands confirmed that this result is in contrast to the unimanual results of the first experiment, where we found higher thresholds for the opponent shapes than for the congruent shapes.

The results for the biases in the opponent condition are in accordance with the previous experiments. Subject-dependent biases were obtained in the congruent condition, as Van der Horst and Kappers (2007) already showed, when they measured this condition.

3.5 General discussion

3.5.1 Threshold

We studied human performance of haptic curvature discrimination using opponent shapes and congruent shapes. When subjects used only a single index finger, a clearly higher threshold was found for the opponent mode than for the congruent mode (first experiment). However, similar thresholds for the opponent mode and the congruent mode were obtained when subjects used two index fingers, one finger per stimulus surface (third experiment). When the unimanual mode and the bimanual mode for the opponent shapes were directly compared, a slightly higher threshold was found in the unimanual mode, although this was not significant. However, significant or not, the important message is that this finding is different from previous research on the curvature discrimination of congruent shapes, where higher thresholds were found in the bimanual mode (Van der Horst and Kappers 2007).

Previous research has demonstrated that the slope difference and the curvature are the important cues in curvature discrimination in a congruent, unimanual mode (Pont et al. 1997, 1999; Louw et al. 2002a, 2002b). The results of the congruent conditions we measured in the first experiment were in agreement with this concept, since we observed similar thresholds for the convex-convex mode and the concave-concave mode. The fact that we found significantly higher thresholds in the opponent mode of the first experiment does not necessarily mean that the slope difference and the curvature are not important cues in this mode, but probably indicates that subjects were not able to use these cues directly. In section 2.3, we hypothesized that mental alignment processes such as rotation or mirroring, or the orientation of the stimuli with respect to the fingers and the external space made the curvature discrimination task more difficult with opponent shapes than with congruent shapes. However, the third experiment showed that the curvature discrimination performance did not depend on whether opponent or congruent shapes were used, when these surfaces were presented bimanually. This excluded a contributing factor of the orientation of the stimuli in the external space and made the assumption that mental alignment processes were involved in the comparison of opponent stimuli superfluous for the bimanual case. This leaves the question whether the unimanual curvature discrimination of opponent stimuli was performed by these processes. A clear difference between the unimanual opponent mode and the other modes we have studied is that in the unimanual opponent mode, opponent surfaces were sensed by the same finger, whereas in the unimanual congruent conditions and the bimanual opponent conditions this was not the case. We can imagine that the mental processing of opposite signals from a single finger is more complex to perform than the processing of congruent signals from a single finger. Probably, this processing of opposite signals was performed bilaterally, just like the bimanually obtained signals. Recently performed brain imaging studies have shown that, dependent on the task, unimanual tasks are processed unilaterally (Roland et al. 1998), bilaterally (Zhang et al. 2005), or dominantly in one hemisphere (Van Boven et al. 2005). A disadvantage of bilateral processing is that the information degrades by interhemispheric transmission, but an advantage is that the task load is shared between both hemispheres (Bradshaw et al. 1998). Of course, we cannot prove that the unimanual opponent signals have been processed bilaterally, but it is a possible explanation for the obtained results and makes the mental alignment hypothesis redundant.

3.5.2 Bias

Biases were found in all modes in which either opponent shapes or two hands were involved. Concerning the opponent shapes, significant, positive biases were found for the weakly curved condition of the first experiment and for all three conditions of the second experiment. A nearly significant, positive bias was obtained in the third experiment. Remind, a positive bias means that the curvature of a convex shape is systematically underestimated compared to the curvature of a concave shape. A further observation with respect to the biases is that the size of the bias differed strongly among subjects and conditions, which is in accordance with previous bimanual curvature discrimination studies (Kappers and Koenderink 1996; Sanders and Kappers 2006; Van der Horst and Kappers 2007). We suggest that the cause of the bias is twofold. The idiosyncratic part of the bias might result from the rather complex mental process of comparing bimanual or opponent signals. We suppose that the positive part of the bias originates from the manner in which the surfaces of the stimuli are explored. As the finger itself has a convex shape, a larger part of the finger is at each time in contact with a concave stimulus than with a convex stimulus of the same curvature, assuming that the stimulus is touched with an equal amount of force. However, in the experiments we performed, the finger is not in static contact with the stimulus surface, but moves over the stimulus surface. Due to the shape of the finger itself, a shorter exploration distance and time suffices to explore the whole stimulus

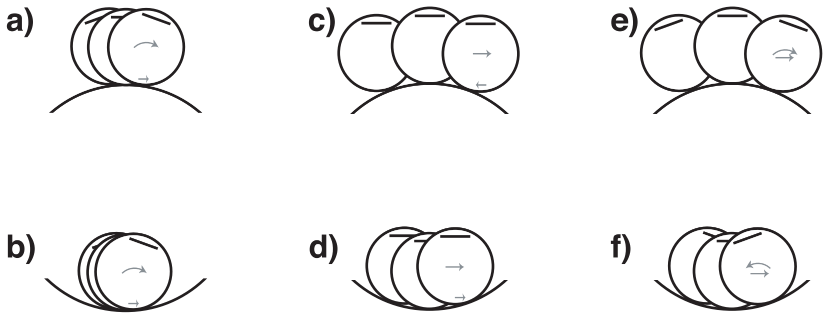


Fig. 3.8 Movement profiles of different finger explorations of a rightward movement on a convex (**a**, **c**, **e**) and a concave (**b**, **d**, **f**) surface. Inspiration for **a-d** has been derived from Fig. 3 in Hayward (2008). When the finger rolls over the surface (**a**, **b**), the contact point of the finger with the surface shifts rightwards. When the finger slides over the surface, the contact point shifts either leftwards on a convex surface (**c**) or rightwards on a concave surface (**d**). As subjects tended to keep their finger in such a way that the contact point did not shift, the movement of the finger on a convex surface resulted from a combination of rolling and sliding (**e**). However, on a concave surface, the movement resulted from a combination of rotation and sliding, but the rotation was in the opposite direction of rolling (**f**).

surface of a concave stimulus compared to a convex stimulus. Finally, the finger can be rotated when it is moved over the stimulus surface. The question that arises is how the way of exploration might have caused the biases we found.

Recently, Hayward (2008) described how the contact point between the finger and the stimulus surface shifts when the finger makes a rightward movement over the stimulus surface, by either rolling or sliding. For a convex surface, rolling shifts the contact point rightwards and sliding shifts the contact point leftwards; for a concave surface, both rolling and sliding shift the contact point rightwards (Fig. 3.8a-d). Now the question is: did the subjects in our experiments perform rolling or sliding movements, or was the movement pattern different? Informal observations of the exploration strategy of our subjects showed that subjects tended to keep the finger in such a way that the nail was parallel to the tangent plane of the contact surface. On convex surfaces, this was achieved by a combination of rolling and sliding (Fig. 3.8e). However, on a concave surface, this could not be realized by a combination of rolling and sliding, but was achieved by a combination of sliding and rotation, but, importantly, a rotation in the opposite directing of rolling (Fig. 3.8f). This type of movement differs from that described by Hayward for concave surfaces.

What might this difference in exploration mean for the ways in which the curvature of the convex and concave surface are perceived? From mechanics, it is known that the friction force that a surface exerts on a circular object like a wheel is lower when this object rolls than when it slides over the surface. Applied to our setup, the friction force that a convex surface exerts on the finger consists of a roll friction component and a slide friction component. This total friction force is lower than when the finger would only slide over the surface. The force that a concave surface exerts on the finger consists of a slide friction component of the translation with, in addition, a slide friction component of the rotation. For this case, the total friction force is higher than when the finger would slide over the surface, without rotation. This means that the friction exerted by a concave surface is higher than the friction exerted by a convex surface. This might explain why the curvature of the convex surface is underestimated compared to the curvature of a concave surface, as it has been shown that the sensation of a larger force can be interpreted as a higher perceived curvature (Robles-de-la-Torre and Hayward 2001; Drewing and Ernst 2006). Future studies might test the validity of this explanation by further disentangling how exploration differences in scanning length and time, in rolling and rotational movement, and in exerted force and pressure, contribute to this interesting finding.

3.6 Conclusion

When the ability to discriminate the curvature of opponent shapes was compared to the ability to discriminate the curvature of congruent shapes, a significant decrease in performance was found when a single finger was used to explore both surfaces, but similar results were obtained when different fingers touched each surface. The result for the bimanual mode shows that a congruent or incongruent orientation of the surfaces with respect to the fingers or with respect to the external space does not necessarily influence the sensitivity to perform the task. The decrease in performance in the unimanual mode might be due to the difficulty of processing opposite signals from a single finger.

Humans are systematically biased when they have to compare the curvature of opponent shapes, either unimanually or bimanually. This means that the curvature of convex shapes is generally underestimated compared to the curvature of concave shapes. We suggest that these biases result from the manner in which convex and concave shapes are explored.

4 Using curvature information in haptic shape perception of 3D objects

Van der Horst BJ, Kappers AML (2008) Exp Brain Res (in press)

Abstract Are humans able to perceive the circularity of a cylinder that is grasped by the hand? This study presents the findings of an experiment in which cylinders with a circular cross-section had to be distinguished from cylinders with an elliptical cross-section. For comparison, the ability to distinguish a square cuboid from a rectangular cuboid was also investigated. Both elliptical and rectangular shapes can be characterized by the aspect ratio, but elliptical shapes also contain curvature information. We found that an elliptical shape with an aspect ratio of only 1.03 could be distinguished from a circular shape both in static and dynamic touch. However, for a rectangular shape, the aspect ratio needed to be about 1.11 for dynamic touch and 1.15 for static touch in order to be discernible from a square shape. We conclude that curvature information can be employed in a reliable and efficient manner in the perception of 3D shapes by touch.

4.1 Introduction

The shape of a standard drinking glass is a cylinder with a round contour, but is the contour really a circle? One way to check is by measuring the diameter at several places with a ruler, or a vernier caliper. Alternatively, you may grasp the glass and judge whether the shape feels circular or not. However, does your haptic sense provide you with accurate and reliable information about the shape of the drinking glass? If you grasp another object, like a square glass vase, are you able to distinguish whether the contour of the vase is a square or a rectangle? Are you better in judging the regularity of circles or squares?

Klatzky et al. (1985) showed that humans are accurate and fast in recognizing daily life objects by touch. However, daily life objects are characterized by a multitude of properties, like shape, weight, temperature, and compressibility. To study the role of shape information in object perception and recognition, objects that are made from the same material but differ in shape should be used as stimuli. Studies that focused on shape recognition performance used stimuli like polyhedrons (Lakatos and Marks 1999), unfamiliar objects created from LEGO bricks (Newell et al. 2001), or solid copies of bell peppers (Norman et al. 2004). Using stimuli like these provide insight into the global and local aspects that are characteristic for objects that are explored by touch; however, an inconvenience is that many aspects of the stimuli that are compared change concurrently.

A more systematic approach to shape perception uses a stimulus set in which the elements are from the same, geometrically well-defined class; successive stimuli vary only slightly in the magnitude of a single stimulus parameter. Roland and Mortensen (1987) investigated discrimination performance of 3D objects like ellipsoids and parallelepipeds. The task was to discriminate the more oblong object from the less oblong object, for objects of equal volume. They found a high performance for the ellipsoids, shapes that are characterized by differences in local curvature. Ellipsoids are geometrically well-defined shapes but rather complex, since, in terms of size, they are described by three independent parameters; the curvature is defined locally by two independent parameters. The complexity of the stimulus makes it difficult to relate the performance of the subject to the shape of the stimulus.

In order to obtain a more direct relationship between shape and perception, several discrimination studies have been conducted that used stimuli with a constant curvature. Using this kind of stimuli allowed systematic variations in the stimulus size and the exploration mode. One group of studies concentrated on shape perception by static touch, either with a single fingertip (Goodwin et al. 1991, 1997; Jenmalm et al. 2003), with a part of the hand (Pont et al. 1997, 1999), or with the whole hand (Vogels et al. 1999). Other studies focussed on curvature perception by dynamic touch, which was performed with a single finger (Gordon and Morison 1982; Pont et al. 1998, 1999; Van der Horst and Kappers 2007), with various amount of fingers (Davidson 1972) or with the whole hand (Kappers et al. 1994; Kappers and Koenderink 1996). Analogous experiments have been conducted on shapes that were created in a virtual environment (Henriques and Soechting 2003; Provancher et al. 2005; Drewing and Ernst 2006). This overview is far from complete but illustrates the variety of studies that have been performed on constant curvature shape perception. These studies have shown that human subjects are able to perceive small differences in curvature but can be biased by differences in the orientation of the stimulus (Pont et al. 1998; Henriques and Soechting 2003), the length of exploration (Pont et al. 1999), or the finger that is employed (Van der Horst and Kappers 2007).

The stimuli that were used in these studies were not whole objects, only surface parts. In general, the task for a subject was to compare the curvature of one surface to the curvature of another surface. The question arises whether this ability to discriminate curvature differences can be used when judgments are made about the shape of complete 3D objects, like drinking glasses. Therefore, we designed stimuli that contained curvature differences in one direction within a stimulus and, for comparison, stimuli without curvature information. The first category of stimuli is cylinders with an elliptical cross-section; the other category is cuboids, which have a rectangular cross-section (see Fig. 4.1). Since the cross-sections are the determining aspects, we refer to these stimuli as ellipses and rectangles, respectively.

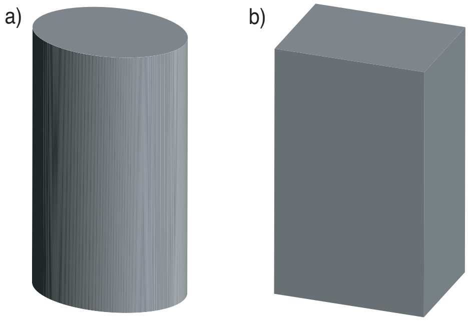


Fig. 4.1 Illustrations of the stimuli, a right elliptical cylinder (**a**) and a cuboid (**b**). The horizontal cross-sections of these stimuli are an ellipse and a rectangle, respectively. The height of a stimulus was 150 mm. Details about the dimensions of the cross-sections are provided in Fig. 4.2.

In the experiment that we conducted, subjects had to distinguish either an ellipse from a circle or a rectangle from a square. For the rectangles, only the ratio between the lengths of the perpendicular main axes is informative about the shape. For the ellipses, differences in local curvature may provide additional information to this aspect ratio information. However, this theoretical advantage for ellipses does not necessarily result in a higher performance since the performance depends on the ability and accuracy to extract information from the stimulus. When the orientation of the stimulus is unknown in advance, it is evident in which directions the two main axes of a rectangle are oriented; thus, it is obvious which lengths should be compared, but this is not true for an ellipse. This suggests that, if the judgement is only based on aspect ratio information, performance should be better for rectangles than for ellipses.

