HAPTIC PERCEPTION OF SHAPES AND LINE DRAWINGS

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HAPTIC PERCEPTION OF SHAPES AND LINE DRAWINGS

HAPTISCHE PERCEPTIE VAN VORMEN EN LIJNTEKENINGEN

(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 voor promoties in het openbaar te verdedigen op woensdag 3 september 2008 des middags te 4.15 uur

door

Maarten Willem August Wijntjes

geboren op 1 november 1977, te Utrecht

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

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"What can it matter to you? You just drift along. You don't give a good godamm about the universal consequences that can flow from our most trifling acts, our most unforeseen thoughts ... It's no skin off your ass ... You're caulked ... hermetically sealed ... Nothing means anything to you ... Am I right? Nothing. Eat! Drink! Sleep! Up there as cozy as you please ... All warm and comfy on my couch ... You've got everything you want ... You wallow in well-being ... the earth rolls on ... How? Why? A staggering miracle ... how it moves ... the profound mystery of it ... toward and infinite unforeseeable goal ... in a sky all scintillating with comets ... all unknown ... from one rotation to the next ... Each second is the culmination and also the prelude of an eternity of other miracles ... of imprenetable wonders, thousands of them, Ferdinand! Millions! billions of trillions of years! ... And you? What are you doing in the midst of this cosmologonic whirl? this vast sidereal wonder? Just tell me that! You eat! You fill your belly! You sleep! You don't give a damn ... That's right! Salad! Swiss cheese! Sapience! Turnips! Everything! You wallow in your own muck! You loll around, befouled! Glutted! Satisfied! You don't aks for anything more! You pass through the stars ... as if they were raindrops in May! ... God, you amaze me, Ferdinand! Do you really think this can go on forever?... " [1]

Death on Credit (1936)
Louis Ferdinand Celine

[1] Translated by Ralph Manheim, John Calder (Publishers), London (1989).

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Chapter 1

Introduction

From metaphysics to psychophysics

"Picture men dwelling in a sort of subterranean cavern with a long entrance open to the light on its entire width. Conceive them as having their legs and neck fettered from childhood, so that they remain in the same spot, able to look forward only, and prevented by the fetters from turning their heads. Picture further the light from a fire burning higher up and at a distance behind them, and between the fire and the prisoners and above them a road along which a low wall has been built, as the exhibitors of puppet-shows have partitions before the men themselves, above which they show the puppets." "All that I see", he said. "See also, then, man carrying past the wall implements of all kinds that rise above the wall, and human images and shapes of animals as well, wrought in stone and wood and every material, some of these bearers presumably speaking and others silent." "A strange image you speak of," he said, "and strange prisoners." " Like to us," I said, "for to begin with, tell me do you think that these men would have seen anything of themselves or of one another except the shadows cast from the fire on the wall of the cave that fronted them?" "And again, would not the same be true of the objects carried past them?" "Surely." "If then they were able to talk to one another, do you not think that they would suppose that in naming the things that they saw they were naming the passing objects?" "Necessarily." "And if their prison had an echo from the wall opposite to them, when one of the passersby uttered a sound, do you think that they would suppose anything else than the passing shadow to be the speaker?" "By Zeus, I do not," said he. "Then in every way such prisoners would deem reality to be nothing else than the shadows of the artificial objects." "Quite inevitable," he said. [1]

Although Plato's allegory is often used to explain metaphysics, it also helps to explain psychophysics. We perceive the world indirectly, namely via our senses. Although we may not be aware of it, we only perceive a shadow of reality, our subjective expe-

[1] First part of book VII of Plato's The Republic, translated by Paul Shorey, Harvard University Press, Cambridge; William Heinemann Ltd, London (1980).

rience. Whereas philosophers have used *pure reasoning* to solve the problem of what is real (and what is really real), psychologists in the nineteenth century started to use *experiments* to relate subjective experience to the physical reality. Fechner called this approach *psychophysics* (Fechner, 1860/1964). Some psychophysical techniques are used to directly compare the shadow with reality (perceptual biases); others aim to measure the accurateness of the shadow (detection and discrimination thresholds).

In many cases we need to perform a well-designed experiment in which we measure many repetitions in order to reveal a clear difference between subjective experience and physical reality. In case of sensory illusions one does not need thorough experiments to comprehend that there are differences between perception and reality.

The skin is one big retina, but haptics is more

In this thesis I investigate some aspects of haptic perception using psychophysical methods. Haptic perception means perceiving with your skin (cutaneous sensation) as well as with the biomechanics of your limbs (kinaesthesia). These biomechanics include movement and the forces exerted by the limbs. Cutaneous and kinaesthetic sensations are two very distinct types of sensory processing, which makes them challenging subjects to study. To get an idea of how haptics works, let us compare it with vision. The architectures of the retina and the skin resemble each other: a surface covered with sensors that detect light or mechanical pressure, respectively. These sensory surfaces are both controlled by muscles. The important difference is that only limbs physically interact with the environment. Since this interaction is processed by the brain and used as an information source, haptics is more than merely a surface of sensors.

Although the cutaneous and kinaesthetic senses are physiologically different, they are tightly coupled higher up in the hierarchy of the central nervous system. De Vignemont et al (2005) studied this coupling by inducing a kinaesthetic illusion in which a finger is perceived to be elongated. They found that the kinaesthetic illusion induced a cutaneous illusion: the distance between two points on the skin of the elongated finger was also perceived as longer. Intuitively, this finding may seem not surprising, but it does show that our body is well organised and integrates information from distinct sensory sources in a seemingly effortless fashion. This high-quality sensory integration makes the study of the separate sensory inputs a tricky business, at least in case of haptics. This thesis focuses more on how different aspects of the *world* contribute to our perception than on the different parts of our *sensory system*. These aspects of the world are the physical properties of our environment. There is a large number of physical properties that can be sensed by haptics: shape (Kappers et al, 1994), compressibility (Srinivasan and LaMotte, 1995), weight (Weber, 1834/1996), moments of inertia (Turvey, 1996), heat conductivity (Bergmann Tiest and Kappers, 2008), temperature (Stevens and Choo, 1998), viscosity (Beauregard et al, 1995), etc. I even think that haptics is the sense with which we can perceive the largest number of physical properties in comparison with any other sense. This makes it an interesting subject for psychophysical studies.

A square with a triangle on top

The shape of an object is that what remains after removing size, translation and orientation information. In Fig. 1.1A, a grey shape is drawn. Inside the grey shape are copies of that shape that are translated, rotated and isotropically scaled but maintain the same shape. Outside of the grey area, the shapes are not the same; the transformations have become too complicated to preserve shape. If we want to mathematically describe a shape, we have multiple options. As illustrated in Fig 1.1B, we could describe the position of the line $\mathbf{x}(s)$, parametrised by the path length s. If this description is known, then the shape is fully specified. However, we can also describe the shape by the tangent of the line $\mathbf{x}'(s)$, or by its curvature $\mathbf{x}''(s)$. No matter which description we use, we can switch to another description by differentiation or integration. Curvature is defined by how much the tangent changes along the path, $\mathbf{x}''(s)$. If we look at the curvature along a circle we find a constant value. The inverse of the radius of a circle is conveniently used as the unit of curvature (see Fig. 1.1B). A sharp bend as in the upper right corner means a high curvature, because the radius of the circle is small. Whether the circles are inside or outside denotes the sign of the curvature: convex and concave, respectively. If a surface is flat, we need a circle with an infinite radius, meaning that the curvature is zero. All of this may seem somewhat abstract and disconnected from haptic perception, but as we will see later, all three shape descriptions are available to the haptic sense. Since mathematically we need only one descriptor to fully specify a shape, the interesting question is how the haptic system handles this over-specification.

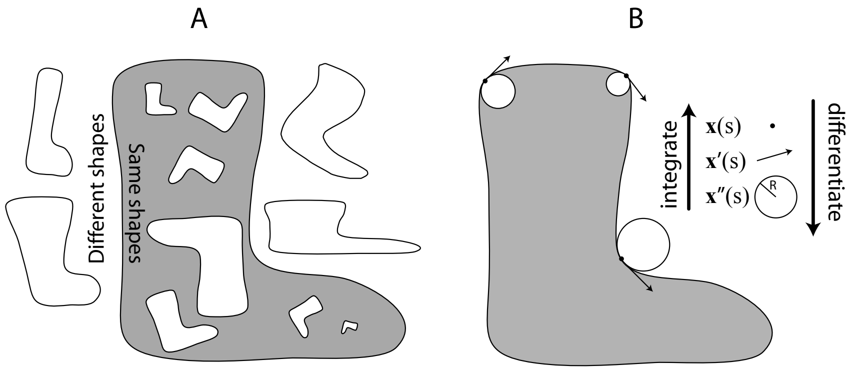

Figure 1.1: A: Inside the grey shape similar shapes are shown whereas the shapes outside are dissimilar. B: Three different shape descriptors that each fully specify a shape.

It may seem that the shapes drawn in Fig. 1.1 resemble boots. This illustrates the importance of shape perception: it helps one to identify everyday objects. The description 'a square with a triangle on top' only consists of geometrical information. Visualising this description, most people would identify the object (otherwise: sketch it!). Shape is one of the many features that are used to identify the objects in our environment. All of the physical properties mentioned earlier can be used to identify objects. Each sense uses different properties, although shape is a typical feature available to both haptics and vision.

Elements of the elements

A starting point of understanding how humans perceive 'complex' shapes as shown in Fig. 1.1 is to study how humans perceive the elements of a shape. Many investigators have studied length, orientation and curvature perception. These already may seem to be very specialised topics, but the specialisation goes even further. Most studies focus on which sub-elements are important for the perception of a certain shape element. For example, it has been shown that for length perception, direction is important. Armstrong and Marks (1999) found that a stimulus in the radial direction is perceived to be longer than one in a tangential direction.

In chapter 2, we investigated which elements of angles are important for haptic perception. Looking at two lines making an angle with each other, it may not be apparent that there are more elements than the angle itself. However, to haptically perceive an angle, there are several elements involved. Haptic perception often depends on how you touch an object. In chapter 2 we investigated whether angle perception would indeed depend on how the angle is explored. Another element of angles is the distinction between local and global properties. When exploring an angle, the finger runs from one line to the other, in different directions (if the angle is not 180°). These directions are the global properties. The finger also senses the apex, the transition of the two lines. This element does not depend on the directions of the movement of the finger, but rather on the direct (cutaneous) contact with the apex. By removing this apex the relative contributions of these local and global properties can be investigated.

In chapter 5 the elements of curvature were investigated. Recall that a shape can be described by the three shape descriptors shown in Fig. 1.1B. To determine whether all three are necessary to perceive the shape we can remove these cues one by one, and then quantify the individual contributions. We investigated this question for two cues: the position $\mathbf{x}(s)$ and orientation $\mathbf{x}'(s)$. Pont et al (1999) already addressed this for static touch. For dynamic touch, it is more difficult to design stimuli that only possess these isolated cues. In fact, it is impossible to produce a real shape in which these cues are isolated. The solution is to simulate the shape using a virtual reality device.

In Fig. 1.2 the workings of such a device are illustrated. The device consists of a contact area on which the finger can be placed. Using electrical motors, it is possible to independently control the height and the orientation of the contact area. This design allows the experimenter to study the contribution of each shape cue individually.

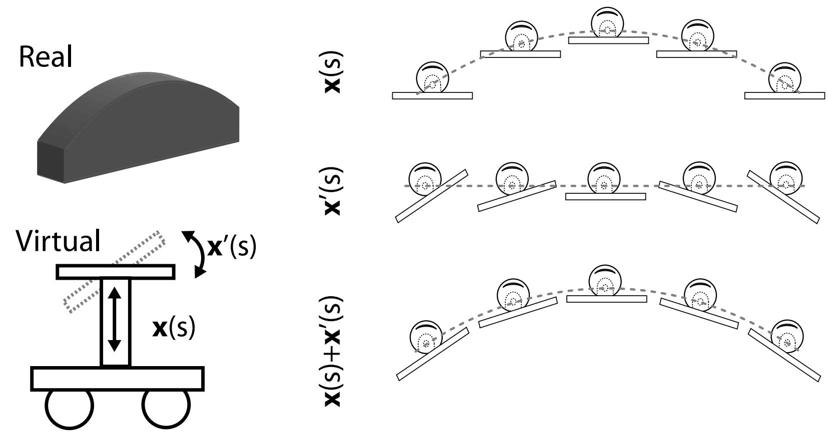

Figure 1.2: Elements of curvature

When does a shape become an object?

Both haptics and vision can be used to perceive shapes and recognise objects. The ability to visually identify common day objects does not need proof. Also with haptics, identification of common day objects seems an easy and effortless task, as shown by Klatzky et al (1985). The following question thus arises: how are these two processes related?

To understand the (dis)similarities between the two processes it is first necessary to understand how object recognition works in general. Although there is disagreement between scientists on this topic, a fairly safe assumption is that we match a percept to an internal representation. This internal representation (memory) is some generic description that matches a large number of different percepts that belong to the same category. This category could, for example, be ‘chair’, ‘dog’, ‘house’, or a one-member category such as ‘Johnny’. For humans this task is effortless; for computers, however, it is nearly impossible.

Although both senses seem successful for real, three-dimensional objects, they show different success rates for line drawings. To make line drawings accessible for touch, the lines can be embossed and made tangible. In chapters 3 and 4 we investigated why this difference between visual and haptic perception is so large. A line drawing is a projection of the three-dimensional world on a two-dimensional sheet of paper, similar to the projection of the three-dimensional world on the two-dimensional retina. Thus, vision is accustomed to these kinds of patterns, whereas haptics is not. But that does not fully explain the difference: even if we use line drawings that have hardly any projective properties, haptic identification is often impossible. In chapter 3 we began investigating whether we could enhance line drawing recognition by using larger stimuli than those normally used in the literature. We also studied how observers use their hands to perceive the image and let them 'think out loud' to see which cognitive steps were taken by the observer to solve the problem. In chapter 4 we came closer to the central problem that causes haptics to fail at line drawing identification. We studied what would happen if, after a line drawing could not be haptically identified, the observer was allowed to sketch what he had just felt.

A new haptic illusion

As mentioned earlier, illusions are quick psychophysical experiments that show how what one perceives differs from reality. Many illusions have been found for, in particular, the visual, haptic and auditory sense. There are many more illusions known for the visual sense than for the other senses. One reason is that visual stimuli are easy to make. Vision researchers have developed a good intuition for new illusions that sometimes occur by accident in the designing process of visual stimuli. While designing an experiment with curved stimuli, if I felt a straight and a curved shape simultaneously, the straight shape also felt curved. The sketches made by participants from chapter 4 also suggested that if observers feel straight and curved raised lines, they get confused.

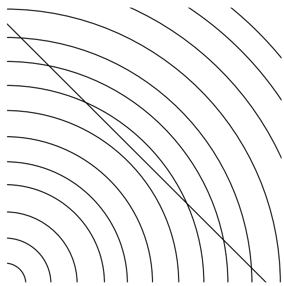

Figure 1.3: Visual curvature contrast

Gibson (1933) showed that when looking at a straight line that is surrounded by curved lines, the straight line appears to be curved towards the other side (Fig. 1.3). He also investigated what would happen if one first sees curved lines and then a straight line (this is called 'successive curvature contrast') and found the same illusion. Finally, he tested whether the successive curvature contrast effect would also be present in the haptic modality. However, he did not measure the simultaneous haptic curvature contrast. In chapter 6 we investigated whether a haptic curvature contrast effect exists and how general this effect is.

The connection between the various topics

I have studied topics that may seem remote to one another. This is partly due to the fact that during my PhD project I wanted to learn about different topics and techniques and therefore took the freedom to study both haptic line drawing perception, perception of two- and three-dimensional shapes and even a bit of robotics. It is also due to reasons that are not explicitly present in the chapters, which are written as journal papers and should thus serve as independent units that may interest various researchers with different backgrounds. Therefore, the chapters are written within the context of a certain topic and not within the context of my own PhD project. Since the papers have now been bundled in this thesis I will briefly discuss them within the context of my own PhD project.

Studying angle discrimination was part of a larger plan to systematically investigate discrimination thresholds for two-dimensional shape features and to use those to infer and test hypotheses about global shapes. After the angle discrimination study I wanted to make a shortcut and immediately advance to the perception of global, two-dimensional shapes, namely line drawings. While studying the identification-after-sketching-effect reported in chapter 4, we observed that the sketches that observers made showed rather dramatic distortions. These distortions could not only be attributed to inaccurate perception of shape features such as length, orientations or curvature, but showed configuration errors (misplacement of subparts) and topological violations. The sketches were very interesting but difficult to analyse systematically. Instead of focusing on the perception of various shape features of two-dimensional stimuli, I became interested in a single shape feature (curvature) expressed in different physical forms: two-dimensional, three-dimensional and through a haptic interface. One of the reasons for this is that there is a large difference between the haptic identification of two-dimensional objects (line drawing) and real three-dimensional objects. My interest in the haptic perception of differently expressed shapes first resulted in the study where we compared virtual and real shapes and found that as long as a certain shape feature (contact orientation) is present in the stimulus, the exact expression (virtual or real) does not influence haptic perception. The second comparison I made was between two-dimensional raised line shapes and three-dimensional solid shapes. Interestingly we found that the curvature of two-dimensional shapes is more difficult to discriminate than three-dimensional shapes, but that both types showed similar contrast effects. The approach of studying different expressions of shape proved to be a fruitful basis for the last two chapters, but as always in science, it only felt like a modest beginning.

Chapter 2

Angle discrimination in raised line stimuli

M.W.A. Wijntjes and A.M.L. Kappers (2007) Perception **36**, 865–879.

Abstract

In this study we investigated the angular resolution subserving the haptic perception of raised line drawings by measuring how accurate observers could discriminate between two angle sizes under various conditions. We found that for acute angles discrimination performance is highly dependent on exploration strategy: mean thresholds of 2.9° and 6.0° were found for two different exploration strategies. For one of the strategies we found that discriminability is not dependent on the bisector orientation of the angle. Furthermore, we found that thresholds almost double when the angular extent is increased from 20° to 135°. We also found that local apex information has a significant influence on discrimination for acute as well as obtuse angles. In the last experiment we investigated the influence of depiction mode but did not find any effect. Overall, the results tell us that the acuity with which angles in raised line drawings are perceived is determined by the exploration strategy, local apex information and global angular extent.

2.1 Introduction

The vast quantity of visual line drawings used in everyday life indicates that representing a real object with a line drawing conserves the visual recognisability to a large extent. With haptic perception, on the other hand, there is a large difference between recognising real objects and their 2D raised line depictions (Klatzky et al, 1993). Whereas for the haptic recognition of real objects latencies of a few seconds are typically found (Klatzky et al, 1985), latencies can easily last a minute or more in the case of raised line drawings (Heller, 1989; Lederman et al, 1990; Magee and Kennedy, 1980). One of the causes of these high latencies is the serial nature of spatial information acquisition by the fingertip. The study by Loomis et al (1991) showed that if the visual field of view is limited to the effective field of a fingertip, recognition latencies for vision and touch become of comparable length.

Numerous studies have reported on various aspects of the recognition process, such as the influence of visual status (Heller, 1989; Lederman et al, 1990), the benefit of categorical information (Heller et al, 1996) and the influence of depiction technique (Thompson et al, 2003). However, little is known about the perceptual performance subserving this recognition process. To understand the perceptual capabilities of the haptic system, one needs to study both perceptual biases and discrimination ability. The first category of experiments has already received some attention in the literature: Armstrong and Marks (1999) showed that linear extent explored radially tends to be overestimated with respect to tangentially explored lines, and Lakatos and Marks (1998) showed that haptically explored angles consisting either of raised lines or of wooden blocks tend to be overestimated. Furthermore, the subject of haptic illusions has been broadly studied (e.g. Gentaz and Hatwell, 2004; Heller, 2002; Millar and Al-Attar, 2000, 2002). Although these investigations of perceptual biases are important for our understanding of distortions that occur in line drawing perception, they do not give any insight into the accuracy with which the haptic system encodes or decodes a stimulus.