This disadvantage in obtaining aspect ratio information from ellipses might be compensated or overcome when curvature information can be used. The local curvature varies over the surface of an ellipse, whereas it is constant for a circle. Hence, an ellipse can be distinguished from a circle when differences or changes in curvature can be perceived. However, the ability to extract shape information from an object may be biased by spatial factors and exploratory procedures. When elliptical contours were traced in the horizontal plane with a finger in a thimble, an ellipse that was elongated in the tangential direction (aspect ratio of 1.06) was perceived as a circle (Hammerschmidt 1934; Von Skramlik 1937). Henriques and Soechting (2003) found similar biases for ellipses that were traced in a virtual environment. Experiments on length perception have also shown that radially explored lengths were overestimated compared to tangentially explored lengths; the magnitude of the effect depended on the exploration mode (e.g., Armstrong and Marks 1999; McFarland and Soechting 2007). Depending on the spatial orientation of the stimulus or the manner of exploration, a square may be perceived as a rectangle and a circle may be perceived as an ellipse, or vice versa.

The manner of exploration might determine how accurate and efficient shape information can be obtained from the stimulus. As mentioned, several factors may bias the result. In the current experiment we made a distinction between static touch and dynamic touch. In static touch, the stimulus is touched by a single grasp with the hand; in dynamic touch, free explorations around the stimulus surface are allowed. Manipulation of the stimulus is not allowed in order to exclude inertia differences that could influence shape perception (see e.g., Turvey 1996). Judging the shape of an ellipse by static touch might be difficult, since the local curvature impression at one place of the hand should be compared to the local curvature impression at another place of the hand. Dynamic touch seems advantageous, since touching a circle gives a constant impression over time, whereas an ellipse provides a changing profile. For the rectangles, dynamic touch may also be more informative than static touch. In static touch, the side lengths of the stimulus should be compared with different parts of the hand. In dynamic touch, a combination of different grasping postures and movements along the stimulus surface may provide more information. For both ellipses and rectangles, dynamic touch may provide more but possibly conflicting information, due to exploratory dependent biases. This may impair the performance in dynamic touch.

4.2 Methods

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. The stimuli are right cylinders, which means that all horizontal cross-sections lie directly on top of each other. The height was 150 mm. The stimuli are defined in terms of the aspect ratio of the horizontal cross-section (α), which is defined as the quotient of the semi major axis (a) and the semi minor axis (b). The product of a and b is equal for all ellipses, which means that the areas of the cross-sections are equal and thus the volumes of the elliptical stimuli are equal. A circle is a special case of an ellipse, in which the length of a and b are equal and coincide with the radius (r) of the circle. The length of r is 35 mm. The areas of the cross-sections of the rectangles are also equal but differ from the areas of the cross-sections of the ellipses. The dimensions of the rectangles are chosen in such a way that the perimeter of the square equals the perimeter of the circle. Fig. 4.2 illustrates the cross-sections of the stimuli.

In each condition, a reference stimulus was combined with seven test stimuli. For the conditions with the ellipses, test stimuli with aspect ratios of 1.006, 1.010, 1.016, 1.020, 1.04, 1.06, and 1.08 were used; the reference stimulus was a circle. For the conditions with the rectangles, aspect ratios of 1.06, 1.08, 1.10, 1.12, 1.17, 1.22, and 1.27 were used; the reference stimulus was a square. The ranges of the test stimuli were based on pilot experiments.

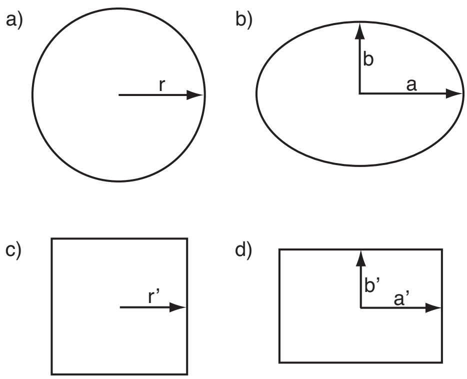


Fig. 4.2 Schematic illustrations of the cross-sections of the stimuli. **a)** Cross-section of a circular cylinder with radius r of 35 mm. **b)** Cross-section of a noncircular, elliptical cylinder, with semi major axis a and semi minor axis b. The aspect ratio is the quotient of a and b. The product of a and b is equal to r squared. **c)** Cross-section of a square cuboid. The perimeter of this square equals the perimeter of the circle in (**a**). **d)** Cross-section of a rectangular cuboid. The product of a' and b' is equal to r' squared.

Procedure

Subjects were seated behind a table. A blindfold prevented them from seeing the stimuli. A stimulus was placed in front of the subject at 40 cm from the edge of the table. The experimenter held the stimulus at the upper part to prevent translation or rotation of the stimulus. The orientation of the stimuli, i.e., the direction of the semi major axis in the plane of the table, was random, but for the rectangle conditions, similar for both stimuli within a trial. During a trial, a subject touched a test stimulus and subsequently a reference stimulus, or vice versa. The task was to indicate which of the two stimuli was the circle (square).

In the dynamic conditions, subjects explored the stimuli with their right hand. They were free to explore the surface of the stimuli in the way that they liked but were not allowed to explore the surfaces and edges at the upper and lower parts of the stimuli. In practice, they performed a combination of grasping and sliding movements. In the static conditions, subjects were instructed to grasp the stimuli with the whole hand without making further sliding contact with the surface of the stimuli.

Each condition consisted of 98 trials, which were presented in a pseudorandom order: groups of all possible combinations of test and reference stimuli were randomized and presented successively. Four conditions (two shapes × two exploration modes) were included. The order in which the conditions were measured was different for each subject; either two condition with the same exploration mode or two conditions with the same shape were presented in a single session. A single session lasted about 60-90 minutes. For one subject, we had to repeat the experiment in the rectangle × static condition with an adjusted stimulus range.

Subjects

The results for eight paid subjects (four male and four female, mean age 20 years) are reported. The result of another subject was not included, since no psychometric curve could be fitted to the data of two conditions. All subjects were right-handed, as established by a standard questionnaire (Coren 1993).

Analysis

For each subject and condition, the fraction of correct responses was calculated for each test stimulus value. The data were plotted against the relative aspect ratio ($\alpha - 1$), which is a Weber fraction, on a logarithmic scale. The logarithmic scale enables an analysis that assumes that performance is at a chance level when the relative aspect ratio reaches zero.

The detection threshold was determined by fitting a psychometric function (cumulative Gaussian) to the data. Fig. 4.3 shows an example of two psychometric curves for one subject in an ellipse condition and in a rectangle condition.

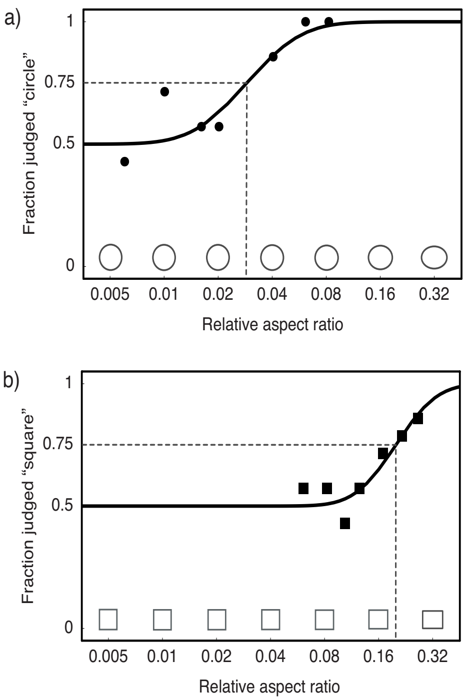


Fig. 4.3 Examples of psychometric curves for an ellipse condition (**a**) and for a rectangle condition (**b**). The response is plotted against the relative aspect ratio, which is defined as the aspect ratio minus 1. Note that a logarithmic scale is used. The ellipses (*rectangles*) that are drawn above the horizontal axis illustrate the shape of the ellipse (*rectangle*) for the values that are indicated on the horizontal axis. 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.

4.3 Results

Fig. 4.4 shows the mean detection thresholds for eight subjects in all conditions. The error bars represent the standard errors. Note that the results are plotted on a logarithmic scale. The significance of the results was tested by performing a two (shape) by two (exploration) ANOVA. Both main factors were significant ($F_{1,7} = 55$, $p < 0.001$ for shape; $F_{1,7} = 6.4$, $p = 0.04$ for exploration), but there was no significant interaction between shape and exploration ($F_{1,7} = 0.6$, $p = 0.5$).

4.4 Discussion

The experiment reveals a considerable difference in performance to distinguish an ellipse from a circle and a rectangle from a square. The mean threshold for the ellipses is about four times lower than for the rectangles. In addition, the experiment shows that allowing dynamic touch improves the performance in comparison to static touch, although this effect is rather modest. The large difference in performance between ellipses and rectangles indicates that curvature information can be used in a reliable manner.

Roland and Mortensen (1987) showed previously that curvature differences could be used in the detection of 3D shapes that varied in three dimensions. The stimuli that we used were also 3D objects, but the informative shape varied only in two dimensions, which allows a comparison with several studies that have been conducted previously.

4.4.1 Comparison with 2D tasks

A visual analogue of our experiment was conducted by Zanker and Quenzer (1999), who used 2D ellipses and

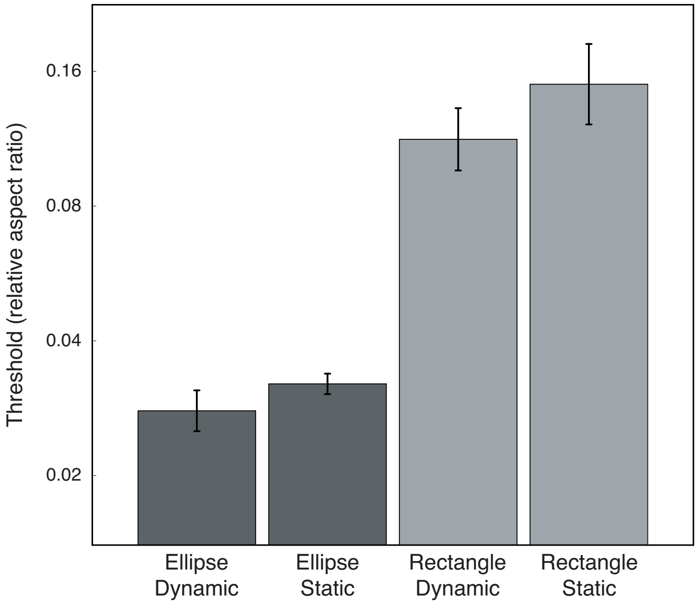


Fig. 4 Mean detection threshold results of eight subjects in all conditions. The error bars represent standard errors. Note that the scale is logarithmic.

rectangles that were presented on a computer screen. They found similar thresholds for distinguishing an ellipse from a circle and a rectangle from a square (on average 0.04 and 0.05, respectively). Obviously, task and performance in the visual experiment were different from those in our experiment; we found a slightly better performance for the ellipse conditions and a much worse performance for the rectangle conditions (on average 0.03 and 0.13, respectively).

Helbig and Ernst (2007) compared visual and haptic performance for ellipse discrimination of small, elliptical ridges (circle radius of 5 mm). In the haptic condition, the top of a ridge was explored with a single index finger; subjects had to judge whether the stimulus was elongated in the horizontal or vertical direction. The $thresholds_{75}$ were 0.03 in the visual condition and 0.07 in the haptic condition.[3] We should be careful in comparing the findings of Helbig and Ernst to our results, since the dimensions of the stimuli differed between the studies and the designs of the experiments were different (discrimination experiment versus detection, respectively). However, the thresholds differ by more than a factor of two, which indicates that extracting the 2D shape from the surface of a 3D object is more efficient than when only the top surface and edges are used.

[3] $Threshold_{75}$ means that the magnitude of the threshold was determined originally in a discrimination experiment at a 84% level, but converted by us to a 75% level. The conversion factor is 0.67.

In the introduction, we referred to studies in which orientation dependent biases were found when elliptical contours were traced (Hammerschmidt 1934; Von Skramlik 1937; Henriques and Soechting 2003). In addition, the thresholds that Henriques and Soechting (2003) reported were on average 0.17, which is much higher than the threshold of 0.03 that we found. We cannot exclude the possibility that the thresholds found in our experiment were influenced by orientation dependent biases, since we did not measure this. However, a large effect would have resulted in higher detection thresholds. Our findings confirm a previous observation (Van der Horst and Kappers 2007) that shape perception with bare fingers is much more reliable than perceiving shapes in a virtual environment, as in the study by Henriques and Soechting (2003).

4.4.2 Comparison with curvature discrimination

It would be interesting to make a quantitative comparison between the results of the ellipses and the results of previous studies on curvature discrimination. The curvature range of the stimuli that Van der Horst and Kappers (2007, 2008) used coincides with the range of local curvature of the ellipses. In their curvature discrimination experiment, two curved surfaces were presented subsequently in the same orientation and were explored by dynamic touch. The task was to indicate which of the two stimuli felt more curved. The mean $threshold_{75}$ expressed in terms of a Weber fraction is 0.06.

An ellipse might be distinguished from a circle by perceiving the difference between the maximum and minimum curvature within the ellipse. A difficulty might be that these points of curvature extrema are at perpendicular orientations with respect to each other and, in addition, that the ellipses were positioned randomly with respect to the external space. However, to perform the detection task, it is not necessary to know the positions of the curvature extrema and to discriminate the maximum from the minimum curvature, but it is sufficient to detect that there are curvature differences within the stimulus, which seems to be an easier task to perform.

The detection thresholds that we measured are expressed in terms of relative aspect ratio. How can we convert these values into relative curvature differences? An obvious way is to take the difference between the maximum and minimum curvature and to divide this value by the curvature of the circle, which results in 0.09. However, it has been shown that curvature discrimination is not based on the comparison of local curvatures but on a comparison of the differences in slope over the contact length (Gordon and Morison 1982; Pont et al. (1997, 1999). Applied to the ellipses, it is probably more realistic to assume that curvature differences are perceived by comparing the mean curvature at one place of the ellipse to the mean curvature at another place on the ellipse.