Research into haptic spatial acuity relevant for haptic line drawings is confined to the well-known two-point threshold (Weber, 1834/1996) and to studies of the limited spatial bandwidth of touch (e.g. Loomis, 1981, 1990). These studies tell us what cutaneous limitations are to be expected and should be taken into account when the perception of raised line stimuli is studied. Russier (1999) investigated the influence of visual status (i.e. blind or sighted) on a person's ability to discriminate circles from ellipses but this study did not yield quantitative discrimination thresholds.

The main purpose of the study presented here is to provide more insight into the discriminability of the geometric features of raised line drawings, in particular how well observers can discriminate between two angle sizes. We studied two main factors that could influence angle discrimination: the exploration mode and the geometric properties of the angle, such as bisector orientation and angular extent.

The first experiment investigates the influence of the bisector orientation on the discriminability of the sizes of acute angles around 20°. Movement was restricted to moving the fingertip between the arms of the angle which means following the imaginary bisector as can be seen in figure 2.1. In pilot experiments this exploration strategy yielded the lowest discrimination thresholds. During pilot experiments it was also observed that this type of exploration was spontaneously used by subjects who were free to move and received feedback upon their performance.

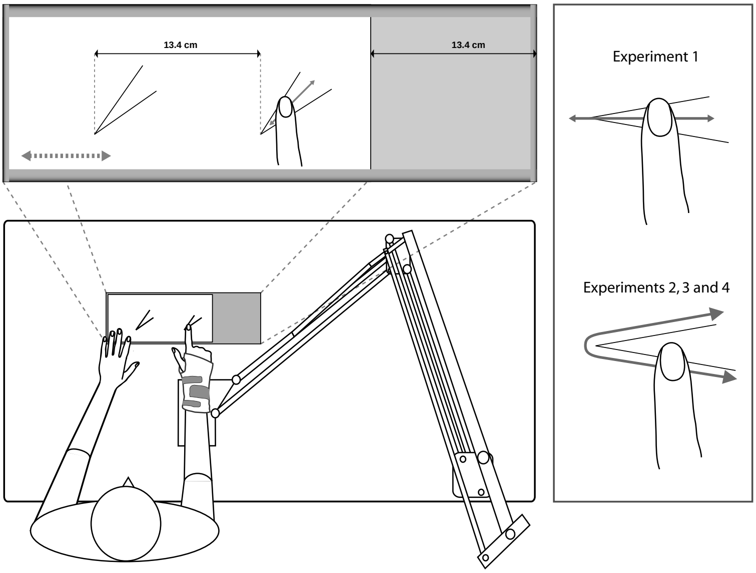

Figure 2.1: **On the left** a top view of the setup for experiment 1 is presented. Because the parallel drafting machine only allows translational motion, the index finger is always pointing in the vertical direction. At the start of each trial, the stimulus sheet was placed on the left hand side as depicted. In the magnification inset of the mould, the dashed arrow indicates the movement of the sheet controlled by the left hand when the stimuli had to be switched; the arrow under the finger indicates the movement of the fingertip following the imaginary bisect. **On the right** a sketch of the two exploration movements is presented.

Cutaneous perception of spatial features such as gratings or gaps has been shown to depend on the orientation with which it is presented to the finger (e.g. Essock et al, 1997; Wheat and Goodwin, 2000; Gibson and Craig, 2005), although some findings seem to contradict each other (compare Essock et al (1997) with Craig (1999)). There is not much known about the orientation dependence of more complex shapes such as angles. Investigating orientation dependence could resolve this question and thus contribute to the field of cutaneous shape perception.

In the second experiment we studied the influence that two general geometric properties of an angle have on discriminability: angular extent and apex presence. Instead of using the exploration strategy from experiment 1, we instructed participants to follow the arms of the angle. This strategy is applicable to both acute and obtuse angles. By using the same reference angle for the acute angle condition as we used in the first experiment, thus again measuring discrimination performance around 20°, we could quantitatively compare the two exploration strategies. Research done by Voisin et al (2002a) showed that the 75% correct response threshold for reference angles of 90° consisting of two metal strips is 4.7°. They also found that cutaneous and kinaesthetic input were of equal importance for angle discrimination. In our experiment we used two reference angles and looked at the effect of angular extent. Information about the angular extent can be retrieved from the global line orientations and from the local apex information. The line orientation information is likely to be encoded kinaesthetically (although guidance is always mediated by cutaneous cues) and the local information encoding of the apex is likely to be of a more cutaneous nature. To investigate the contribution of apex information in a discrimination task, we altered its availability by removing the apex in one condition. On the basis of the results of experiment 1 we hypothesised that information from the apex would be particularly helpful for the discrimination of acute angles. The hypothesised result would thus be that discrimination thresholds increase only for acute 20° angles but not for obtuse 135° angles when the apex is removed.

A large effect of angular extent on discriminability was found in the second experiment. To investigate what influence movement direction had on this effect, we conducted a third experiment in which we looked closer at this factor.

The fourth experiment was designed to investigate the role of depiction mode, i.e. raised lines or raised surfaces boundaries. The question we want to answer is whether discrimination ability is altered if a raised boundary instead of a raised line is used to constitute the angle. It could be that a raised line is better than a raised surface boundary at guiding the finger along the arms of an angle, or vice versa. For the raised surface boundaries we also looked at the effect of touching the edge of the surface on its convex or concave side. (Fasse et al, 2000) noted that with virtual shape perception, moving along the inside of an angle is easier than along the outside. This hypothesis is tested by looking at the discriminability of convex and concave angles. Furthermore, research into haptic picture perception showed that pictures consisting of raised surfaces are better recognised than pictures consisting of raised lines (Thompson et al, 2003). Finding lower discrimination thresholds for raised surface boundary angles could give us a better understanding of the recognition improvement found by Thompson et al (2003).

2.2 Experiment 1: The influence of orientation

In the first experiment, we investigated whether discrimination performance of angles near 20° depends on the orientation of the bisector. Using the method of constant stimuli we measured the 84% correct response threshold values. Participants were instructed to follow the imaginary bisector between the two arms of the angle (see figure 2.1). Since the influence of angle rotation was being investigated, hand movements were restricted to translational motion.

2.2.1 Method

Participants

Six participants were reimbursed for their participation. All participants were rated 'strongly right handed' according to the handedness test of Coren (1993). The participants were naive with respect to the purpose of the experiment and had not participated in a related experiment before.

Stimuli

Examples of the stimuli can be found in figure 2.2. All stimuli were produced with Zytech Swell Paper. The arms of the angles were printed on regular A4 paper. The width of the lines was 1 mm. To prevent participants from using the distance between the endpoints as a cue, the length of each individual line was randomised between 45 and 68 mm. It should be noted that the only purpose of the length manipulation was to avoid the use of improper cues and not to analyse the effect of arm length on angle perception. The printed images were photocopied on Zytech Swell Paper which was treated with a special infrared heating device to emboss the lines. The resulting height of the lines was approximately 0.5 mm.

In all conditions the reference angle was 20°; the test angles differed from the reference angle by $\pm(1°, 2°, 3°, 5°)$. The five bisector orientations were varied between 0° and 90° in steps of 22.5°. The bisector orientation of a stimulus pair was always the same, i.e. the reference and test angle within a trial had the same orientation.

Procedure

In the following, the terms vertical and horizontal are defined as both lying in the horizontal (table) plane, vertical meaning parallel to the observers' midsagittal plane and horizontal meaning parallel to the observers' frontoparallel plane. In order to keep the index finger in the vertical direction, the forearm was fixed to the end of a parallel drafting machine, as can be seen in figure 2.1. At the location where the drawing compass is normally fixed, a wrist holder was constructed by attaching a modified wrist protector (normally used for skating) to a steel plate. The right hand of the observer was placed in the wrist protector and the tilt of the forearm was adjusted until the fingertip could easily touch the stimulus. The hand movements were videotaped in order to check whether the finger was in an appropriate position.

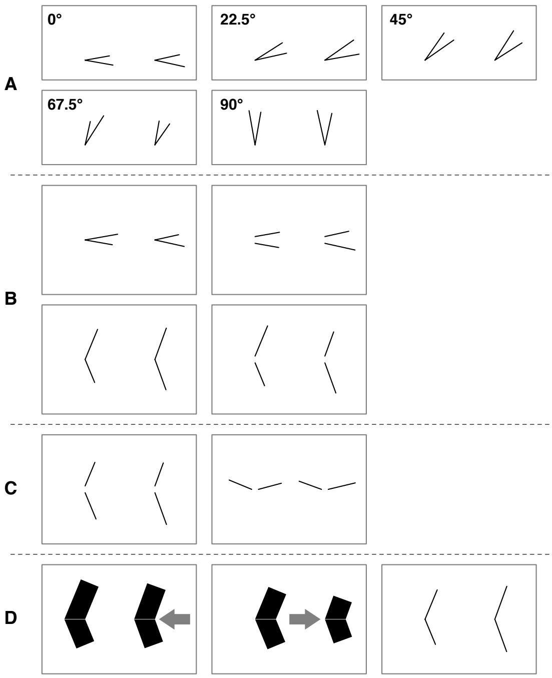

Figure 2.2: Examples of the stimulus sheets. For clarity, the scale of the gap sizes and line width is doubled. In these examples, angles on the left of the sheets are equal to the reference angle and angles on the right are 5° larger. **A** Stimulus sheets used for experiment 1. At the top left the 0° bisect orientation stimulus sheet is depicted, followed by 22.5°, 45°, 67.5°, and 90°. **B** The stimuli used for experiment 2. The upper graphs show the 20° angles with and without apex, the lower graphs show the 135° angles. Note that the apexes and gaps are located at a fixed position. **C** Stimulus set used for experiment 3. **D** Stimulus set used for experiment 4, from left to right the concave, convex, and line condition. The grey arrows indicate the side at which the stimulus was touched. It should be noted that in this condition too the apexes were always in the same position.