The mean curvature of a part of an ellipse with arc length Δs is defined as the change in turning angle $\Delta\varphi$ divided by the arc length Δs. In the limit that Δs approaches zero, the mean curvature is equal to the local curvature ($d\varphi/ds$). Fig. 4.5 illustrates the magnitude of $\Delta\varphi$ for equal lengths of Δs, positioned symmetrically around the points of maximum and minimum curvature, C_{max} and C_{min}, respectively. For this situation, a new value for the relative curvature difference at the mean threshold$_{75}$ level can be calculated by dividing the difference between $\Delta\varphi_1/\Delta s_e$ and $\Delta\varphi_2/\Delta s_e$ by the curvature of the circle. This results in a value of 0.06, which is clearly lower than the value previously calculated but similar to the value obtained by Van der Horst and Kappers (2007, 2008).

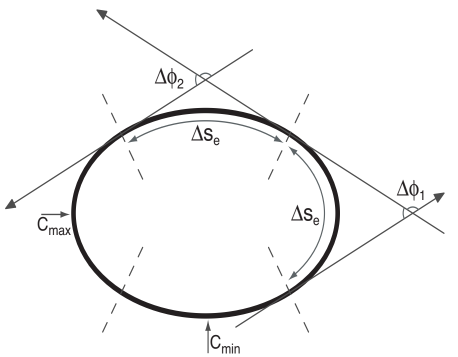


Fig. 4.5 Illustration of the ellipse parameters curvature (C), arc length (Δs) and turning angle ($\Delta\varphi$). C_{max} and C_{min} represent points of local maximum and minimum curvature. The arc length between two of these local extrema is Δs_e. The dashed lines mark the points halfway the local extrema, hence the arc length between these points is also Δs_e. Tangent lines are drawn at these places. The turning angles between two subsequent tangent lines are represented by $\Delta\varphi_1$ and $\Delta\varphi_2$, respectively.

This analysis indicates that the performance to distinguish an ellipse from a circle is similar to the discrimination of curved surfaces. However, the finding of a quantitative similarity does not necessarily mean that the detection task is performed as in a discrimination task, by comparing the mean curvature at one part of the ellipse to the mean curvature at another part of the ellipse. Alternatively, humans might be sensitive to the change in curvature within the ellipse, information that is not available in the curvature discrimination tasks that we discussed.

4.4.3 Comparison with length discrimination

Curvature information is not available when a rectangle has to be distinguished from a square. Only the ratio between the perpendicular lengths provides information about the shape. Gepshtein and Banks (2003) investigated the ability to discriminate the distance that is perceived when two parallel surfaces are grasped between the thumb and index finger. They found a threshold$_{75}$ of 0.07; this value is lower than the values that we found for the rectangles (on average 0.11 in dynamic touch and 0.15 in static touch). However, in the experiment of Gepshtein and Banks, the lengths that had to be compared were at the same place and in the same direction. Orientation and exploration dependent anisotropies might have caused an increase of the detection thresholds, as we previously suggested.

4.4.4 Dynamic versus static touch

The experiment showed that the detection performance was higher in dynamic touch than in static touch. This difference was especially clear for the detection of rectangles from squares. In dynamic touch, subjects grasped the stimulus from different directions, which provided more information than they could obtain from the single grasp in static touch. For the detection of circles from ellipses, the difference in performance in surprisingly small. We expected to find a better performance for dynamic touch than for static touch. In static touch, only the instantaneous curvature profile on the hand is available. In dynamic touch, additional temporal information might be obtained when the stimulus is explored; the temporal profile of a circle is constant, whereas the profile of an ellipse changes in time. Performance was slightly better for dynamic touch, but the low performance for static touch shows that humans are able to judge whether the curvature profile on the hand is constant or not by only applying static contact.

4.5 Conclusions

This study demonstrates that humans are proficient in extracting available curvature information from the surface of objects that are perceived by touch. In contrast, performance was much poorer when curvature information was lacking. It suggests that the haptic sense is suitable to perceive shape aspects from an object, like curvature information, but is less appropriate to obtain veridical information about spatial aspects, like lengths and orientations.

Finally, we return to our original questions about the ability to judge the circularity of a drinking glass and the squareness of a square vase. By only using the haptic sense, we can confidently judge that our drinking glass is circular, otherwise we should be able to feel this. However, for the judgments about a square vase, it might be better to rely on our eyes.

5 Intramanual and intermanual transfer of the curvature aftereffect

Van der Horst BJ, Duijndam MJA, Ketels MFM, Wilbers MTJM, Zwijsen SA, Kappers AML (2008) Exp Brain Res 187:491-496

Abstract The existence and transfer of a haptic curvature aftereffect was investigated to obtain a greater insight into neural representation of shape. The haptic curvature aftereffect is the phenomenon whereby a flat surface is judged concave if the preceding touched stimulus was convex and vice versa. Single fingers were used to touch the subsequently presented stimuli. A substantial aftereffect was found when the adaptation surface and the test surface were touched by the same finger. Furthermore, a partial, but significant transfer of the aftereffect was demonstrated between fingers of the same hand and between fingers of both hands. These results provide evidence that curvature information is not only represented at a level that is directly connected to the mechanoreceptors of individual fingers but is also represented at a stage in the somatosensory cortex shared by the fingers of both hands.

5.1 Introduction

The neural representation of haptic information can be investigated using different approaches. The representation of object shape perceived with the fingers has mainly been studied using neurophysiological tools. It has been found that especially slowly adapting type I (SAI) mechanoreceptors in the finger but also fast-adapting type I (FAI) receptors are sensitive to curvature (Goodwin et al. 1997; Jenmalm et al. 2003). In order to perceive curvature, a combination of responses from a population of receptors is required (Goodwin and Wheat 2004). This processing occurs along several stages up to at least the somatosensory cortex (SI) (Gardner and Kandel 2000). Taking a neurophysiological approach is useful to uncover the pathways underlying curvature processing, but is less appropriate to establish the levels at which perceived curvature is essentially represented.

A psychophysical approach that has been successful in providing greater insight into the neural representation of perceived properties is the study of the aftereffect, and especially, the transfer of the aftereffect. In vision, for example, the finding of partial, interocular transfer of the motion aftereffect has been explained by the involvement of both monocular and binocular cells in the processing of motion information from the stimulus (Moulden 1980; Wade et al. 1993; Tao et al. 2003). In a similar way, establishing the transfer characteristics of a haptic curvature aftereffect would provide insight into the representation of shape information. Finding aftereffect transfer between different fingers would indicate that curvature is represented at a level shared by these fingers, whereas no transfer would imply that each finger has a separate representation of curvature.

A curvature aftereffect is the phenomenon whereby a flat test surface feels concave following prolonged contact with a convex adaptation surface (see Fig. 5.1a). Curvature aftereffects have been found for different shapes and exploration modes. Gibson (1933) reported that a flat cardboard edge felt concave after the prolonged dynamic exploration of a convex cardboard edge. Vogels et al. (1996) demonstrated the existence of an aftereffect when the whole hand was placed on spherically curved shapes. They performed extensive experiments to examine the characteristics of this static curvature aftereffect. They found a linear relationship between the magnitude of the aftereffect and the curvature of the adaptation stimulus. Furthermore, they showed that the magnitude of the aftereffect increased with the adaptation time up to about 10 s. Finally, they found a decrease of the aftereffect with an increase of the interstimulus interval. In a follow-up study, they showed that the aftereffect also existed for alternative exploration modes, like touching a stimulus with only the five fingertips of the hand or performing small movements of the hand over the stimulus surface (Vogels et al. 1997). Given the strength and consistency of these findings, we supposed that curvature aftereffects should also occur for alternative ways of touching, such as the situation in which curved surfaces are statically being touched with only a single fingertip. However, this phenomenon has not yet been investigated, and consequently, any curvature aftereffect transfer between the fingers also remains unexplored.

The purpose of the present study was to obtain a better understanding of the representation of haptically perceived shape information, by probing the transfer of the curvature aftereffect. In the first experiment, we established the existence of an aftereffect when a curved surface is touched by a single finger and measured whether this aftereffect transferred to other fingers of the same hand. The second experiment was set up to determine whether the aftereffect depended on the finger used. Finally, in the third and fourth experiments, we investigated the transfer of the aftereffect between fingers of both hands.

5.2 Materials and methods

Subjects

A total number of 40 subjects participated [n = 8 for experiments 1, 2 and 4, n = 16 for experiment 3; 18 were male and 22 were female; the mean age was 22 years; 37 were right-handed, 3 were left-handed, according to a standard questionnaire (Coren 1993)]. Subjects in experiments 1 and 2 received course credit for their participation. Subjects in the third and fourth experiments received monetary compensation.

Stimuli

The stimuli comprised of a compound of polyurethane foam and artificial resin (Cibatool BM 5460). A computer-controlled milling machine was used to produce cylinders with a flat bottom and a spherically curved top. The top was either pointing outward (convex) or inward (concave). Both convex and concave adaptation stimuli were used, with curvature values of +36 m^{-1} and –36 m^{-1}, respectively; the curvature of the nine test stimuli ranged from –16 to +16 m^{-1}, in steps of 4 m^{-1}. Illustrations of the stimuli and their cross-sections are given in Fig. 5.1a, b, respectively.

Procedure

A subject was seated behind a table. The preferred arm rested on a platform, which was 30 mm above the tabletop. In the third and fourth experiments, both arms rested on the platform. Only the fingertips projected over the platform. The experimenter placed the stimulus underneath a fingertip. A curtain prevented the subjects from seeing the stimulus. During a trial, the tip of one finger was placed on an adaptation stimulus for 10 s. Subsequently, the subject placed a finger on a test stimulus and had to judge whether this test stimulus felt convex or concave. Subjects were not allowed to move the finger over the stimulus surface, and the experimenter checked for this. No instructions were given on the force to contact the stimulus, nor was it measured. No feedback was provided on the response.

Three conditions were measured in the first experiment. In all conditions, the adaptation stimulus was touched with the index finger. In one condition, the test stimulus was also touched with the index finger. In the other two conditions, the test stimulus was touched with the middle finger or the little finger of the same hand, respectively. Each condition consisted of 10 repetitions of a group of 18 trials (two adaptation stimuli × nine test stimuli) with trials randomized within a group. One complete condition was measured in a single session of about one and a half hours. The separate sessions were spread over different days. The order in which the conditions were conducted was counterbalanced for the first six subjects and randomly chosen for the last two subjects.

In the second experiment, both the adaptation and the test stimuli were touched by the middle finger. In the third and fourth experiments, the adaptation stimulus was contacted by

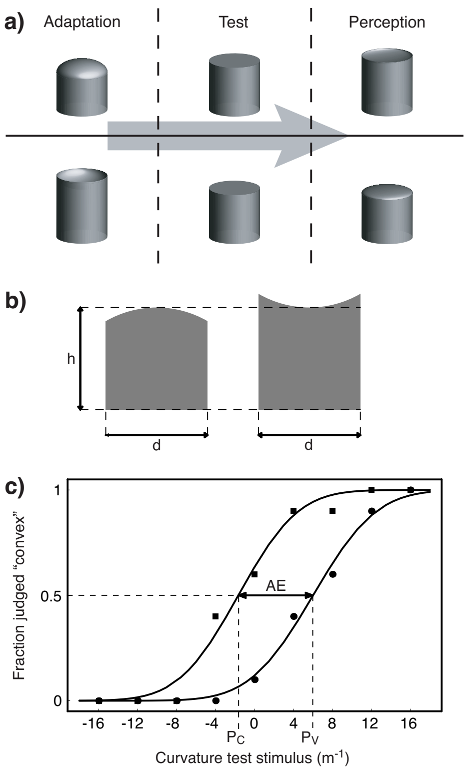


Fig. 5.1a Schematic overview of a haptic curvature aftereffect: when you first touch a convex (concave) surface for some time, say 10 s, and subsequently touch a flat surface, this latter surface feels concave (convex). **b** Schematic drawings of the cross-sections of a convex and a concave stimulus. The stimuli had a cylindrical shape with a spherical top (see illustration **a**). The distance from the bottom to the centre of the top (*h*) was consistently 30 mm. The diameter of the cylinders (*d*) was also 30 mm. **c** Examples of two psychometric curves. The circular data points and the fit through these points results from adaptation to the convex adaptation stimulus. The PSE is represented by P_V. The square data points and the fit through these points result from adaptation to the concave adaptation stimulus. In this case, the PSE is represented by P_C. The magnitude of the aftereffect (AE) is defined as the difference between P_V and P_C.

the index finger of the preferred hand; the test stimuli were touched with the index finger (third experiment) or middle finger (fourth experiment) of the non-preferred hand.

Analysis

The data for each subject and each condition were analyzed separately for the convex and the concave adaptation stimuli. The percentage of “convex” responses was plotted against the curvature of the test stimulus. The point of subjective equality (PSE) was determined by fitting a psychometric function (cumulative Gaussian) to the data. The PSE represents the curvature value that in 50% of the test cases was judged “convex” and in 50% of the cases was judged “concave”. The magnitude of the aftereffect is defined as the difference between the PSE resulting from the adaptation to a convex surface and the PSE resulting from the adaptation to a concave surface. Examples of psychometric curves for a convex and a concave adaptation are given in Fig. 5.1c.

5.3 Results

The mean results for the aftereffect values are shown in Fig. 5.2. The error bars indicate the standard errors of the mean.

5.3.1 Experiment 1

We tested the occurrence of an aftereffect in each condition by performing separate one-tailed t tests. A significant result was obtained in all conditions ($t_7 = 6.3$, $p < 0.001$ for the index finger; $t_7 = 9.8$, $p < 0.001$ for the middle finger; $t_7 = 3.4$, $p = 0.006$ for the little finger). Subsequently, an ANOVA with a repeated measures design was performed to determine any differences between conditions. A significant main effect was found ($F_{2,14} = 22.5$, $p < 0.001$). Pairwise comparisons showed a significant difference between the index finger and the middle finger ($p = 0.007$) and between the index finger and the little finger ($p = 0.004$), but not between the middle finger and the little finger ($p = 1.0$). The p-values were adjusted with a Bonferroni correction.

5.3.2 Experiment 2

A one-tailed t test showed that there was a significant aftereffect ($t_7 = 8.0$, $p < 0.001$). Inspection of Fig. 5.2 shows that the aftereffect of the middle finger condition of the second experiment was comparable to the index finger condition of the first experiment and was much higher than the middle finger condition of the first experiment. Independent samples t test confirmed that there was no significant difference in the first case ($t_{14} = 0.6$, $p = 0.6$), but that there was a significant difference in the second case ($t_{7.4} = 6.1$, $p < 0.001$).

5.3.3 Experiment 3

A one-tailed t test highlighted a significant aftereffect ($t_{15} = 2.7$, $p = 0.009$). The magnitude of this aftereffect was much lower than for the index finger

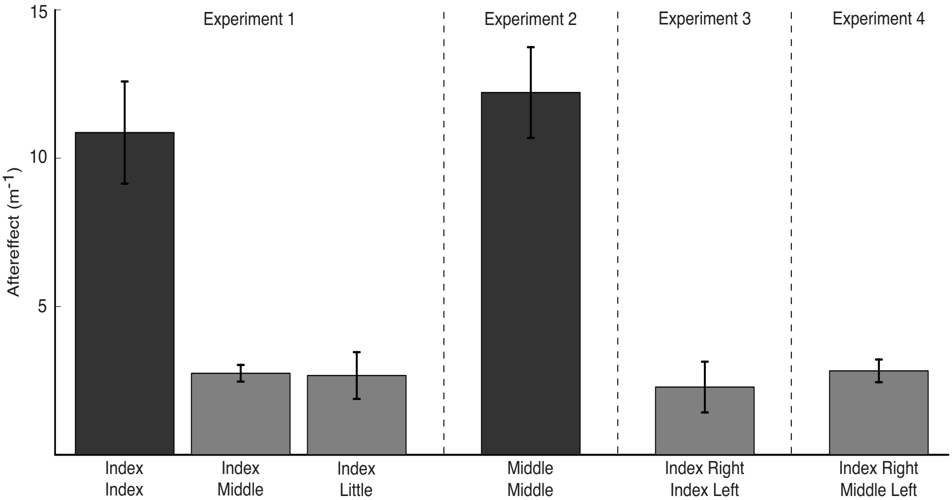


Fig. 5.2 Mean results of the aftereffect. The indicated error bars are the standard error in the mean for each condition. Experiment 1: eight subjects participated. Adaptation was performed by the index finger of the preferred hand. Testing was done using the index finger, middle finger, or little finger of the same hand. Experiment 2: eight subjects participated. Adaptation and testing was performed by the middle finger of the preferred hand. Experiment 3: sixteen subjects participated. Adaptation was performed by the index finger of the preferred hand; testing was done by the opposite index finger. Experiment 4: eight subjects participated. Adaptation was performed by the index finger of the preferred hand; testing was done by the middle finger of the non-preferred hand.

condition of the first experiment. This was confirmed by an independent sample t test ($t_{22} = 5.0$, $p < 0.001$).

5.3.4 Experiment 4

A significant aftereffect was obtained, as was confirmed by a one-tailed t test ($t_7 = 7.4$, $p < 0.001$).

5.4 Discussion

The first novel observation of this paper is that the perception of surface curvature by a single fingertip is influenced by preceding contact of this finger with another curved surface. The magnitude of this curvature aftereffect did not depend on the finger employed, as shown by a comparison between the results of the first and the second experiment. Previously, Vogels et al. (1996, 1997) reported the existence of a static curvature aftereffect, when the whole hand was used. We suppose that our finding of a one-finger aftereffect falls in the same class of phenomena. A quantitative comparison between the results of Vogels et al. (1996) and our finding can be made by calculating the relative magnitude of the aftereffect, i.e. the aftereffect divided by the difference between the adaptation stimuli. This value equals 0.17 ± 0.02 for the results of Vogels et al., whereas it was 0.15 ± 0.07 for the index finger condition of the first experiment and 0.17 ± 0.06 for the middle finger condition of the second experiment, respectively. These values are in the same order of magnitude, irrespective of the differences in manner of touching and curvature range of the stimuli.

The second important finding of our study is that the aftereffect partially transfers between fingers of the same hand. This means that the sensation of shape with a certain finger influences the perception of a shape touched by another finger. This suggests that the sensations obtained by the different fingers share a common representation. However, the transfer is far from complete, indicating that curvature perception by each finger also yields a substantial, individual part in the representation. Interestingly, the aftereffect does not only transfer from the index finger to the neighboring middle finger, but also to the distant little finger. This result is unlike recently performed localization (Schweizer et al. 2000) and learning studies (Sathian and Zangaladze 1997; Harris et al. 2001), in which the reported transfer effects were obtained in the neighboring finger, but not in the distant fingers. This indicates that the processes involved in detecting the finger that is stimulated or increasing the skills to discriminate punctate pressure or roughness are quite different from those concerned in shape perception of an object.

The third interesting result of this study is that there was a small, but significant transfer of the aftereffect between fingers of both hands, irrespective of whether opposite fingers (experiment 3) or different fingers (experiment 4) were employed. This result is different from the result reported by Vogels et al. (1997), who did not find intermanual transfer. However, in their experiments, whole hands were involved, whereas only single fingertips were used in our experiment. Moreover, their conclusion was based on the performance of only 2 subjects, whereas 24 participants provided the data for our study. The results of the third and fourth experiments suggest that the representation of shape information obtained with one hand is not completely distinct from the representation of shape information received by the other hand, but shares a common, bilateral component.

How can our findings be interpreted in the context of neurophysiological literature? Firstly, our finding that the aftereffect only transfers partially between fingers of the same hand shows that a substantial part of the processing occurs at a stage where each finger is individually represented. On this stage, which spreads from the mechanoreceptors in the fingers up to area 3b in SI, no overlap occurs in signals from the slowly adapting receptors and the fast-adapting receptors (Gardner and Kandel 2000). Slowly adapting receptors respond with a sustained discharge when the finger is in contact with a surface, whereas fast-adapting receptors only respond at the onset and removal phase of the finger (Johansson and Vallbo 1983). Vogels et al. (1996) showed that the magnitude of their curvature aftereffect increased with an increase in adaptation time. These findings point to an important role for the slowly adapting receptors in the curvature aftereffect. Therefore, we suggest that the aftereffect at the stage related to an individual finger mainly originates from the processing of the slowly adapting receptors. Secondly, the fact that we found a transfer between the fingers of the same hand implies that a significant part of the processing of curvature information occurs at a level shared by the different fingers. In physiological terms, this indicates that at least area 1 or 2 of SI are involved, as receptive fields in these areas cover several fingers of a single hand (Gardner and Kandel 2000), but processing may also occur at an even higher stage. Thirdly, our finding of an intermanual transfer shows that the processing of curvature information also takes place on a higher, bilateral level. We can only speculate on the neural correlates of this bilateral processing. Possible candidates include area 2 of SI, areas 5 and 7 of the posterior parietal cortex, and the secondary somatosensory cortex (Iwamura 2000; Gardner and Kandel 2000).

It is interesting to mention that the aftereffects in the intramanual transfer conditions (experiment 1) and the intermanual transfer conditions (experiment 3 and 4) are similar in magnitude. This suggests that no important curvature processing occurs at a level that is devoted to a single hand, but that all processing takes place at a higher stage. The similar results for experiments 3 and 4 provide further support that the hands and fingers are not somatotopically represented at this stage. From a previous study, it is known that subjects also performed similarly in intramanual and intermanual curvature discrimination tasks, but that higher performance was obtained when only a single finger was employed (Van der Horst and Kappers 2007). The analogy between that study and the current study is that curvature information is mainly represented at the level of the individual finger, but partly available at a higher, finger- and hand-independent level. We should be careful in ascribing a specific function to the involvement of the higher level areas in the processing of curvature information. The role of more cognitive aspects should not be excluded, since it is known that processes like tactile attention (Burton and Sinclair 2000; Spence and Gallace 2007), working memory (Burton and Sinclair 2000), and object recognition (Reed et al. 2004) also engage the somatosensory areas.

The aftereffect that we found in the present study is a similar phenomenon as the aftereffect that was previously reported by Vogels et al. (1996, 1997). However, this does not entail that the representation of curvature is identical for touching with a single finger or with the whole hand. Vogels et al. (1997) already showed that, although similar aftereffects were found when either the whole hand or only the five fingertips were used, only a small transfer between these exploration modes was obtained, which points to a limited overlap in representation. Similarly, we suppose that there is a difference in representation between curvature that is perceived by a single finger and curvature that is perceived by the whole hand. In the single finger case, the representation is mainly at the level of the individual finger, whereas in the whole hand case, the representation is spread over all fingers and the palm of the hand.

This study shows that establishing the intramanual and intermanual transfer of the aftereffect is a useful tool in obtaining more insight into the representation of object properties as perceived by the fingers. In general, studying aftereffect transfer is attractive, because it enables a connection between psychophysics and neurophysiology. The convergence of these approaches leads to a better understanding of human perception.

6 Transfer of the curvature aftereffect in dynamic touch

Van der Horst BJ, Willebrands WP, Kappers AML (2008) Neuropsychologia (in press)

Abstract A haptic curvature aftereffect is a phenomenon in which the perception of a curved shape is systematically altered by previous contact to curvature. In the present study, the existence and intermanual transfer of curvature aftereffects for dynamic touch were investigated. Dynamic touch is characterized by motion contact between a finger and a stimulus. A distinction was made between active and passive contact of the finger on the stimulus surface. We demonstrated the occurrence of a dynamic curvature aftereffect and found a complete intermanual transfer of this aftereffect, which suggests that dynamically obtained curvature information is represented at a high level. In contrast, statically perceived curvature information is mainly processed at a level that is connected to a single hand, as previous studies indicated. Similar transfer effects were found for active and passive dynamic touch, but a stronger aftereffect was obtained when the test surface was actively touched. We conclude that the representation of object information depends on the exploration mode that is used to acquire information.

6.1 Introduction

A haptic curvature aftereffect is a phenomenon in which a flat surface feels concave after the prolonged touching of a convex surface, and vice versa. The occurrence of this phenomenon has been demonstrated for different exploration modes. Gibson (1933) reported that when subjects ran their fingers along the edge of a convexly curved cardboard for three minutes, the subsequently explored flat edge felt concave. Recent studies have focused on the properties of static rather than dynamic curvature aftereffects.

Vogels et al. (1996) studied the characteristics of an aftereffect when curved surfaces were touched by static contact with the entire hand. They found a linear dependence of the magnitude of the aftereffect on the curvature of the adaptation stimulus. In addition, they showed that the magnitude of the aftereffect increased with adaptation time (up to about 10 seconds) but decreased with increasing interstimulus intervals. Later, they showed that the aftereffect also occurred when small variations in the exploration manner were applied, but no aftereffect was found when the adaptation and test stimuli were touched by different hands (Vogels et al. 1997). Finally, they demonstrated that two consecutively presented adaptation surfaces together contributed to the magnitude of the aftereffect (Vogels et al. 2001). Recently, we presented the existence of an aftereffect when curved surfaces were statically touched by only a single fingertip (Van der Horst et al. 2008). Furthermore, we found a significant effect when the adaptation and test stimuli were touched by different fingers, but the magnitude of this transferred aftereffect was only about 20 to 25% of the original effect.

In the present study, we investigated the existence and transfer of an aftereffect when curved surfaces were explored dynamically by a single finger. Studying the aftereffect and its transfer can provide more insight into the representation of perceived curvature information.

6.1.1 Exploration modes to perceive curvature

The haptic perception and representation of curvature has been investigated for several manners of exploration. In this section, we consider a number of studies on static and dynamic curvature perception.

One way to perceive the shape of an object is through static contact of a single fingertip on a curved stimulus. This exploration manner is appropriate to obtain information from highly curved surfaces. Neurophysiological studies have provided evidence that curvature information is processed on the basis of the response profile of the population of mechanoreceptors in the fingerpad. This response profile correlates to the contact shape and the force that is applied to the finger (LaMotte and Srinivasan 1993; Goodwin et al. 1995, 1997; Jenmalm et al.

2003). However, psychophysical studies have shown that this exploration manner is unsuitable to perceive the shape of weakly curved surfaces, i.e., when the curvature is below the 84% threshold of about 7 m^{-1} (Goodwin et al. 1991; Pont et al. 1999).

Nevertheless, the shape of weakly curved stimuli can be perceived by static touch when the contact length with the stimulus is increased by placing the whole finger or several fingers together on the stimulus surface (Pont et al. 1997, 1999). The thresholds decreased with increasing contact length, up to about 0.5 m^{-1} for a contact length of 15 cm.

A different way to perceive the shape of an object is by dynamic contact between a single fingertip and the object surface. In a number of psychophysical studies, the curvature of the stimuli was below the threshold for static touch with a single fingertip (Davidson 1972; Gordon and Morison 1982; Pont et al. 1999). Hence, movement was required to perceive the shape of the surface. Also in this case, the discrimination threshold decreased with the increasing contact length. For a contact length of 20 cm, a discrimination threshold of 0.4 m^{-1} was found. Similar thresholds were found for static and dynamic touch, when the same contact length was used (Pont et al. 1999).

Several other studies have investigated curvature perception by dynamic touch, but the curvature of the stimuli that were used varied from 19 to 120 m^{-1}, which is above the threshold for static touch with a single finger (Bodegård et al. 2000, 2001; Provancher et al. 2005; Van der Horst and Kappers 2007, 2008). In such cases, dynamic contact was not required to perceive the shape of the stimulus, but it might have improved the accuracy.

6.1.2 Representation of curvature information

Static and dynamic touch provide different ways to acquire shape information from an object. Higher performance can be achieved for dynamic touch than for static touch, in which only a single finger is used. Dynamic contact between the finger and the stimulus provides additional information about the shape of the stimulus. This suggests that curvature information is processed in a different way for dynamic touch. Consequently, the representation level of the curvature information may depend on the exploration mode.

More insight into the representation of curvature information can be obtained by studying the aftereffect and its transfer. In vision, establishing aftereffect transfer has successfully uncovered the representation of perceived phenomena like motion (see e.g., Moulden 1980; Wade et al. 1993; Mather et al. 1998; Tao et al. 2003). In haptics, the aftereffect transfer paradigm has only scarcely been employed. Our recent study on the static curvature aftereffect demonstrated a partial transfer of this effect. We suggested that an important part of the representation is situated at a neural level that is directly connected to the processing of the responses of the mechanoreceptors in the individual finger; a small part of the representation is located at a higher, bimanual stage (Van der Horst et al. 2008).

Analogous to the static aftereffect, establishing the existence and transfer characteristics of a dynamic curvature aftereffect could provide information about the representation of dynamically perceived curvature. If similar results are obtained for dynamic touch as were found for static touch, this would suggest that, irrespective of the differences in exploration mode, curvature is represented at similar levels. In contrast, finding different patterns would indicate that curvature representation occurs in different ways, depending on the mode of exploration.