Participants were blindfolded and did not receive feedback throughout the experiment. The experimenter placed the stimulus sheet in a stainless steel mould (see figure 2.1) which was mounted on the table. Every stimulus sheet contained a reference angle and a test angle. The vertical size of the sheets and mould was 14.3 cm and the apices of the angles were located at a vertical distance of 3.8 cm. The distance between the apices of the two angles was 13.4 cm. The mould was 13.4 cm longer than the length of the stimulus sheet. After the stimulus sheet had been placed on the left side of the mould, the participants started to feel the right angle with their right-hand index finger. The participants were instructed to move their fingertip between the arms of the angle following the imaginary bisector (see figure 2.1) without losing contact with either of the lines. After moving maximally four times back and forth, participants lifted their right index finger, shifted the stimulus sheet with their left hand to the right and began to feel the left angle. This procedure could be repeated until each angle was felt twice. At the end of such a trial the participant indicated verbally which angle was perceived as larger.

The different bisector orientations were presented randomly and were balanced within a session which consisted of 80 trials. Each bisector orientation set consisted of 8 different test angles which were presented 10 times each, except for the 45° and 90° orientations which were presented 20 times. This resulted in a total number of 560 trials per subject spread out over 5 sessions of approximately one hour. For each test and reference stimulus pair, two stimulus sheets were fabricated, one with the reference angle on the left and one on the right. The reference stimulus was presented equally often on the left and on the right.

Observing the videotapes of the first three participants suggested that the hand orientations of the participants might have systematically deviated from vertical. To prevent further biases, the last three participants were equipped with an extra hand fixation kit: a material normally used in physiotherapy was used to fabricate fixation gloves around the wrist and lower phalanx of the right hand index finger. This fixation glove could be worn between the hand and the modified wrist protector.

The collected Two Alternative Forced Choice (2AFC) responses were transformed into fractions of the number of times that the test angle was judged to be larger than the reference angle. The psychometric function to which the data were fitted was chosen to be the (normalised) cumulative Gauss distribution which can be written as:

$$f(\alpha,\sigma,\mu) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\alpha} e^{-\frac{(\alpha'-\mu)^2}{2\sigma^2}}\, d\alpha' \tag{2.1}$$

where α denotes the test angle and μ the point of subjective equality (PSE). Since the stimulus set was completely counterbalanced, we only fitted the threshold value σ and not the PSE μ. The discrimination threshold at 84% correct is defined by the parameter σ since $f(\sigma,\sigma,0) = 1 - f(-\sigma,\sigma,0) \simeq 0.84$.

A one-way repeated measures design with bisector orientation as factor was used to analyse the effect of orientation on discriminability.

An estimate of the variability of the fitted threshold parameters was determined using the bootstrap method described by Wichmann and Hill (2001b). From the stimulus set interval, the number of trials per test stimulus, and the measured threshold value as initial conditions we calculated a set of $N = 10000$ simulated threshold values. From this distribution we calculated the 95% confidence interval.

To investigate whether participants showed a learning effect we analysed changes in performance between the first and second half of the experiment. We did this by collapsing the data of all conditions per participant and split this into a first and second half. We then calculated the threshold values for these two data sets and used paired *t*-tests to investigate whether the discrimination performance was different between the first and second half of the experiment.

2.2.2 Results

Individual thresholds as a function of bisect orientation are presented in figure 2.3. Visual inspection does not reveal a general effect of orientation on discrimination performance. This is confirmed by a repeated measures Analyses of Variance (ANOVA) which shows that the influence of the bisector orientation on discrimination thresholds is not significant ($F_{4,20} = 2.764$, $p = 0.056$). The average discrimination threshold for all directions and participants is 2.9°. An ANOVA with the participants as independent variable revealed that there was no significant difference between their performances ($F_{5,24} = 1.615$, $p = 0.194$). The 95% confidence interval of a 2.9° threshold value was calculated to be $[1.9°, 4.2°]$. All threshold values are within the 95% confidence interval of the mean threshold. This indicates that the within-participant fluctuations are probably due to chance. So there is no general trend for all participants, nor is there any significant idiosyncratic behaviour found. Also, no learning effect was found.

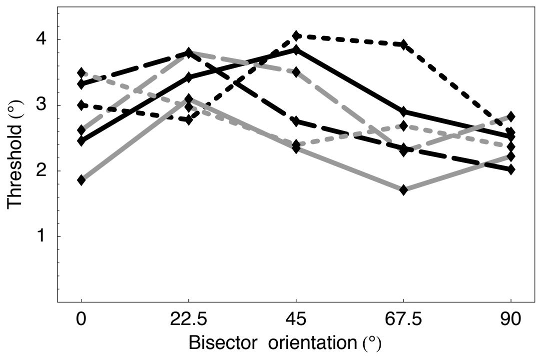

Figure 2.3: Threshold values as a function of bisector orientation for all 6 participants in experiment 1.

2.2.3 Discussion

The variation of thresholds between different directions and participants seems to fall within a well-defined range of 2° to 4°. This indicates that the strategy whereby the fingertip follows the bisector yields a robust discrimination performance. This is confirmed by the absence of significantly different performances across participants.

2.3 Experiment 2: The influence of angular extent

A second experiment was designed to measure the discrimination performance for both acute and obtuse angles. To enable us to make comparisons with experiment 1 we chose the angle of reference for the acute angles to be 20°; the angle of reference for the obtuse angles was 135°. Angular extent and presence of the apex were both independent variables. Differential use of the local apex information could account for possible differences between the discrimination of acute and obtuse angles. Participants were instructed to follow the arms of the angles for the exploration of the angles.

The two exploration strategies differ with regard to the simultaneous contact with the two lines. Although to a lesser extent than with the first strategy, there is still simultaneous contact of the fingertip with the two lines using the second strategy. This is caused by the fingertip moving along one arm and already touching the other line while approaching the apex and thus feeling how fast the lines are converging and diverging. The amount of simultaneous contact obviously decreases with increasing angular extent. If this phase of the exploratory trajectory is to be beneficial for discrimination, then the removal of the apex will particularly influence the discriminability of acute angles. Thus we hypothesise that removing the apex will mainly have an effect on the discriminability of the 20° angle.

2.3.1 Method

Participants

Eight strongly right-handed (Coren, 1993) participants were reimbursed for their participation. The participants were naive with respect to the purpose of the experiment and had not participated in a previous, related experiment.

Stimuli

The stimuli, which can be seen in figure 2.2, were produced in the same way as in experiment 1. The same length randomisation was applied as in the first experiment. The size of the reference angle was either 20° or 135° and the bisector orientation was fixed at 0° with respect to the horizontal. The gap caused by cutting off the apex was chosen not to exceed the contact area of the exploring finger because this would generate extra

Table 2.1: Overview of the angular differences between test and reference angles for experiment 2. The asterisk (*) denotes the set used for the last three participants.

Apex condition	Reference angle	
	20°	135°
Without gap	$\pm(2,4,6,8,10)$	$\pm(2,4,6,8,10,14)$
	$\pm(5,10,15,20,25,30)^{\star}$	
With gap	$\pm(3,6,9,12,15)$	$\pm(3,6,9,12,15,20)$
	$\pm(6,12,18,24,30,36)^{\star}$	

path-following difficulties during exploration. Contact area measurements during pilot experiments indicated that a gap size of 6.5 mm should be well within the range of average fingertip contact area. The gap-size was independent of the angle size. The vertical size of the sheets and mould were 21 cm and the apices of the angles were located at a vertical distance of 10.5 cm. As in the first experiment, the two angles were printed 13.4 cm apart. Pilot experiments indicated that different thresholds across different conditions could be expected. The sets of test stimuli were adjusted accordingly; the range of test angles was larger for larger predicted discrimination thresholds. An overview of different test stimulus sets per condition can be found in table 2.1.

Procedure

In all the following experiments the observers were free to move, i.e. no movement-restricting apparatus was used. The exploration of the angle was prescribed in the following way: the arms of the angle were to be followed with the index finger of the preferred hand (see figure 2.1). Subjects were allowed to move the finger maximally twice back and forth along the complete angle path. The starting point could be chosen freely but during instructions the observers learned to use the apex or the gap as a starting point. Each angle could be felt not more than twice. Thus, if we assign a to the apex location and b and c to the locations of the endpoints, the maximum movement permitted is described by *abacabaca*. The switching procedure between test and reference stimulus which involved shifting the stimulus sheet was the same as in the first experiment. Before the start of the experiment, a training period including not more than six randomly chosen stimuli allowed the participants to become familiar with the procedure and the stimuli. No feedback was given during the training or the experiment.

Participants were presented with all of the acute angle stimuli (reference 20°) with randomly assigned gap conditions, followed by all the obtuse stimuli (reference 135°). Possible order effects influencing the data will be commented on in the discussion. In the 20° reference block, the sampling set consisted of $d = 10$ different test stimuli which were presented $N = 12$ times and in the 135° reference block, the sampling set consisted of $d = 12$ different test stimuli which were presented $N = 10$ times. As in the first experiment, test and reference angles were presented an equal number of times to be felt first. For each participant, 480 trials ($N \times d \times conditions$) were distributed over 6 sessions of approximately 1 hour.

The experiment was a within-subjects design with repeated measures taken on the apex presence (present, absent) and the angular extent (20°,135°).

2.3.2 Results

The 84% correct response thresholds defined by the best fit parameter σ from Equation 2.1 are plotted in figure 2.4. A repeated measures two-way ANOVA reveals that both the presence of the apex ($F_{1,7} = 9.893$, $p = 0.016$) and the angular extent ($F_{1,7} = 19.307$, $p = 0.003$) have a significant influence on discrimination performance. There is no significant interaction between the two conditions ($F_{1,7} = 2.383$, $p = 0.167$). As can be seen in the lower graph of figure 2.4, the thresholds almost double from 20° to 135°, independent of the apex condition. Visual inspection of figure 2.4 shows that the effect of apex information has a more idiosyncratic influence on the discrimination of 135° angles than on 20° angles. Table 3.1 lists all mean thresholds, standard deviations and the quotients of variation (standard deviation divided by the mean) of all experiments. There, it can be seen that the relative variation of the 135° in the with gap condition is much larger than for other conditions. Removing the apex increased the discrimination thresholds for both the acute and the obtuse angles. The learning effect analysis was done similar to experiment 1 and was performed on the 20° and 135° data sets separately. In neither of these sets we found significant learning effects.

In order to compare the different exploratory procedures used in the first and second experiments, two groups were compared: the first group consisted of thresholds of the six participants from experiment 1 for the 0° bisector orientation condition; the second group consisted of data drawn from the 20° reference angle with apex thresholds from the second experiment. The mean thresholds were 2.8° for the 'bisector-following' procedure and 6.0° for the 'arm-following' procedure. An unrelated t-test for unequal group sizes showed a significant difference ($t = 4.985$, $p < 0.001$) between the discrimination of 20° angles depending on whether the 'arm-following' procedure or the 'bisector-following' procedure was used.

2.3.3 Discussion

Since no learning effects were found and the threshold for the 135° without gap condition was reproduced fairly well in experiments 3 and 4 (see table 3.1), there is no reason to assume that order effects would be responsible for the difference between the 20° and 135° thresholds.

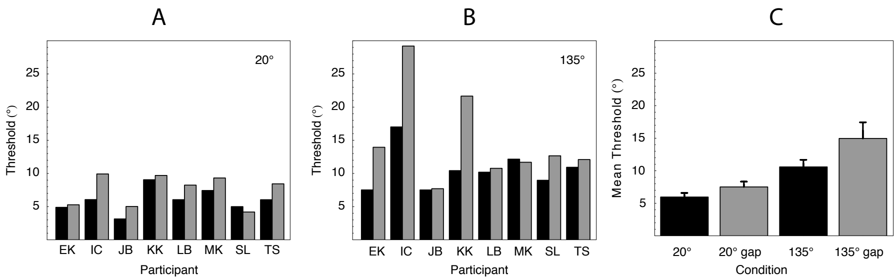

Figure 2.4: Comparison of thresholds per participant. Black bars denote thresholds for stimuli without gap, grey bars denote thresholds for stimuli with gap. A: Angle of reference is 20°. B: Angle of reference is 135°. C: Mean results across conditions. Error bars denote standard errors.

Both the angular extent and the presence of local apex information influence the discriminability significantly. We controlled the local apex information as an independent variable in this experiment because we predicted that the apex would be of particular importance for discriminating acute angles but not for obtuse angles. If our assumption was correct, then a different use of the apex would explain why obtuse angles are more difficult to discriminate than acute angles. Since this hypothesis has been disproved we need to find other explanations for the large effect of angular extent on discriminability. For acute and obtuse angles the average path length is equal and the only geometric difference is that the distance between the midpoints of lines is larger for obtuse angles than for acute angles. It could thus be that the encoding of an angle is more efficient if the lines are close to each other. Before continuing this line of reasoning we need to be certain that there are no other differences between the acute and obtuse angle condition. One experimental difference is the average movement direction used for the exploration. To analyse this difference we conducted a third experiment.

2.4 Experiment 3: The influence of movement direction

In experiment 2 there was an uncontrolled factor between the small and large angles which had to be ruled out as a cause of discrimination differences: average movement direction. Since the exploration procedure in experiment 2 is different from that of experiment 1 we do not know whether the same movement direction independence holds for the 'arm-following' mode. The movement for the 20° stimuli can be characterised as being more horizontal than that for 135° stimuli. Although unlikely, it is possible that the use of horizontal movement yields higher acuity than vertical movement. To address this issue experiment 3 was performed.

The horizontal movement employed for the 20° in the previous experiment can be simulated by the rotation of a 135° stimulus. By looking at the effect of a 90° counterclockwise rotated 135° stimulus with respect to a non-rotated one, we isolate the direction of exploration movement as an independent variable.

2.4.1 Method

Four observers participated in the third experiment, all of whom had participated in the second experiment. We used the 135° angle with gap stimuli and compared this with the same stimuli rotated 90° counterclockwise. The two conditions can be seen in figure 2.2 C. The stimuli were presented in 24-trial blocks with the same bisector orientation condition. The test stimulus set consisted of 12 angles distributed symmetrically and equidistantly around the reference angle. The stimulus set was designed individually for each participant on the assumption that the thresholds measured in experiment 2 would be reproduced approximately. Each test angle was presented 10 times. The bisector orientation of the first block was counterbalanced among the participants. The total number of trials per subject was 240; these were distributed over three sessions of approximately one hour. The same procedure and data analysis were used as in the second experiment.

2.4.2 Results and discussion

The results for the four participants are presented in figure 2.5. For each subject the first two bars show the results of experiment 2, and the second two bars show the results of experiment 3. The first bar denotes the threshold found for the 20° condition and the second bar the threshold for the 135° condition, both from experiment 2. The third bar denotes the threshold for the rotated 135° condition and the fourth bar the non-rotated 135° condition. The first and third bar thus denote thresholds found for horizontal movement and the second and fourth bar for vertical movement. The second and fourth bar originate from the same condition, which shows that three out of the four subjects performed better the second time for the non-rotated 135° condition. Half of the subjects performed better for the rotated 135° condition in experiment 3 than for the non-rotated 135° condition in experiment 2.

It can be clearly seen that rotating the angle does not lead to discrimination improvement. There would be discrimination improvement when the third bar was lower than the fourth, i.e. if horizontal movement would decrease discrimination thresholds. The contrary seems to be the case: for all participants the threshold for the 0° bisector orientation is lowest. Since only four participants participated in this experiment it would be inappropriate to use a statistical test for further interpretation.

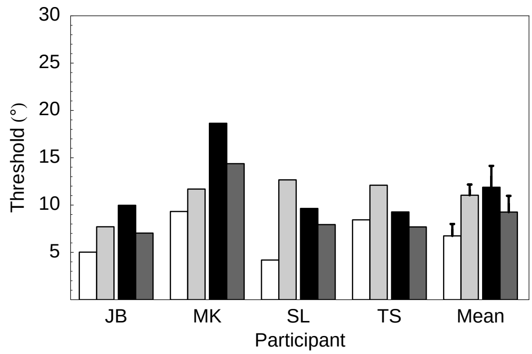

Figure 2.5: Comparison of thresholds per subject of experiment 3. The first two bars are results from experiment 2: from left to right the bars indicate the with-gap conditions for 20° and 135° respectively. For the second two bars, the first (black) denotes the result for the rotated 135° stimulus and the second (dark grey) denotes the non-rotated 135° stimulus. For the first and third bars movement direction is more horizontal and for the second and fourth bars the movement is more vertical.

2.5 Experiment 4: The influence of depiction mode

In the fourth experiment we investigated the influence of angle depiction mode. The first objective was to measure whether discrimination performance changes when the angle is depicted by a raised surface boundary instead of a raised line. The second objective was to measure whether there is a difference between feeling concave or convex surface boundary angles. For an explanation of how concavity and convexity are defined, first inspection of figure 2.2 D is required. As can be seen, convex and concave are defined with respect to the not embossed, white area.

The reference angle was chosen to be 135° in order to allow comparison with previous experiments.

2.5.1 Method

Participants

Eight participants who had no experience with the experimental design and were naive with respect to the purpose of the experiment were reimbursed for their time. Seven participants were strongly right handed and one (participant SH) was moderately left handed (Coren, 1993).

Stimuli

The stimulus set, which can be seen in figure 2.2 D, was produced in roughly the same way as the sets used for previous experiments. The raised surfaces consisted of 4 cm wide lines. On all stimulus sheets the location of apices was independent of angular extent. The ends of the wide lines constituting the surfaces were cut off perpendicularly. The average path length over which the angles were explored was independent of the three conditions and was equal to that of the stimuli used earlier, i.e. the arm-lengths were randomised in the interval between 45 and 68 mm.

Procedure

The setup was the same as that used in experiments 2 and 3 and participants were given the same instructions. The three different conditions were presented in blocks of 24 trials. The order of presentations was semi-randomly assigned to the participants in order to balance the starting condition. The sampling intervals were the same for all conditions and consisted of 12 different test angles that were distributed $\pm(4°, 8°, 12°, 16°, 20°, 24°)$ degrees around the 135° reference angle. Each reference angle was presented 10 times, balanced for test and reference order. This resulted in a total of 360 trials distributed over four to five sessions of one hour. Each threshold value per depiction mode and participant was thus calculated from a psychometric curve fitted to 120 trials. The experiment was a one factor (depiction mode) design with repeated measures on the participants.

The stimuli were presented in the same orientation for all participants. The only difference for the left-handed participant (SH) was that in his case the stimulus sheet was presented on the right, but the orientation of the angles was the same for him as for the other participants.

2.5.2 Results and discussion

In figure 2.6 the threshold values for all participants are presented. As can be seen, participants do not show consistent discrimination performance for the three conditions. A one-way repeated measures ANOVA confirms the absence of main effects ($F_{2,14} = 1.257$, $p = 0.315$). The average threshold value for the raised line condition of 10.2° is comparable to the threshold of 10.6° for the without gap condition from experiment 2. Furthermore, no learning effect was found. As was found previously there are large discrimination differences within and between participants. Table 3.1 gives an overview of all mean thresholds for all experiments. The results show that the depiction mode does not have an influence on angular acuity. Introspective reports collected after the experiment also indicated that there was not a strong preference for any one of the conditions.