6.1.3 Active and passive dynamic touch

A distinction is made between active and passive dynamic touch. In active dynamic touch, the subject moves the finger over the surface of a fixed stimulus; in passive dynamic touch, the stimulus moves underneath a finger that the subject keeps at a fixed position. Passive dynamic touch shares with active dynamic touch that there is an analogous moving contact between the finger and the stimulus. Therefore, similar results might be expected for active and passive dynamic touch. However, passive dynamic touch has in common with static touch that the finger stays in the same location. If self-induced movement is an important factor, then the results for passive touch should deviate from the results for active touch.

6.2 Experiment 1

In the first experiment, we studied the existence and transfer of a dynamic aftereffect in active and passive dynamic touch.

The first goal was to demonstrate the existence of a curvature aftereffect in dynamic touch. Gibson (1933) reported the occurrence of an aftereffect after three minutes of adaptation. However, in the current study, we used a shorter adaptation time (11 seconds), comparable to the adaptation times that have been used in studies on the static aftereffect.

The second purpose of this experiment was to establish whether, and to what extent, the dynamic aftereffect transfers between both hands. The transfer characteristics might be similar to those of the static aftereffect, since the ability to perceive curvature is comparable for static and dynamic touch, when there is controlled for contact length. However, having the same ability to acquire shape information does not necessarily imply that this information is represented at the same level. Moreover, no comparable results were found for static and dynamic touch when only a single finger was used. Thus, the transfer pattern might deviate from the transfer characteristics of static aftereffects, as previously reported (Vogels et al. 1997; Van der Horst et al. 2008). In order to make a proper distinction between static curvature representation and dynamic curvature representation, we used stimuli in the curvature range below the threshold for single-finger static touch. Consequently, the shape could not be deduced from the immediate contact between the finger and the stimulus, but movement was required.

The third goal was to determine whether active and passive dynamic touch demonstrate similar aftereffects. The same results might be obtained, since there is a comparable moving contact between the finger and the stimulus. However, there might be differences in the magnitude of the aftereffect and the extent of transfer, since there is self-induced movement in the active but not in the passive case.

6.2.1 Methods

Design

Four conditions were studied in a two (exploration) x two (finger) design. The exploration mode was either active or passive dynamic touch. In the active mode, the stimuli were explored by a self-induced movement with the index finger over the surface of a stationary stimulus. In the passive mode, the stimuli moved underneath a statically sustained finger. A further distinction was made between the employment of either a single finger or different fingers. In the same-finger mode, the same index finger was used to touch both the adaptation and the test stimulus; in the opposite-finger mode, the right index finger touched the adaptation stimulus, and the left index finger touched the test stimulus.

Setup

Subjects were seated behind a table, with their arms resting on a support. The stimuli could be placed in two slits on a platform in front of the support. Only the right slit was used in the same-finger mode. In the opposite-finger mode, the adaptation stimulus was placed in the right slit, and the test stimulus was placed in the left slit. In the passive conditions, the platform moved back and forth at a constant speed of 0.11 m/s, driven by a computer controlled stepping motor. The platform remained in position in the active conditions. Fig. 6.1 illustrates the setup of the experiment.

Stimuli

The stimuli were produced from PVC. The top surface was a circular cylinder part, which curved either outward (convex) or inward (concave). One convex adaptation stimulus and one concave adaptation stimulus were used, with curvature values of $+3.8\ m^{-1}$ and $-3.8\ m^{-1}$, respectively. The curvature of the 10 test stimuli varied from $-1.8\ m^{-1}$ to $+1.8\ m^{-1}$, in steps of $0.4\ m^{-1}$.

Fig. 6.1 Experimental setup. The arms rested on a support that was 19 cm above the tabletop. The stimuli were placed in slits on a platform, which was 14 cm above the tabletop. The distance between the centres of the slits was 40 cm. In this example, the subject explores the concave adaptation stimulus with the right index finger before touching the test stimulus with the opposite index finger. In the active conditions, the stimuli remained in a fixed position; in the passive conditions, a computer controlled stepping motor moved the platform. The surface of the stimuli was circularly curved. The length of the stimuli was 200 mm, and the width was 20 mm. The height at the side of the stimuli was 40 mm.

Procedure

During a trial, the adaptation stimulus was touched by the index finger of the right hand for 11 seconds. Three back-and-forth movements were made during the adaptation phase. After four seconds, the test stimulus was touched with an index finger for a single side-to-side movement. The task of the subject was to indicate whether this test stimulus felt convex or concave. Practice trials were conducted to accustom the subjects to the proper exploration time. No feedback was provided.

Each condition consisted of 10 repetitions of a group of 20 trials (2 adaptation stimuli x 10 test stimuli). The presentation order of the trials within a group was randomized. A complete condition was measured in a single session, which took about 90 minutes. The order in which the experimental conditions were conducted was partly counterbalanced. One half of the subjects first performed the active conditions followed by the passive conditions; the other half of the subjects started with the passive conditions. The order in which the same-finger conditions and the opposite-finger conditions were conducted was counterbalanced among the subjects.

Subjects

Eight, paid subjects participated (four male and four female, mean age 21 years). All subjects were right-handed, as established by a standard questionnaire (Coren 1993).

Analysis

For each subject and condition, the responses in the convex adaptation trials were separated from the responses in the concave adaptation trials. The fraction of “convex” responses was calculated for each curvature value of the test stimuli. A psychometric function (cumulative Gaussian) was fitted to the data to determine the point of subjective equality (PSE). The PSE is the curvature value that is judged as convex in 50% of the cases and as concave in 50% of the cases. In other words, on average, this curva-

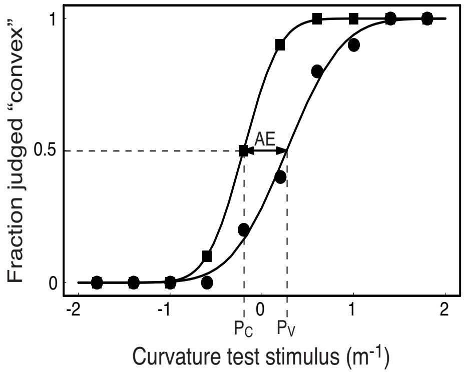


Fig. 6.2 Examples of two psychometric curves of one subject in an active, same-finger condition. The response is plotted against the curvature of the test stimulus. The psychometric curves were obtained by fitting cumulative Gaussians to the data. The circular data points represent the response when adaptation was performed with the convex adaptation stimulus; the square data points result from adaptation with the concave adaptation stimulus. The points of subjective equalities are given by P_V and P_C, respectively. The magnitude of the aftereffect (AE) is defined as the difference between P_V and P_C.

ture value is judged as flat. The magnitude of the aftereffect is defined as the difference between the PSE resulting from convex adaptation (P_V) and from concave adaptation (P_C). Fig. 6.2 shows an example of the psychometric curves for one subject and one condition. The PSEs and the magnitude of the aftereffect are indicated.

6.2.2 Results

The mean results for each condition are given in Fig. 6.3a. The error bars represent the standard errors. Visual inspection of this graph shows that an aftereffect was obtained in all conditions. Most importantly, similar magnitudes of the aftereffect were found in the same-finger conditions and in the opposite-finger conditions, which points to a complete transfer of the aftereffect. In addition, the magnitude of the aftereffect was higher in the active conditions compared to the passive conditions. Statistical analyses confirmed these observations. For each condition, a one-tailed, one-sample *t*-test was conducted to determine whether the aftereffect deviated from zero. Significant aftereffects were found in all conditions ($t_7 = 5.4$, $p < 0.001$ for the active same-finger condition; $t_7 = 4.2$, $p = 0.002$ for the active opposite-finger condition; $t_7 = 2.9$, $p = 0.012$ for the passive same-finger condition; $t_7 = 9.0$, $p < 0.001$ for the passive opposite-finger condition). A 2x2 ANOVA with a repeated measures design showed a significant main effect for the factor exploration ($F_{1,7} = 27.5$, $p = 0.001$) but no significant effects for the factor finger or for the interaction between exploration and finger ($F_{1,7} = 0.1$, $p = 0.7$ and $F_{1,7} = 0.2$, $p = 0.7$, respectively).

6.2.3 Discussion

This experiment shows the existence of a dynamic curvature aftereffect and, most surprisingly, a full transfer of this effect. This result differs from the partial transfer of the static curvature aftereffect, as obtained in our previous study (Van der Horst et al. 2008). To place the finding in a broader perspective, only some specific visual

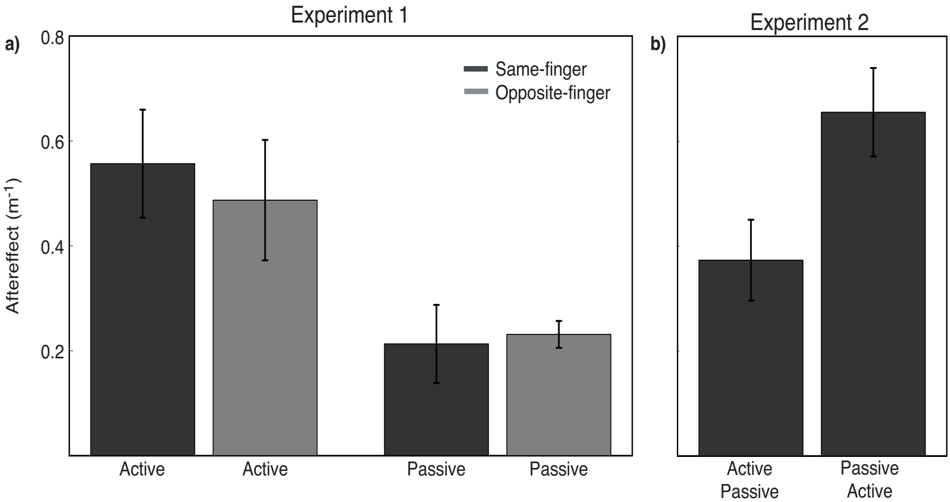


Fig. 6.3a Mean results of the aftereffect for eight subjects. The error bars represent the standard errors. In the active conditions, the adaptation and test stimuli were explored by self-induced exploration with the index finger. In the passive conditions, the stimuli moved underneath the index finger. The dark bars represent the results for the conditions in which the adaptation and test stimuli were touched by the same index finger. The light bars represent the results for the conditions in which the adaptation stimulus was touched by the right index finger and the test stimulus was touched by the opposite index finger. **b** Mean results of the aftereffect for eight subjects. In the active-passive condition, the adaptation stimulus was explored actively, while the test stimulus was touched passively. In the passive-active condition, passive contact with the adaptation stimulus was followed by active exploration of the test stimulus.

motion aftereffects show a full interocular transfer. In general, there is only partial transfer of the effect, the strength of which depends on several stimulus and measurement parameters (Wade et al. 1993; Tao et al. 2003). Our finding of a complete transfer suggests that curvature perception by dynamic touch is a complex process that is represented at a high level in the brain. A further account of this finding will be provided in the general discussion.

Complete intermanual transfer was found for both active and passive touch, but the magnitude of the aftereffect was higher in the active conditions than in the passive conditions. The fact that we found a complete transfer of the aftereffect in both active and passive dynamic touch suggests that curvature information is represented similarly in both exploration modes; however, analogous phenomena do not necessarily share a common representation. Furthermore, the difference in magnitude of the aftereffect indicates that there are differences in curvature representation of active and passive dynamic touch. Therefore, we performed a second experiment to determine whether adaptation by active dynamic touch induces an aftereffect in passive dynamic touch, and vice versa.

6.3 Experiment 2

In the second experiment, the transfer between active and passive dynamic touch was investigated. Two conditions were considered. In the active-passive condition, adaptation was performed by active dynamic touch, and testing was performed by passive dynamic touch. In the passive-active condition, the order was reversed. In both conditions, subjects used only their right hands for adaptation and testing.

Before the experiment, we formulated two main hypotheses. One hypothesis was that there would not be a transfer between active and passive touch. This would imply that the existence and intermanual transfer of the aftereffect for active and passive touch are analogous phenomena but do not share a common representation. The other hypothesis predicted that there would be a transfer between active and passive touch, which would suggest that both exploration modes share a common representation. In this case, several results were possible. First, a similar aftereffect could be found in both conditions; only the representation shared by active and passive touch would be reflected by the aftereffect. Second, a higher aftereffect could be obtained in the active-passive condition; this would suggest that active and passive touch share the same representation, but adaptation is stronger for active touch. Third, a stronger aftereffect could be found in the passive-active condition. In this case, the manner of touch during the test phase, not the exploration mode in the adaptation phase, determines the magnitude of the aftereffect.

6.3.1 Methods

The same setup was used for this experiment as in the previous experiment. We did not use the ± 1.8 m^{-1} stimuli but increased the number of repetitions per stimulus. As a result, each condition consisted of 192 trials in total (12 repetitions of a group of 2 x 8 trials). The order in which the experiment was performed was counterbalanced among subjects. There were eight, right-handed subjects (four male and four female, mean age 21 years), none of whom were involved in the first experiment.

6.3.2 Results

The mean results for each condition are presented in Fig. 6.3b. Significant aftereffects were found in both conditions, as one-tailed *t*-tests demonstrated ($t_7 = 4.8$, $p = 0.001$ for the active-passive condition; $t_7 = 7.8$, $p < 0.001$ for the passive-active condition). A dependent-samples *t*-test showed that the magnitude of the aftereffect was significantly higher in the passive-active condition than in the active-passive condition ($t_7 = 2.8$, $p = 0.025$).

Independent samples *t*-tests were

performed in order to compare the results of the second experiment to the same-finger results of the first experiment. The magnitude of the aftereffect for the active-passive condition did not differ significantly from the active and passive conditions of the first experiment ($t_{14} = -1.4$, $p = 0.18$, $t_{14} = 1.5$, $p = 0.16$, respectively). The result for the passive-active condition was not significantly different from that of the active condition but was significantly higher than that of the passive condition ($t_{14} = 0.7$, $p = 0.5$ and $t_{14} = 3.9$, $p = 0.001$, respectively).

6.3.3 Discussion

This experiment reveals an aftereffect transfer from active to passive dynamic touch, and vice versa. The magnitude of the effect was higher in the passive-active condition than in the active-passive condition. The correspondence between the first and the second experiment is that a stronger aftereffect is obtained when the test stimulus is actively explored, irrespective of the manner of touching the adaptation stimulus.