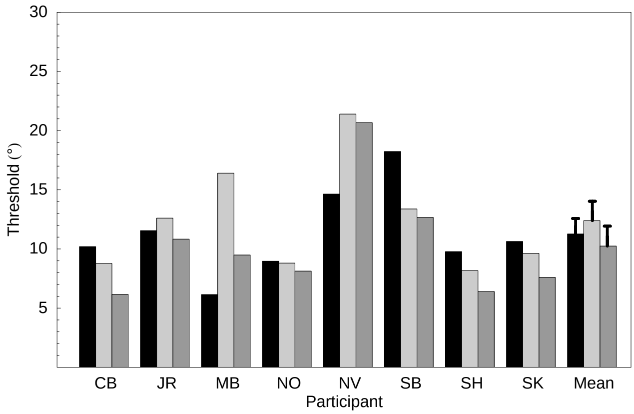

Figure 2.6: Thresholds per subject for the conditions 'concave', 'convex' and 'line' from left to right. The ninth bar trio represents the results per condition averaged over the participants.

2.6 General discussion

The research presented here investigated what factors influence angular acuity in raised line drawings. First, we found that movement direction did not influence discriminability in experiment 1. Furthermore we found that exploration strategy, angular extent and the apex have a significant influence on discrimination ability. We will now discuss how these results can be interpreted.

In the first experiment, no directional influence on discrimination performance was found for bisector orientations between 0° and 90°. The apparent independence from movement direction, the non-significant difference between participants and the low relative variation (see table 3.1) show that the discrimination threshold values are fairly robust. It is thus likely that participants used the same cues or mental strategy to perform the discrimination task. We already mentioned in the introduction that the primary motivation of varying orientation was to investigate whether cutaneous angular information also showed anisotropic behaviour as have other studies shown for the cutaneous sense (e.g. Essock et al, 1997; Wheat and Goodwin, 2000; Gibson and Craig, 2005). Although we did not find orientation dependence we should justify whether the spatial information is indeed cutaneous before we can start comparing the results between the first and second experiment. It is possible to acquire kinaesthetic information about the angular extent from the path length followed by the finger from the apex until the fingerpad loses contact with the lines, i.e. where the distance between the lines equals the effective diameter of the contact area. This distance scales with the cotangent

Table 2.2: All mean thresholds per experiment per condition. For the first experiment the average was taken over all conditions and participants. The conditions *135 apex*, *135 bisect 0* and *135 line* are identical. The quotient of variation equals the quotient of standard deviation and the mean.

Experiment	Condition	Mean (°)	Standard deviation (°)	Quotient of variation (°)
1	20 bisect	2.87	0.64	0.22
2	20 apex	5.96	1.76	0.30
	20 gap	7.52	2.31	0.31
	135 apex	10.59	3.06	0.29
	135 gap	14.97	7.00	0.47
3	135 bisect 0	9.26	3.43	0.37
	135 bisect 90	11.88	4.52	0.38
4	135 concave	11.27	3.69	0.33
	135 convex	12.39	4.63	0.37
	135 line	10.24	4.76	0.46

of the angle and could thus be used to discriminate angles. From our data we cannot be completely sure whether participants used this kinaesthetic information source. However, looking at the video recordings which were made to check whether the orientation of the finger stayed constant during the experiment revealed that participants did not use this strategy systematically. For five participants it was observed that the finger largely overshoots the above defined endpoint for angles in the 90° orientation. For the other orientations it could not always be seen clearly due to viewpoint limitations. These observations, though not quantified objectively, led us to assume that the spatial information used for the first strategy is cutaneous.

Comparison between experiments 1 and 2 showed that exploration strategy has a marked influence on discrimination performance. Moving the fingertip between the arms of an angle yields discrimination thresholds which are twice as low as thresholds for angles explored by following the lines. That exploration strategy can influence haptic perceptual performance has been found previously by Davidson (1972). He showed that curvature perception was more veridical for blind than sighted observers. However, he also observed that multiple exploration strategies were spontaneously used and that blind observers used a certain strategy ('grip') markedly more often than the sighted observers. In a subsequent experiment the superiority of this strategy was confirmed. Also, in tactile map research it has been shown that some aspects of spontaneous exploration such as line following and shape distinction, predict the quality of the map reader (Berla et al, 1976). Furthermore it has been found that, in general, humans use a variety of spontaneous exploratory procedures in order to perceive various 3D object properties (Lederman and Klatzky, 1987). These findings illustrate a difficulty which haptic scientists often encounter: how to control for the information input when subjects explore stimuli in different ways? Evidently it is important, when conducting haptic psychophysics, to restrict or at least register the manual exploration in order to properly relate the stimulus with the perceptual judgement. These finding can furthermore have implications for studies of the perception of raised line drawings: if there are different exploration modes that are best for the assessment of different geometric features, it could be useful to instruct observers to use those particular modes. In tactile map reading it has already been shown that training of exploration improves map reading qualities (Berla and Butterfield, 1977).

The second experiment showed that both angular extent and the presence of the apex influence discriminability significantly. Our results do not explain why large angles are more difficult to discriminate than small angles, although experiment 2 and experiment 3 show that both the information from the apex and the average movement direction cannot account for this effect. Since angular extent is a periodic unit we did not expect that Webers' law (Weber, 1834/1996), which states that the fraction of threshold and intensity is constant for different intensities, would apply to our data. This was in line with our data: Weber fractions for 20° and 135° angles were 0.30 and 0.08, respectively.

Introspective reports of the participants revealed another difference between the acute and obtuse angles: the 135° angles were sometimes perceived as being curved, but not having a well-defined angle. More research on this topic is certainly needed since not only does it give insight into fundamental processes of haptic perception, it could also be of importance for research into the distorted perception of raised line drawings.

The influence of the apex was not what we had hypothesised. Not only does the presence of the apex influence discrimination for acute angles but it also influences discrimination for obtuse angles. In both the acute and the obtuse angle condition, 7 out of 8 participants showed higher discrimination thresholds for angles without an apex.

As mentioned in the introduction, there has already been research into haptic angle discrimination. Voisin et al (2002a) investigated haptic discrimination ability of a 90° angle made of two metal strips. They found a mean threshold for 75% correct responses of 4.7° corresponding to an 84% threshold of 7.0°. Even though the study of Voisin et al (2002a) made use of different stimulus material and restricted movement by allowing only shoulder joint movement, it is remarkable that the 7.0° thresholds for a 90° angle are well within the range of thresholds of 6.0° and 10.6° for our raised line angles of 20° and 135° respectively. In an accompanying study, Voisin et al (2002b) showed that kinaesthetical and cutaneous information contributed equally to discrimination ability. This could also hold for our results if we interpret the apex primarily as a cutaneous information source and the movement along the angle arms as kinaesthetical information. Coming back to the comparison of the two exploration strategies this implies that a strategy purely dependent on cutaneous input (experiment 1) yields thresholds twice as low as a strategy which uses both cutaneous and kinaesthetic information (experiment 2). This counterintuitive notion points out that combining sensory input does not always yield higher accuracy if multiple exploration strategies are considered.

The fact that we only investigated discrimination performance for two reference angles leaves some interesting questions unanswered. What kind of behaviour will be revealed when a wide range of reference stimuli is mapped onto discrimination performance? The angles' inherent periodicity predicts at least non-linear behaviour. Furthermore, in some cases discrimination performance could be influenced by cues such as the alignment of one of the angle arms with body midline. Future research should address these issues.

The last experiment showed that whether an angle is formed from a raised surface boundary or from raised lines does not influence the discriminability. Fasse et al (2000) noticed that moving inside a virtual rectangle was easier than moving it along the outside edge. They did not actually test this hypothesis experimentally; it is based on the hypothesis that moving along the inside of a corner yields a more stable mechanical situation which benefits haptic spatial perception. If these stability matters would also held for raised surface boundaries instead of impenetrable 'walls', then concave angles would yield lower discrimination thresholds than convex angles. Thus we cannot conclude from these experiments that the recognition improvement found by Thompson et al (2003) for raised surface drawings is caused by a higher angular acuity evoked by the nature of the depiction mode.

Our results show that it could be interesting to study in greater depth the exploratory behaviour of raised line stimuli. Knowledge about what exploration strategy fits which geometric feature, and training persons to use this knowledge would be helpful to the visually impaired who use tactile pictures in everyday life. The effect of increasing thresholds with increasing angular extent is also worth investigating further. If we can understand what geometric properties influence the mental load of spatial information we will be in a much better position to understand why the haptic recognition of raised line drawings is so difficult.

CHAPTER 3

SIZE INFLUENCES HAPTIC LINE DRAWING IDENTIFICATION

M. W. A. Wijntjes, T. van Lienen, I. M. Verstijnen and A. M. L. Kappers (2008), Perception (**37**), 602–614.

Abstract

In this article we demonstrate the influence of picture size on haptic recognition and exploratory behaviour. The stimuli we used were raised line drawings of everyday objects. Participants were instructed to think aloud during haptic exploration of the pictures. We measured the delay between initial correct speculation and final correct response. The results indicate that picture size influenced accuracy but not response latency: large drawings were recognised more often but not faster. By analysing video recordings of the experiment we found that two-handed exploration increases when picture size increases and that on average 83% of the exploration time was spent using two hands. Furthermore the thinking-aloud data showed that the average time difference between the initial correct speculation and final correct response amounted to 23% of the total exploration time. We will discuss our results with respect to the design of tactile aids and the ecological validity of single-finger exploration.

3.1 Introduction

Embossing the lines of a drawing makes the spatial information accessible for the haptic modality. Besides serving as a learning aid for the blind, this also inspired psychologists to investigate whether line drawing recognition can be extended to another modality besides vision. Although all studies on this subject show that it is possible to recognise a raised line drawing without the use of vision, the task has proved to be notoriously difficult Heller (e.g. 1989); Loomis et al (e.g. 1991). Haptic exploration of raised line drawings often leads to an incorrect semantic interpretation and when recognition is finally correct, the process may well have taken several minutes. A possible way to look at raised line drawing recognition is to split up the process into two components which will probably be temporally overlapping: The first component is the process of exploration, which is concerned with aspects such as stimulus properties and exploratory behaviour. The second component is concerned with how the acquired spatial information is processed and interpreted. We will briefly review the literature on raised line drawing recognition with respect to the exploration and interpretation components.

Two important factors have been identified as having a critical influence on spatial information acquisition. Firstly, Magee and Kennedy (1980) have shown that active exploration of raised line drawings yields lower recognition accuracy than passively guided exploration . The recognition difference between actively and passively exploring raised line drawings can be understood by considering active exploration as a dual task where the observer is in charge of both the exploration and the recognition process, whereas passively guided observers can focus fully on recognition. Other studies report similar findings on passive superiority for raised line drawing recognition (D'Angiulli et al, 1998; Symmons et al, 2004). However, one should be cautious to generalise passive superiority beyond haptic perception of raised line drawings (Symmons et al, 2004). Secondly, irrespective of whether the finger is guided, the spatial information is acquired serially, which contrasts with the parallel nature of visual perception. Loomis et al (1991) showed that when the visual field of view is matched to the effective field of the fingertip the quality of the visual recognisability of line drawings decreases and becomes comparable to that of haptic recognition. It can be tentatively argued that the difference between visual and haptic perception of line drawings is to be found not in specific object recognition processes of different modalities but rather in the difference between parallel and serial information acquisition, independent of modality. Further findings concerning the exploratory component of the recognition process indicate that using five fingers significantly increased recognition accuracy compared to single-finger exploration (Klatzky et al, 1993). In contrast, Symmons and Richardson (2000) found that observers spontaneously explored raised line drawings with a single finger. In attempting to increase the recognisability of raised line drawings Thompson et al (2003) found that 'filled' drawings (the whole region between the lines is embossed instead of only the lines themselves) are recognised more accurately than raised line stimuli.

An interesting question concerning the interpretation of a raised line drawing is whether congenitally blind observers, having no experience with interpreting the projection of the 3D environment on a 2D surface, can recognise raised line drawings. Heller (1989) found that late blind observers were superior to both sighted and congenitally blind and that sighted and congenitally blind were equally poor at tactile picture recognition, whereas Lederman et al (1990) found that sighted observers were superior to the congenitally blind. The difference between sighted and congenitally blind was later replicated by Heller et al (1996) who found no differences between late blind and sighted observers but did find that both of these groups outperformed the group of congenitally blind. These studies together suggest that visual experience is an important factor and that late blind observers could benefit from their exploratory experience; this is in line with the increase in recognisability that occurs when observers are guided (Magee and Kennedy, 1980). Further studies investigating the interpretation component of haptic line drawings showed that recognition increases when categorical information about the drawing is provided (Heller et al, 1996). As suggested by Klatzky and Lederman (1987), the recognition process seems to be an inferential, hypothesis-testing procedure. This suggestion was later strengthened by Kennedy and Bai (2002) who observed that during exploration, guesses are made about the identity of the referent. These guesses are labelled with a 'fit judgement' and are either rejected or accepted according to how well they correspond ('fit') to the perceived stimulus. Kennedy and Bai (2002) showed that the fit judgement that observers gave to their last guess, i.e. final answer, predicted the accuracy.

The study we present here will be concerned with both the exploration and the interpretation components of raised line drawing recognition. Apart from the study by Thompson et al (2003), surprisingly little attention has been given to the role of stimulus properties. The influence of properties such as picture size, material, textures, line thickness or dashing patterns has not been systematically studied up to now. It is peculiar that previous research used relatively small stimulus sizes compared to the size of a typical medium on which the stimuli are printed, namely on a sheet of A4 (21×29.7 cm). Drawings used in all the above cited papers range between 4 and 15.2 cm, with one notable exception. Kennedy and Bai (2002) used stimuli ranging between 15.5 and 22.5 cm; the size was explicitly motivated by the authors' wish 'to increase the likelihood that subjects would detect small features of the displays and their proportions' (p. 1015). Indeed, the overall accuracy rate in their studies (61%) was higher than in earlier studies with comparable picture sets. They suggested that the difference in accuracy was caused by the use of large stimuli. The first objective in our study is to test the hypothesis that larger stimuli are more accurately recognised than small stimuli. We will also present a concise review of the literature in which we relate stimulus material and picture size to recognisability.

The second objective of this study is to clarify current findings concerning spontaneous exploratory behaviour. As mentioned, Symmons and Richardson (2000) found that blindfolded sighted observers spontaneously use a single finger for the exploration of a raised line drawing during the larger part of the exploration time. This finding may lack some generality. Firstly, the pictures were rather small (8.5 cm) and if according to our first hypothesis larger pictures are more easily recognised, the exploratory behaviour would have to be reinvestigated for large stimuli. Secondly, observers had to stand upright, a factor that might induce them to use one hand for balancing purposes and hence lead to misleading results. Besides these possibly experimental imperfections, it has been noted (e.g. Heller et al, 2002a) that blind observers do not use merely one finger and they object when the experimenter suggests they should. This might indicate that blindfolded observers use a different exploratory strategy than blind observers. It could also indicate that the findings of Symmons and Richardson (2000) are not as general as the authors believed them to be. Lastly, research in tactile map perception has suggested that spontaneous behaviour is often two handed (Berla et al, 1976, p. 270, 272), although this is task dependent. Together with our own observations during pilot experiments, the above-mentioned indications motivated us to reinvestigate the spontaneous exploratory behaviour with regard to raised line drawings.

The third objective of our study focuses on the interpretation component of raised line drawing recognition. As described by Klatzky and Lederman (1987) and Kennedy and Bai (2002), observers are continuously guessing about the correct referent during the exploration process. We also observed this during pilot experiments and became intrigued by the time it took for the observers to accept their last hypothesis. We presented participants with a think-aloud protocol with which we could quantify this delay between initial guess and final correct response. Besides being interested in how large a portion of the total exploration time is devoted to confirm the initial correct guess, we investigated the relationship between the delay and the difficulty of the stimulus. D'Angiulli et al (1998) found that recognition scores per picture correlated significantly between different groups of participants. This indicates that pictures contain some inherent difficulty which is invariant with respect to different observers. We first verified whether our data also revealed such an inherent difficulty by correlating recognition scores for small and large stimuli. A reconfirmation of this inherent difficulty evoked by different pictures was used to investigate whether response delay would depend on the difficulty of the task.

3.2 Method

3.2.1 Participants

A total of 28 observers (17 males and 11 females) participated. Participation was voluntary. Only 21 were videoed because the video facility was not available for the last seven. Participants were naive with respect to stimuli and the purpose of the study. Since some of the participants were colleagues working at the same lab as the authors, there was a possibility that they might have accidentally encountered a stimulus previously. They were asked to notify the experimenter if this occurred, whereupon that trial was excluded from the analysis.

3.2.2 Stimuli and materials

The set of 12 raised line drawings used in this experiment can be seen in figure 3.1. The hammer, umbrella and scissors were adopted from the picture set used in (Kennedy and Bai, 2002). Large and small versions of the drawings were produced on A3 and A4 Zytech swell paper (29.7×42 cm and 21×29.7 cm, respectively). The size of a stimulus is defined according to its horizontal or vertical size, whichever is the larger. The size of the large and small stimuli were 35 cm and 10 cm, respectively. So as not to have representations of objects of unbalanced prototypical sizes of the depicted objects which might induce a size effect, we selected drawings such that half of the stimulus set consisted of depicted objects which have typical sizes that are more near 10 cm than 35 cm (envelope, puzzle, open-end wrench, bath-tub duck, light bulb and scissors). Scaling the length of the umbrella and puzzle piece drawings to 35 cm resulted in a width which exceeded the width of an A3 sheet. Therefore, the size of the umbrella was was reduced to 26 cm and the size of the puzzle piece was reduced to 30 cm. The width of the lines was 1 mm and the approximate height of both small and large stimuli was 0.5 mm.

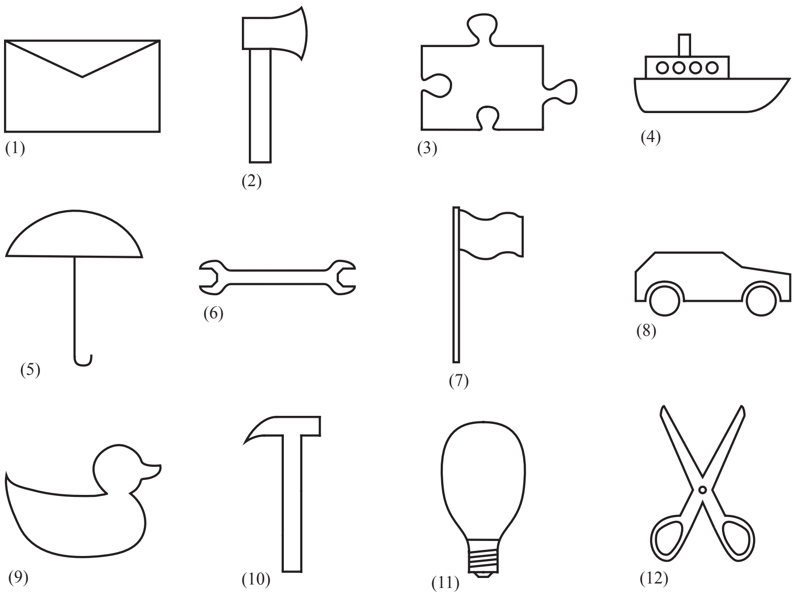

Figure 3.1: Stimuli used in the experiment, from left to right and top to bottom: (1) envelope; (2) axe; (3) puzzle piece; (4) boat; (5) umbrella; (6) open-end wrench; (7) flag; (8) car; (9) bath-tub duck; (10) hammer; (11) light bulb; and (12) scissors.

For each of the two sizes a stainless steel mould was made in which the stimuli sheets could be fixed. The appropriate mould was placed on the table, in front of the observer, and was fixed with respect to lateral movement. A microphone was positioned on the table and above the mould a video camera was suspended. The setup can be seen in Figure 3.2. The video recordings were performed on a VCR video recorder to which both the microphone and camera were connected.