6.4 General discussion

6.4.1 The existence of a dynamic curvature aftereffect

We demonstrated the occurrence of an aftereffect when curved surfaces are dynamically touched with a single index finger. This finding is a considerable extension of the original discovery of Gibson (1933), since we employed a quantitative approach and displayed the existence of the effect for a relatively short adaptation time. In this respect, the dynamic curvature aftereffect is similar to previously reported static curvature aftereffects (Vogels et al. 1996; Van der Horst et al. 2008).

6.4.2 Dynamic touch versus static touch

One of the most important findings of this study is the complete intermanual transfer of the dynamic curvature aftereffect. The magnitude of the aftereffects in the opposite-finger and same-finger conditions was the same. In contrast, no intermanual transfer has been demonstrated for the static whole-hand aftereffect (Vogels et al. 1997); only partial transfer has been found for the static single-finger aftereffect (Van der Horst et al. 2008). This dissimilarity between the transfer of the dynamic curvature aftereffect and transfer of the static curvature aftereffect indicates that the representation of curvature perceived by dynamic touch deviates considerably from the representation of curvature perceived by static touch. The origin of this difference might be found at the basis of curvature perception, namely, the way in which curvature information is achieved by the finger(s). In the subsequent paragraphs, we consider how curvature information can be derived from static and dynamic contact with a stimulus surface.

When a single finger is in static

contact with a stimulus surface, the indentation profile of the stimulus on the finger is directly related to the shape of the surface (Fig. 6.4a). The curvature of the surface can be derived by assembling the responses of the cutaneous mechanoreceptor population in the finger pad (Goodwin et al. 2004; Van der Horst et al. 2008). For weakly curved stimuli, the local, immediate contact of the finger on the stimulus does not provide sufficient information about the shape of the stimulus, since the curvature of the stimulus is below the threshold for single-finger static touch (Goodwin et al. 1991; Pont et al. 1999). However, the shape can be perceived by static touch when the whole hand or different parts of the hand are in contact with the stimulus surface. In this case, the shape may be derived from combining the local slant at each contact point with knowledge about the position of the fingers (see Fig. 6.4a). Note that for single-finger static touch as well as multi-finger static touch, the available information remains constant in time.

The situation is different for dynamic touch. Since the immediate contact of a single finger is insufficient, curvature information must be derived from the dynamic contact between the finger and the stimulus surface. Several events occur simultaneously and change over time when the finger makes a horizontal movement over the stimulus surface: the finger skin slips and stretches; the finger is displaced in the vertical direction; the orientation of the finger with respect to the external space (rotation around the finger axis) and to the stimulus surface (change in contact point) may be altered (Fig. 6.4b).

The question is how the shape of the stimulus can be deduced from various information sources. Theoretically, knowing the starting position, the vertical displacement is the only information source that is directly related to the shape of the stimulus. However, for weakly curved stimuli, the height differences are too small to provide sufficient information about the shape of the stimuli (Pont et al. 1999). The remaining sources cannot individually provide information about the shape of the stimulus, since they are indistinguishable for convex and concave shapes. Therefore, they must be combined: a change in contact point only provides information about the shape when it is combined with knowledge about the rotation of the finger and the direction of movement. The latter can be derived from the self-induced movement of the finger or from the stretch and slip of the finger skin.

Information sources like rotation and change in contact point cannot provide instantaneous information, only information over time. Our finding of a complete transfer of the dynamic curvature aftereffect is in agreement with this analysis. Adaptation cannot occur at a low level, since information from individual sources is similar for convex and concave stimuli and non-informative at an instantaneous moment. Adaptation can only arise at a stage in which these different

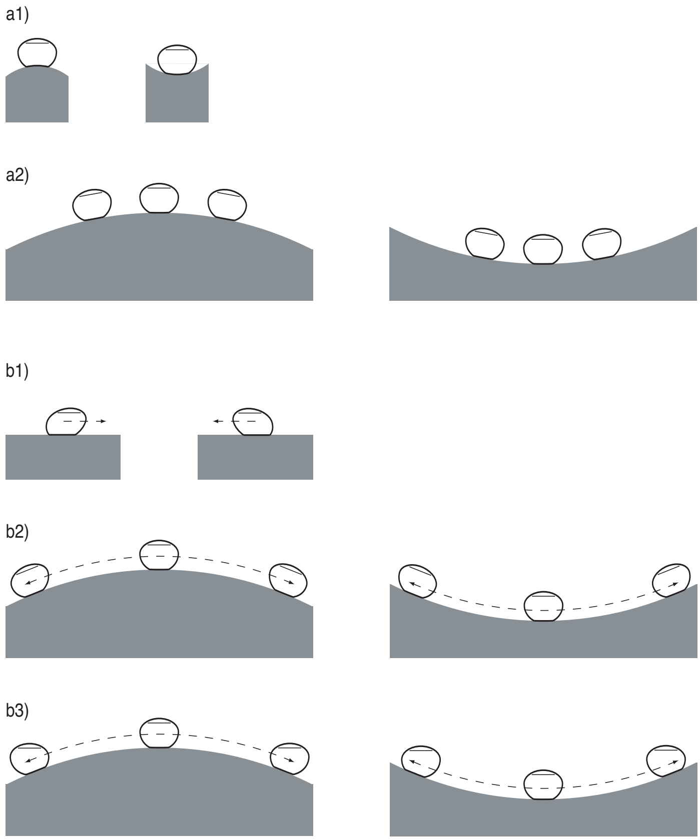


Fig. 6.4 a1) Illustration of convex and concave stimuli in contact with a single finger by static touch. There is a direct relationship between the shape of the stimulus and its indentation profile on the finger. **a2)** Static touch with different parts of the hand that contact the stimulus surface (in this case, three fingers). Local slant information from each contact point must be combined with information about the position of the finger in order to obtain curvature information from the stimulus surface. **b)** Illustrations of information sources when there is dynamic contact between the finger and a stimulus. **b1)** The finger slips and stretches due to friction between the finger and the stimulus. The deformation depends on the direction of movement contact, as indicated by an arrow. **b2)** The orientation of the finger with respect to the external space can change (rotation), when the finger moves over the stimulus surface. In the example, the finger remains parallel to the stimulus surface. In this specific situation, the point of contact on the finger does not change. Besides, the finger displaces in the vertical direction, but this displacement is too small to provide sufficient information. **b3)** The orientation of the finger with respect to the stimulus surface can change when the finger moves over the surface. As a consequence, the contact point can change. In the example, the finger does not rotate.

sources are integrated into a concept of curvature.

Pont et al. (1999) demonstrated a similar performance to discriminate curvature by static and dynamic touch. Nevertheless, the current study shows that a similar performance does not require the same representation but can be reached through different ways of processing information. Our finding of a high level of representation for dynamic touch deviates from the brain imaging study by Bodegård et al. (2001), which indicated that curvature was represented at a level that was connected to a single hand. However, the curvatures of the spheres that were rolled on the finger pad were clearly above the static single-finger threshold; thus, the dynamic component may not have contributed to the representation in this case. In contrast, dynamic contact was required in the current study, since the curvatures of the stimuli were too low to be perceived by static contact.

6.4.3 Active dynamic touch versus passive dynamic touch

Intermanual transfer of the aftereffect was found for both active and passive dynamic touch. This suggests that self-induced movement of the finger is not essential for perceiving curvature. In the previous section, we argued that information about the direction of movement is essential to distinguish a weakly curved shape. To be more precise, information about the direction of the relative movement between the finger and the stimulus is required. Since this information can be deduced from the stretch of the finger skin, information from the movement of the finger itself is redundant. This means that the same sources provide information about shape in both active and passive dynamic touch. Accordingly, curvature is similarly represented, as reflected by the existence and transfer of the aftereffect in both exploration modes and by the transfer from active to passive touch (and vice versa).

Despite the similarities between active and passive touch, significant differences in the magnitude of the aftereffect were found. In the first experiment, the aftereffect was stronger in the active mode than in the passive mode. In the second experiment, the effect was stronger in the passive-active condition than in the active-passive condition. The correspondence between these findings is that a smaller aftereffect was obtained when the test stimulus was touched passively instead of explored actively. It appears that self-induced exploration of the test stimulus enhances the aftereffect. This might be related to small differences in the exploration mode and information pickup between active and passive testing. Although the same sources provide information about shape, there may be differences in the contribution of the individual sources. For example, the amount of rotation and change in contact point might be different, or the amount of stretch may vary, depending on the force that the finger exerts on the stimulus and vice versa. Moreover, the weight given to individual information sources may depend on the exploration mode, similar to material properties that influence the weight given to individual sources in shape perception (Drewing et al. 2008).

A related aspect is that active and passive dynamic touch require different sensorimotor involvement. In active touch, the subject controls the movement of the finger on the stimulus surface. An accurate movement can be made when the efferent copy of the outgoing motor command is integrated with afferent sensory information (Wolpert et al. 1995; Flanagan et al. 2006; Gritsenko et al. 2007). In passive dynamic touch, the movement is supplied by an external agent. However, there might be a role for the sensorimotor system, since the subject himself controls that the finger stays in position.[4] Nevertheless, the contribution of the sensorimotor system to the perception of curvature might be more important in active dynamic touch, which could result in an amplification of the aftereffect. Easton and Falzett (1978) showed that the pressure profile produced in active exploration of a surface is inversely related to the curvature of that surface. Suppose that the exerted pressure profile alters systematically due to adaptation to previously acquired curvature information. Following adaptation to a convex shape to convex curvature information, the pressure profile of exploring a flat surface corresponds to that of a slightly concave surface without adaptation. Accordingly, this flat surface will be judged as concave, which is consistent with the direction of an aftereffect. The enhancement of the aftereffect during active testing does not occur for passive testing, since the dynamic contact of the finger on the stimulus is not controlled by the subject. Concerning the adaptation phase, it is not unlikely that both actively and passively acquired curvature information can cause a change in the movement planning during active testing, since information from different perceptual inputs can influence motor planning (see e.g., Gordon et al. 1991; Goodwin et al. 2004; Flanagan et al. 2006). Therefore, similar aftereffects could be obtained in the active-active condition of the first experiment and the passive-active condition of the second experiment. Future studies might measure in detail the movement and pressure profiles for active and passive touch as function of the curvature of the stimuli and the manner of adaptation.

[4] The definition of passive dynamic touch as used in the current study differs from the more strict definitions of passive touch, in which there is no role for the efferent commands (Loomis and Lederman 1986; Chapman 1993).

6.4.4 Conclusion

The current study demonstrates the existence of a haptic dynamic curvature aftereffect and a complete intermanual transfer of this effect, which suggests that dynamically obtained curvature information is represented at a high level in the brain. In contrast to statically obtained curvature information, we argue that curvature can only be perceived by dynamic touch when information from several sources is combined and integrated in time. A comparison between active and passive dynamic touch shows a larger aftereffect for actively tested curvature. This finding raises interesting questions about the importance of self-induced movement in dynamic touch, which might be the subject of future studies. In conclusion, this study provides evidence that the representation of object information depends on the exploration mode that is used to obtain that information.

7 Conclusion

This thesis reports the findings of several experiments on haptic shape perception. In this concluding chapter, the findings of the different studies are summarized and discussed briefly.

In Chapter 2, we investigated how the ability to discriminate between two curved surfaces depends on the way in which the fingers are employed in order to execute the task. Performance did not depend on the finger that was used but decreased when two fingers were employed. In addition, the two-finger conditions revealed biases, which differed strongly among subjects. Performance decreased even further when the surfaces of the stimuli were explored simultaneously instead of sequentially.

In Chapter 3, we studied the ability to compare the curvature of two opponent shapes. The findings were contrasted against the ability to compare congruent shapes investigated in Chapter 2. When only a single finger was used, higher thresholds were found for the discrimination of opponent shapes than for the discrimination of congruent shapes. However, similar thresholds were found when the bimanual discrimination of opponent shapes was compared to that of congruent shapes. Furthermore, similar thresholds were found for the unimanual and bimanual discrimination of opponent shapes. This finding was unexpected, since higher thresholds were found in the bimanual than in the unimanual condition for the comparison of congruent shapes in Chapter 2. In addition to the results for the thresholds, systematic biases were found: the curvature of concave shapes was overestimated systematically, compared to the curvature of convex shapes. We suggest that these biases originate from differences in the exploration of convex or concave shapes. Taken together, the second and third chapters show that human ability to discriminate curvature is best when two congruent shapes are explored sequentially with a single finger. The performance to achieve curvature information decreases either when the information is acquired by different fingers or when the polarity of the curvature of the stimulus alters. The findings suggest that both the manner of exploration and the way in which curvature information is processed influence the ability to perceive curvature accurately and veridically.

In Chapters 2 and 3, we used surface parts as our stimuli. In Chapter 4, we used objects with complete surfaces to investigate whether curvature information could be used in the perception of 3D objects. We found that the ability to distinguish elliptical shapes from circular shapes was about four times better than the ability to distinguish rectangular shapes from square shapes. Performance in dynamic touch was only slightly better than performance in static touch. These findings show that humans are able to perceive and employ curvature information within 3D objects. It would be interesting to further examine the ability to perceive the shape of 3D objects, for example, by investigating systematically how the perception of shape depends on the orientation of the stimulus with respect to the external space or with respect to the position of the hand.

The studies that are described in Chapters 5 and 6 were developed to obtain more insight into how the representation of curvature information depends on the manner of exploration. Therefore we investigated the properties of curvature aftereffects in static and dynamic touch. Chapter 5 shows the existence of a curvature aftereffect when stimuli are touched statically with a single finger. Only a partial transfer of this aftereffect was found, either between fingers of the same hand or of opposite hands. These findings suggest that curvature information is mainly represented at the level that is directly connected to the individual finger but partially represented at a level that the fingers of both hands share in common. In Chapter 6, we studied the occurrence and intermanual transfer of a curvature aftereffect in dynamic touch on surfaces with a low curvature. Surprisingly, we found a complete intermanual transfer of this aftereffect, which suggests that curvature information is represented at a high, bilateral level in the brain.

Chapters 5 and 6 show that the level on which curvature is represented depends on the manner in which curvature information is achieved. In static touch, shape information can be deduced from the indentation profile on the finger, which is constant in time. In dynamic touch, the instantaneous contact does not provide sufficient information about the shape; hence, shape can only be perceived when information from several sources are combined and integrated over time.

All experiments that are described in Chapters 2 and 3 were conducted in dynamic touch. However, Chapters 5 and 6 show that the processing of shape information obtained by dynamic touch is different from that acquired by static touch. Suppose that experiments are conducted that are similar to those that are described in Chapters 2 and 3, but static touch is employed. Results might be obtained that differ from the findings that were obtained with dynamic touch. For example, although Chapter 2 showed that performance for simultaneous discrimination was worse than for sequential discrimination, performance in static touch might be similar for both manners of comparison.

The studies that are reported in this thesis show that shape information can be perceived in several manners. However, variations in the exploration mode can bias the perception and result in large differences in the representation of curvature information. Nevertheless, humans are surprisingly capable of using curvature information in the perception of 3D objects.

References

Armstrong L, Marks LE (1999) Haptic perception of linear extent. Percept Psychophys 61:1211-1226

Ballesteros S, Manga D, Reales JM (1997) Haptic discrimination of bilateral symmetry in 2-dimensional and 3-dimensional unfamiliar displays. Percept Psychophys 59:37–50

Bodegård A, Geyer S, Grefkes C, Zilles K, Roland PE (2001) Hierarchical processing of tactile shape in the human brain. Neuron 31:317-328

Bodegård A, Ledberg A, Geyer S, Naito E, Zilles K, Roland PE (2000) Object shape differences reflected by somatosensory cortical activation in human. J Neurosci 20 RC51:1-5

Bradshaw JL, Nicholls MER, Rogers MA (1998) An intermanual advantage for tactual matching. Cortex 34:763–770

Braun C, Hess H, Burkhardt M, Wühle A, Preissl H (2005) The right hand knows what the left hand is feeling. Exp Brain Res 162:366–373

Burton H, Sinclair RJ (2000) Attending to and remembering tactile stimuli: a review of brain imaging data and single-neuron responses. J Clin Neurophysiol 17:575-591

Chapman CE (1993) Active versus passive touch: factors influencing the transmission of somatosensory signals to primary somatosensory cortex. Can J Physiol Pharmacol 72:558-570

Charron JF, Collin I, Braun CM (1996) Intermanual transfer of somaesthetic information: a two-point discrimination experiment. Neuropsychologia 34:873–877

Cooke T, Jäkel F, Wallraven C, Bülthoff HH (2007) Multimodal similarity and categorization of novel, three-dimensional objects. Neuropsychologia 45:484-495

Coren S (1993) The left-hander syndrome. Vintage Books, New York

Davidson, PW (1972) Haptic judgments of curvature by blind and sighted humans. J Exp Psychol 93:43-55

Dellantonio A, Spagnolo F (1990) Mental rotation of tactual stimuli. Acta Psychol 73:245-257

Drewing K, Ernst MO (2006) Integration of force and position cues for shape perception through active touch. Brain Res 1078:92-100

Drewing K, Wiecki TV, Ernst MO (2008) Material properties determine how force and position signals combine in haptic shape perception. Acta Psychol 128:264-273

Easton RD, Falzett M (1978) Finger pressure during tracking of curved contours: implications for a visual dominance phenomenon. Percept Psychophys 24:145-153

Evans PM, Craig JC (1991) Tactile attention and the perception of moving tactile stimuli. Percept Psychophys 49:355–364

Evans PM, Craig JC, Rinker MA (1992) Perceptual processing of adjacent and nonadjacent tactile nontargets. Percept Psychophys 52:571–581

Flanagan JR, Bowman MC, Johansson RS (2006) Control strategies in object manipulation tasks. Curr Opin Neurobiol 16:650-659

Gardner EP, Kandel ER (2000) Touch. In: Kandel ER, Schwartz JH, Jessell TM (eds) Principles of neural science, 4th ed. McGraw-Hill, New York, pp 451-471

Gepshtein S, Banks MS (2003) Viewing geometry determines how vision and haptics combine in size perception. Curr Biol 13:483-488

Gibson JJ (1933) Adaptation, after-effect and contrast in the perception of curved lines. J Exp Psychol 16:1-31

Goodwin AW, Browning AS, Wheat HE (1995) Representation of curved surfaces in responses of mechanoreceptive afferent fibers innervating the monkey's fingerpad. J Neurosci 15:798-810

Goodwin AW, John KT, Marceglia AH (1991) Tactile discrimination of curvature by humans using only cutaneous information from the fingerpads. Exp Brain Res 86:663-672

Goodwin AW, Macefield VG, Bisley JW (1997) Encoding of object curvature by tactile afferents from human fingers. J Neurophysiol 78:2881-2888

Goodwin AW, Wheat HE (2004) Sensory signals in neural populations underlying tactile perception and manipulation. Annu Rev Neurosci 27:53-77

Gordon AM, Forssberg H, Johansson RS, Westling G (1991) The integration of haptically acquired size information in the programming of precision grip. Exp Brain Res 83:483-488

Gordon IE, Morison V (1982) The haptic perception of curvature. Percept Psychophys 31:446-450

Gritsenko V, Krouchev NI, Kalaska JF (2007) Afferent input, efference copy, signal noise, and biases in perception of joint angle during active versus passive elbow movements. J Neurophysiol 98:1140-1154

Hammerschmidt O (1934) Über die Genauigkeit der haptischen Verwirklichung geometrischer Grundbegriffe. Sporn, Zeulenroda

Harris JA, Harris IM, Diamond ME (2001) The topography of tactile learning in humans. J Neurosci 21:1056-1061

Hayward V (2008) Haptic shape cues, invariants, priors, and interface designs. In: Grunwald M (ed) Human haptic perception: basics and applications. Birkhäuser Verlag, pp 381-392

Helbig HB, Ernst MO (2007) Optimal integration of shape information from vision and touch. Exp Brain Res 179:595-606

Henriques DYP, Soechting JF (2003) Bias and sensitivity in the haptic perception of geometry. Exp Brain Res 150:95-108

Iwamura Y (2000) Bilateral receptive field neurons and callosal connections in the somatosensory cortex. Philos Trans R Soc B Biol Sci 355:267-273

Jansson G, Monaci L (2004) Haptic identification of objects with different number of fingers. In: Ballesteros S, Heller MA (eds) Touch, blindness, and neuroscience. UNED, Madrid pp 209–219

Jenmalm P, Birznieks I, Goodwin AW, Johansson RS (2003) Influence of object shape on responses of human tactile afferents under conditions characteristic of manipulation. Eur J Neurosci 18:164-176

Johansson RS, Vallbo ÅB (1983) Tactile sensory coding in the glabrous skin of the human hand. Trends Neurosci 6:27-32

Johnson KO (2001) The roles and functions of cutaneous mechanoreceptors. Curr Opin Neurobiol 11:455–461

Johnson KO, Yoshioka T, Vega-Bermudez F (2000) Tactile functions of mechanoreceptive afferents innervating the hand. J Clin Neurophysiol 17:539–558

Kappers AML, Koenderink JJ (1996) Haptic unilateral and bilateral discrimination of curved surfaces. Perception 25:739-749

Kappers AML, Koenderink JJ, Te Pas SF (1994) Haptic discrimination of doubly curved surfaces. Perception 23: 483-1490

Klatzky RL, Lederman SJ, Metzger SJ (1985) Identifying objects by touch: an "expert" system. Percept Psychophys 37:299-302

Lakatos S, Marks LE (1999) Haptic form perception: relative salience of local and global features. Percept Psychophys 61:895-908

LaMotte RH, Srinivasan MA (1993) Responses of cutaneous mechanoreceptors to the shape of objects applied to the primate fingerpad. Acta Psychol 84:41-51

LaMotte RH, Srinivasan MA (1996) Neural coding of shape: responses of cutaneous mechanoreceptors to wavy surfaces stroked across the monkey fingerpad. J Neurophysiol 76:3787-3797

Lederman SJ, Klatzky RL (1987) Hand movements: a window into haptic object recognition. Cognitive Psychol 19:342–368

Lederman SJ, Klatzky RL (2004) Haptic identification of common objects: effects of constraining the manual exploration process. Percept Psychophys 66:618-628

Loomis JM, Lederman SJ (1986) Tactual perception. In: Boff KR, Kaufman L, Thomas JP (eds) Handbook of perception and human performance, vol II: Cognitive processes and performance, John Wiley, New York

Louw S, Kappers AML, Koenderink JJ (2000) Haptic detection thresholds of Gaussian profiles over the whole range of scales. Exp Brain Res 132:369–374

Louw S, Kappers AML, Koenderink JJ (2002a) Active haptic detection and discrimination of shape. Percept Psychophys 64:1108–1119

Louw S, Kappers AML, Koenderink JJ (2002b) Haptic discrimination of stimuli varying in amplitude and width. Exp Brain Res 146:32-37

Mather G, Verstraten F, Anstis S (1998) The motion aftereffect: a modern perspective. MIT Press, Cambridge Massachusetts

McFarland J, Soechting JF (2007) Factors influencing the radial-tangential illusion in haptic perception. Exp Brain Res 178:216-227

Moulden B (1980) After-effects and the integration of patterns of neural activity within a channel. Philos Trans R Soc B Biol Sci 290:39-55

Nefs HT, Kappers AML, Koenderink JJ (2005) Intermanual and intramanual tactual grating discrimination. Exp Brain Res 163:123–127

Newell FN, Ernst MO, Tjan BS, Bülthoff (2001) Viewpoint dependence in visual and haptic object recognition. Psychol Sci 12:37-42

Norman JF, Norman HF, Clayton AM, Lianekhammy J, Zielke G (2004) The visual and haptic perception of natural object shape. Percept Psychophys 66:342-351

Oldfield SR, Phillips JR (1983) The spatial characteristics of tactile form perception. Perception 12:615-626

Pont SC, Kappers AML, Koenderink JJ (1997) Haptic curvature discrimination at several regions of the hand. Percept Psychophys 59:1225-1240

Pont SC, Kappers AML, Koenderink JJ (1998) The influence of stimulus tilt on haptic curvature matching and discrimination by dynamic touch. Perception 27:869-880

Pont SC, Kappers AML, Koenderink JJ (1999) Similar mechanisms underlie curvature comparison by static and dynamic touch. Percept Psychophys 61:874-894

Prather SC, Sathian K (2002) Mental rotation of tactile stimuli. Cognitive Brain Res 14:91-98

Provancher WR, Cutkosky MR, Kuchenbecker KJ, Niemeyer G (2005) Contact location display for haptic perception of curvature and object motion. Int J Robot Res 24:691-702

Reed CL, Shoham S, Halgren E (2004) Neural substrates of tactile object recognition: an fMRI study. Hum Brain Mapp 21:236-246

Robles-De-La-Torre G, Hayward V (2001) Force can overcome object geometry in the perception of shape through active touch. Nature 412:445-448

Roland PE, Mortensen E (1987) Somatosensory detection of microgeometry, macrogeometry and kinesthesia in man. Brain Res Rev 12:1-42

Roland PE, O'Sullivan B, Kawashima R (1998) Shape and roughness activate different somatosensory areas in the human brain. P Natl Acad Sci USA 95:3295-3300

Russier S (1999) Haptic discrimination of two-dimensional raised line shapes by blind and sighted adults. J Vis Impair Blind 93:421–426

Sanders AFJ, Kappers AML (2006) Bimanual curvature discrimination of hand-sized surfaces placed at different positions. Percept Psychophys 68:1094-1106

Sathian K, Zangaladze A (1996) Tactile spatial acuity at the human fingertip and lip: bilateral symmetry and interdigit variability. Neurology 46:1464–1466

Sathian K, Zangaladze A (1997) Tactile learning is task specific but transfers between fingers. Percept Psychophys 59:119-128

Schnitzler A, Salmelin R, Salenius S, Jousmäki V, Hari R (1995) Tactile information from the human hand reaches the ipsilateral primary somatosensory cortex. Neurosci Lett 200:25–28

Schweizer R, Maier M, Braun C, Birbaumer N (2000) Distribution of mislocalizations of tactile stimuli on the fingers of the human hand. Somatosens Mot Res 17:309-316

Spence C, Gallace A (2007) Recent developments in the study of tactile attention. Can J Exp Psychol 61:196-207

Tao R, Lankheet MJM, van de Grind WA, van Wezel RJA (2003) Velocity dependence of the interocular transfer of dynamic motion aftereffects. Perception 32:855-866

Treutwein B (1995) Adaptive psychophysical procedures. Vision Res 35:2503-2522

Turvey MT (1996) Dynamic touch. Am Psychol 51:1134-1152

Van Boven RW, Ingeholm JE, Beauchamp MS, Bikle PC, Ungerleider LG (2005) Tactile form and location processing in the human brain. P Natl Acad Sci USA 102:12601-12605

Van Boven RW, Johnson KO (1994) The limit of tactile spatial resolution in humans: grating orientation discrimination at the lip, tongue, and finger. Neurology 44:2361–2366

Van der Horst BJ, Duijndam MJA, Ketels MFM, Wilbers MTJM, Zwijsen SA, Kappers AML (2008) Intramanual and intermanual transfer of the curvature aftereffect. Exp Brain Res 187:491-496

Van der Horst BJ, Kappers AML (2007) Curvature discrimination in various finger conditions. Exp Brain Res 177:304-311

Van der Horst BJ, Kappers AML (2008) Haptic curvature comparison of convex and concave shapes. Perception (in press)

Vogels IMLC, Kappers AML, Koenderink JJ (1996) Haptic after-effect of curved surfaces. Perception 25:109-119

Vogels IMLC, Kappers AML, Koenderink JJ (1997) Investigation into the origin of the haptic after-effect of curved surfaces. Perception 26:101-117

Vogels IMLC, Kappers AML, Koenderink JJ (1999) Influence of shape on haptic curvature perception. Acta Psychol 100:267-289

Vogels IMLC, Kappers AML, Koenderink JJ (2001) Haptic after-effect of successively touched curved surfaces. Acta Psychol 106:247-263

Voisin J, Michaud G, Chapman CE (2005) Haptic shape discrimination in humans: insight into haptic frames of reference. Exp Brain Res 164:347–356

Von Skramlik E (1937) Psychophysiologie der Tastsinne. Akademische Verlagsgesellschaft, Leipzig

Wade NJ, Swanston MT, de Weert CMM (1993) On interocular transfer of motion aftereffects. Perception 22:1365-1380

Weber EH (1834) De tactu. translation. In: Ross HE, Murray JD (eds) (1996) EH Weber: on the tactile senses. Academic Press, London pp 21–136

Weinstein S (1968) Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In: Kenshalo DR (ed) The skin senses. Thomas Spring Field, Illinois, pp 195–222

Wheat HE, Goodwin AW, Browning AS (1995) Tactile resolution: peripheral neural mechanisms underlying the human capacity to determine positions of objects contacting the fingerpad. J Neurosci 15:5582–5595

Wichmann FA, Hill NJ (2001a) The psychometric function: I. Fitting, sampling, and goodness of fit. Percept Psychophys 63:1293-1313

Wichmann FA, Hill NJ (2001b) The psychometric function: II. Bootstrap-based confidence intervals and sampling. Percept Psychophys 63:1314–1329

Wolpert DM, Ghahramani Z, Jordan MI (1995) An internal model for sensorimotor integration. Science 269:1880-1882

Zanker JM, Quenzer T (1999) How to tell circles from ellipses: perceiving the regularity of simple shapes. Naturwissenschaften 86:492-495

Zhang M, Mariola E, Stilla R, Stoesz M, Mao H, Hu X, Sathian K (2005) Tactile discrimination of grating orientation: fMRI activation patterns. Hum Brain Mapp 25:370-377

Zuidhoek S, Kappers AML, Van der Lubbe RHJ, Postma A (2003) Delay improves performance on a haptic spatial matching task. Exp Brain Res 149:320–330

Samenvatting

In het dagelijks leven zijn mensen voortdurend bezig om voorwerpen met de handen vast te pakken en te gebruiken. Om deze taken goed uit te kunnen voeren is het belangrijk om over nauwkeurige informatie over de vorm van objecten te kunnen beschikken. De gevoeligheid van de vingers voor vorm is onmisbaar in het verkrijgen van deze informatie. In dit proefschrift wordt onderzoek gepresenteerd naar het vermogen om met de hand en de vingers de vorm van objecten te kunnen waarnemen.

In dit onderzoek wordt de term haptisch gebruikt om het perceptuele aspect van het gebruik van de hand aan te duiden. Een vijftal psychofysische studies zijn gedaan waarin is onderzocht hoe de haptische waarneming van vorm afhangt van de manier waarop deze vorminformatie verkregen is. Het doel van deze studies is om een beter begrip te krijgen van de capaciteiten van het haptische zintuig en meer inzicht te krijgen in de onderliggende representaties.

In hoofdstuk 2 hebben we onderzoek gedaan naar het vermogen om gekromde oppervlakken van elkaar te kunnen onderscheiden. De vraag waarin we geïnteresseerd waren was of dit discriminatievermogen afhangt van de manier waarop de oppervlakken geëxploreerd worden. De taak van de proefpersoon was om te beoordelen welke van de twee aangeboden oppervlakken de sterkste kromming had. Een oppervlak kon bevoeld worden door er met de vingertop over te bewegen (dynamische tast). Het experiment dat we uitvoerden liet zien dat het niet uitmaakte welke vinger voor deze taak gebruikt werd. Het discriminatievermogen verminderde echter wanneer verschillende vingers werden gebruikt voor de te vergelijken oppervlakken. Het vermogen om kromming te discrimineren werd zelfs nog slechter wanneer de stimuli gelijktijdig in plaats van na elkaar geëxploreerd werden. In de condities waarin twee verschillende vingers gebruikt werden vonden we bovendien proefpersoonafhankelijke biases, hetgeen betekent dat de kromming die met de ene vinger werd waargenomen systematisch werd overschat ten opzichte van de kromming die met een andere vinger werd waargenomen.

De stimuli die in hoofdstuk 2 gebruikt werden hadden een convexe vorm. Concave vormen kunnen echter door dezelfde kromming gekarakteriseerd worden. In hoofdstuk 3 vroegen we ons af hoe goed mensen in staat zijn om de kromming van een convexe vorm te onderscheiden van de kromming van de concave pendant. Als slechts één vinger gebruikt werd, werden er hogere drempels gevonden voor de discriminatie van tegenovergestelde vormen dan voor de discriminatie van congruente vormen. Vergelijkbare drempels werden echter verkregen wanneer twee verschillende vingers werden gebruikt om de congruente en tegenovergestelde vormen te vergelijken. Wanneer tegenovergestelde vormen werden gebruikt bleek het voor het discriminatievermogen niet uit te maken of één of twee vingers gebruikt werden. Naast de resultaten voor de drempels werden er biases gevonden: de kromming van concave vormen werd systematisch overschat ten opzichte van de kromming van convexe vormen.

De hoofdstukken 2 en 3 laten zien dat het vermogen om kromming te discrimineren het grootst is als twee congruente vormen na elkaar met dezelfde vinger worden geëxploreerd. Minder goede resultaten worden verkregen als twee vingers worden gebruikt of als de polariteit van de kromming verandert. De bevindingen in de hoofdstukken 2 en 3 suggereren dat zowel de manier van exploreren als ook de manier waarop informatie verwerkt wordt van invloed is op het vermogen om krommingsinformatie te kunnen onderscheiden.

In de hoofdstukken 2 en 3 werden gedeeltes van oppervlakken als stimuli gebruikt. In hoofdstuk 4 maakten we de stap naar complete objecten als stimuli. Het doel hiervan was om te onderzoeken of krommingsinformatie gebruikt kon worden in het waarnemen van de vorm van 3D objecten. In het experiment dat we uitvoerden vroegen we aan proefpersonen of ze cilinders met een elliptische doorsnede konden onderscheiden van cilinders met een cirkelvormige doorsnede. Ter vergelijking lieten we ze ook rechthoekige parallellepipeda van vierkante parallellepipeda onderscheiden. Zowel elliptische als rechthoekige vormen kunnen worden gekarakteriseerd door de aspectratio, maar elliptische vormen bevatten bovendien krommingsinformatie. We vonden dat een ellips met een aspectratio van slechts 1.03 onderscheiden kon worden van een cirkel, zowel in statische als dynamische tast. Voor de rechthoeken werd er een aspectratio gemeten van 1.11 in dynamische tast en 1.15 in statische tast als drempel om een rechthoek te kunnen onderscheiden van een vierkant. Deze studie laat zien dat mensen in staat zijn om krommingsinformatie in 3D objecten te kunnen waarnemen en gebruiken.

In de hoofdstukken 5 en 6 presenteren we onderzoek naar het na-effect van kromming. Het na-effect is het verschijnsel dat een plat oppervlak als concaaf (convex) wordt waargenomen als voorafgaand geadapteerd is aan een convex (concaaf) oppervlak. Het na-effect is interessant om te bestuderen omdat het meer inzicht kan geven in hoe krommingsinformatie gerepresenteerd wordt. In hoofdstuk 5 laten we zien dat een na-effect optreedt als gekromde oppervlakken statisch worden aangeraakt met de vingertop. Bovendien laten we zien dat het na-effect slechts gedeeltelijk overdraagt naar andere vingers, van zowel dezelfde hand als van de andere hand. Deze resultaten suggereren dat krommingsinformatie vooral gerepresenteerd wordt op een niveau dat direct verbonden is met de individuele vinger, maar ook gedeeltelijk op een hoger niveau verwerkt wordt. In hoofdstuk 6 onderzochten we de karakteristieken van het na-effect als de stimuli dynamisch geëxploreerd worden. Ook in dit geval werd een na-effect gevonden, en verassend genoeg, was er een complete overdracht van dit na-effect naar de andere hand. Dit resultaat impliceert dat dynamisch verkregen krommingsinformatie op een hoog niveau in het brein gerepresenteerd wordt.

De resultaten van de hoofdstukken 5 en 6 laten zien dat de representatie van kromming afhangt van de manier waarop deze informatie verkregen wordt. De kromming van een oppervlak die met statische tast wordt gevoeld kan direct gerelateerd worden aan het contactprofiel van de vorm op de vinger. Dit profiel is bovendien constant in de tijd. Bij dynamische tast kan de vorm niet gerelateerd worden aan het instantane profiel, maar kan alleen worden afgeleid als informatie van verschillende bronnen wordt gecombineerd en geïntegreerd in de tijd.

Publications and award

Journal papers

Van der Horst BJ, Duijndam MJA, Ketels MFM, Wilbers MTJM, Zwijsen SA, Kappers AML (2008) Intramanual and intermanual transfer of the curvature aftereffect. Exp Brain Res 187:491-496

Van der Horst BJ, Kappers AML (2007) Curvature discrimination in various finger conditions. Exp Brain Res 177:304-311

Van der Horst BJ, Kappers AML (2008) Haptic curvature comparison of convex and concave shapes. Perception (in press)

Van der Horst BJ, Kappers AML (2008) Using curvature information in haptic shape perception of 3D objects. Exp Brain Res (in press)

Van der Horst BJ, Willebrands WP, Kappers AML (2008) Transfer of the curvature aftereffect in dynamic touch. Neuropsychologia (in press)

Conference paper

Van der Horst BJ, Kappers AML (2008) Intermanual transfer of the curvature aftereffect in static and dynamic touch. In: Ferre M (ed) Haptics: perception, devices and scenarios. Proceedings of EuroHaptics 2008 (LNCS 5024), Madrid, Spain, 238-244

Conference abstracts

Van der Horst BJ, Duijndam MJA, Ketels MFM, Wilbers MTJM, Zwijsen SA, Willebrands WP, Kappers AML (2007) Transfer of the curvature aftereffect in static and dynamic touch. In: Three dimensional sensory and motor space: perceptual consequences of motor action. ESF-EMBO symposium, Sant Feliu de Guixols, Spain

Van der Horst BJ, Kappers AML (2005) Curvature discrimination by active touch. In: Proceedings NVP Winter Conference, Egmond aan Zee, The Netherlands, 26

Van der Horst BJ, Kappers AML (2006) Haptic curvature comparison of convex and concave shapes. In: Proceedings of EuroHaptics 2006, Paris, France, 501-502

Van der Horst BJ, Kappers AML (2005) Haptic curvature perception in different finger conditions. In: WorldHaptics Conference 2005, Pisa, Italy

Van der Horst BJ, Kappers AML (2008) Intermanual transfer of haptic curvature aftereffects depends on the manner of touching. In: ECVP 2008, Utrecht, The Netherlands

Award

Best paper in EuroHaptics Conference 2008, Madrid, Spain

Curriculum Vitae

Ik ben in 1979 geboren te Almen (Gorssel). Mijn VWO diploma heb ik behaald aan het Greijdanus College te Zwolle. Vervolgens heb ik van 1997 tot 2004 gestudeerd aan de Universiteit Utrecht. In de Natuurkunde ben ik in twee richtingen afgestudeerd. Voor de afstudeerrichting in de experimentele natuurkunde heb ik onderzoek verricht naar ruisverschijnselen in amorf silicium. Voor de afstudeerrichting in de geschiedenis van de natuurkunde heb ik een scriptie geschreven over de causaliteitsopvatting van Thomas Reid. Met deze scriptie ben ik bovendien afgestudeerd in de Wijsbegeerte van de Exacte Natuurwetenschappen. Van 2004 tot 2008 was ik als promovendus verbonden aan het Helmholtz Instituut aan de Universiteit Utrecht. De resultaten van het onderzoek zijn beschreven in dit proefschrift. Verder heb ik werkcollege gegeven bij de natuurkundevakken Mechanica en Golven & Optica en heb ik bachelorstudenten begeleid in hun onderzoek.

Finishing touch

Dit proefschrift is het resultaat van vier jaar promotietijd. Nu kent een promotietijd veel meer aspecten dan deze bundeling van wetenschappelijke publicaties kan tonen. Er kan nog van alles meer verteld worden, maar ik zal mij beperken tot enkele aspecten.

Om te beginnen is daar de plaats van handeling, het BBL: een ivoren toren, opgetrokken uit beton. In de vormgeving van dit gebouw is men er zeer goed in geslaagd om het op geen enkele wijze een visueel aantrekkelijke uitstraling mee te geven. Het interieur sluit naadloos aan bij de buitenkant: lange, rechte gangen waarin je alleen vanuit symmetrieoverwegingen kunt verdwalen; de kamers zien er allemaal hetzelfde uit en vanzelfsprekend kunnen de ramen niet geopend worden. Kortom, een zeer geschikt gebouw om haptisch onderzoek in te verrichten.

Mijn onderzoek bestond eruit mensen op zeer gecontroleerde wijze in fysiek contact te brengen met objecten, ook wel psychofysica genoemd. De objecten werden speciaal voor dit doel ontworpen en vervaardigd. Hans en de mechanici van de werkplaats hebben een cruciale rol gespeeld in de realisatie van deze unieke collectie. De mensen, dat waren een gros studenten die omgekocht werden om hun handen tijdelijk ter beschikking te stellen aan de wetenschap. Mijn taak bestond eruit om honderdduizend keer een collectors item aan deze mensen ter bevoeling aan te bieden. Gevraagd naar hun mening zeiden ze vaak iets in de trant van “hol”, “bol”, “há” of “bé”.

De resultaten van deze animerende conversaties worden ook wel data genoemd. De volgende stap was om in deze brei verbanden te zien en conclusies te trekken. Gelukkig waren er in die fase collega’s die vergelijkbare sessies hadden gehouden, zodat er uren gediscussieerd kon worden over alle facetten van het programmeren in Mathematica, het fitten van een psychometrische curve en het verschil tussen fysici en psychologen in de benadering van statistiek. Als dan bleek dat er significante en samenhangende resultaten te destilleren waren dan mocht dit vervolgens aan de buitenwereld verteld gaan worden. Na veel geploeter en herschrijverij was er dan een artikel dat het waard leek om gepubliceerd te worden. Anonieme reviewers mochten dan beoordelen of zij dat ook vonden. Het commentaar dat vervolgens werd teruggestuurd varieerde van “Overall, the quality of the presentation left much to be desired” tot “I appreciate the clarity of the authors' writing and explanation”. Dit betekende nog een aantal maanden danwel nog een uurtje extra werk. Zo werkt wetenschap.

Maar gelukkig was wetenschap meer dan werk alleen. Vanaf het begin waren er de haptic boys, met wie ik parallel optrok in de strijd om het wetenschappelijke bestaan. In later tijd kwamen er ook nog de haptic girls, en er waren de andere collega's van de derde verdieping die zich bezighielden met pinguïns, pijlen, pictures, plenopters en vrijwillige perceptie. Er waren de dagelijkse stipt-om-12-uur lunches, waarin de frustraties gedeeld werden ten aanzien van het universitaire beleid inzake erwtensoep en reorganisaties. Er was koffie. Er waren de reizen naar mooie steden, waar niet alleen congressen, maar zeker ook musea en goede eetgelegenheden bezocht konden worden.

Met de voltooiing van dit proefschrift kan het boek van vier jaar promotietijd gesloten worden. Een tijd die begon doordat Astrid, mijn promotor, vertrouwen in mijn capaciteiten stelde. Zij gaf mij de vrijheid om zelfstandig mijn projecten op te zetten en was altijd bereid om tijd vrij te maken om te discussiëren over de resultaten en gerichte feedback te geven op mijn manuscripten.

Tijd voor een volgend boek.