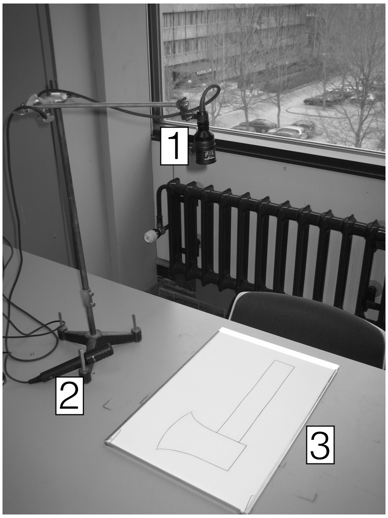

Figure 3.2: Picture of the setup. (1) Camera; (2) Microphone; (3) Stainless steel mould with an A3 stimulus sheet.

3.2.3 Procedure

Participants received written instructions. They were informed that their primary task was to recognise the raised line drawing both as accurately and fast as possible while blindfolded. They were also asked to express their thoughts and guesses verbally during the recognition process. The participants were supposed to explicitly announce their final answer and both the time of their first correct guess and the time of their final answer were noted by the experimenter. Participants were given unlimited exploration time. A trial ended either with a correct or incorrect final answer or could be broken off by the participant if he or she wished. Participants were not told whether their response was right or wrong. Furthermore, the written instructions explained that the observers were free in the way they explored the stimuli. After reading the instructions a raised line drawing of a fork was presented as a practice trial in order to familiarise participants with raised line drawing recognition.

During the experiment, participants were presented with alternating small and large drawings but were never presented with both the small and large version of the same picture. The caption of figure 3.1 describes the order of the drawings (1 to 12) as used for the experiment. By presenting the drawings in reverse order and by starting alternatingly with a large or small stimulus we were able to create four different stimulus sets which were equally distributed among the 28 participants.

3.2.4 Recognition Analysis

To statistically analyse the response latency and accuracy we used what one could call a within-pictures-design. The rationale behind this design is as follows. In general, when performance of the same observers is measured under different conditions, one uses a within-subject (repeated measures) design. The rationale behind this design is that it cancels out inter-subject variability. Inter-subject variability is caused by individual differences, such as IQ, which are supposed to be unrelated to the experimental manipulations. One could apply the same reasoning for pictures: each picture possesses an individual difficulty which is independent of the experimental manipulation. However, before applying this reasoning one first needs to proof that pictures possess an individual difficulty. D'Angiulli et al (1998) found that pictures correlated for different conditions, which proofs that pictures possess individual difficulty. To ascertain that also in our experiment the pictures fulfilled the requirement for a repeated measures design, we tested whether the average recognition scores of the small pictures correlated significantly with the average recognition scores of the large pictures. It should be noted that observers never experienced a picture twice. The data which were used for analysis were the average recognition latency and accuracy per picture per condition. These data points thus reflected the average scores of a group of 14 participants.

Since our accuracy scores were sometimes near 100% correct, we used a non-parametric test because data near 100% cannot be normally distributed, whereas a binomial distribution around 50% is nearly similar to a normal distribution. Also the latencies were analysed non-parametrically since reaction times cannot be normally distributed. If the picture correlation were significant, we used a paired Wilcoxon signed rank test, and if there were no correlation we used a Mann Whitney test. We also reported the correlation values. We predicted an increase in accuracy with increasing picture size (Kennedy and Bai, 2002), and therefore we used a one-tailed p value for this measure. We made no prediction about the response latency.

3.2.5 Video Analysis

The manual explorations by the first 21 participants were videotaped (as noted previously, the video facility was not available for the last seven participants). Raters were instructed to categorise the movement of the participants' hands in one of three strategies: (1) Single-hand use: the other hand does not touch the drawing; (2) Two-handed use: a single hand moves while the other hand rests on the drawing; (3) Two hands move simultaneously. In the discussion we will comment more elaborately on these choices. Figure 3.3 illustrates these strategies. We chose these three categories because video recordings gave the impression that they were unequivocal and would thus be objectively rateable. We categorised by hands and not by individual fingers because individual finger movement was too complex to rate. We used strategy 1 to compare our data to the single-finger exploration data of Symmons and Richardson (2000).

While watching the video recordings the raters pressed a keyboard key specifically to a particular kind of movement strategy. A program made in LabView recorded the times at which a key was pressed and released. Per trial (raised line drawing) the total exploration time for each strategy was calculated. All video data were analysed by a naive rater who was reimbursed for her participation. The first author rated the video data of the first 6 participants in order to calculate the interrater reliability.

The rater reliability was calculated using intraclass correlations as described by Shrout and Fleiss (1979). For the reliability analysis we used the raw data which are the absolute times of each strategy per trial. To analyse the hand use we used proportions of each strategy per trial to prevent the data from being weighted with respect to the trial time. The data of slow observers would otherwise weight more than those of fast observers.

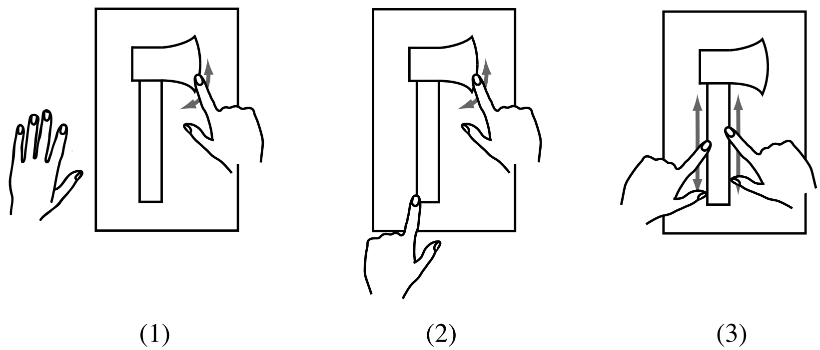

Figure 3.3: Sketches of the three exploration strategies: (1) Single-hand use, the other hand does not touch the drawing; (2) Two-handed use where a single hand moves while the other hand rests on the drawing; (3) Two hands are moving simultaneously.

3.3 Results

In total, during four trials participants commented that they recognised the picture because they had encountered it previously in the lab. These trials were omitted from the analyses. We later verified that all possible outcomes of these trials did not have any effect on the final results. Also dismissing these subjects from the analyses did not influence the outcome. Two stimuli incidentally caused confusion: The hammer was sometimes mistaken for a pick-axe which was counted as a correct response; the exact name of the open-end wrench was occasionally not known whereupon the trial was counted correct if observers were able to correctly describe the execution associated with an open-end wrench.

3.3.1 Response latency and accuracy

The response latency is defined as the time the participant needed from the start of exploration until the final correct response. Response latencies ranged from 5 to 337 seconds. Mean response latencies (standard errors) taken over all trials were 48.8 (4.1) and 47.5 (3.9) seconds for large and small pictures, respectively. The median response latencies for large and small pictures were 33 and 37 seconds. The overall mean proportion of correct responses (standard error) for large and small pictures was 0.84 (0.03) and 0.77 (0.03) respectively.

Whereas the response latency did not show significant correlation between pictures of different sizes ($r = -0.02$, $p = 0.96$), the accuracy showed highly significant correlation ($r = 0.76$, $p = 0.004$). Response latency did not show a significant effect as shown by the Mann-Whitney test ($n_1, n_2 = 12$, $U = 71$, $p = 0.954$, two-tailed) whereas the accuracy did show a significant effect as shown by the Wilcoxon test ($W_+ = 39$, $W_- = 6$, $N = 9$, $p = 0.028$, one-tailed). Furthermore, we did not find a significant correlation between accuracy (averaged per picture) and reaction time ($r = -0.23$, $p = 0.28$).

3.3.2 Response accuracy compared with other studies

Since the response accuracy we found was rather high with respect to previous studies, a reviewer suggested to perform a control experiment in which we measured five new and naive subjects on the large stimuli. The methods for this experiment were similar to the main experiment except that we only used large stimuli and the observers were not asked to think out loud. We found that all five observers recognised 11 of the 12 stimuli, i.e a response accuracy of 91.7%. Four of the five not recognised pictures were unique. To compare our data with literature and to facilitate the discussion on the differences we present an overview in table 3.2. From all studies we took the accuracy scores from adult, sighted observers. When multiple experiments were reported we used the data from the first experiment. In order to compare the different studies we looked at what

Table 3.1: Recognition data per picture. Response latency is expressed in seconds and the accuracy by the proportion of correct responses. Since the mean and median are calculated using the means per picture they can differ from the overall scores reported in the text.

Picture	Response latency		Accuracy	
	Small	Large	Small	Large
Envelope	68	53	0.79	0.86
Axe	49	64	0.71	0.71
Puzzle piece	62	92	0.71	0.79
Boat	65	43	0.93	1.00
Umbrella	18	24	1.00	1.00
Open-end wrench	52	36	0.79	0.64
Flag	35	47	0.79	1.00
Car	52	32	0.93	0.93
Bath-duck tube	32	90	0.43	0.64
Hammer	52	28	0.85	0.93
Light bulb	26	57	0.69	0.79
Scissors	52	43	0.62	0.79
Mean	47	51	0.77	0.84
Median	52	44	0.79	0.82
Minimum	18	24	0.43	0.64
Maximum	68	92	1.00	1.00

kind of pictures were used, what kind of material was used and how large the pictures were. The different picture sets which were used are either subsets of Snodgrass and Vanderwart (1980) or pictures which were inspired by the study of Heller (1989). The stimulus material mostly used is either the Swedish raised line drawing kit or Swellpaper which was used in the current study. The drawing kit uses plastic sheets of paper which are very sensitive to pressure strokes with a pen and produces thin but clear tangible lines. We have also plotted the accuracy scores of these studies against the average sizes of the stimuli (when available), which can be seen in figure 3.4.

3.3.3 Video analysis

On the basis of the video data for the first six participants we calculated the intraclass correlation coefficient (Case 2 model, (Shrout and Fleiss, 1979)) which showed that the rating procedure was highly reliable ($ICC(2,1) = 0.966$, $F(215,216) = 57.468$; $p < 0.001$). For the analysis we used the video rating data of the naive rater for the first 21 participants.

Table 3.2: Review of recognition data of a selection of literature. (*) The accuracy data has been (partly) extracted from a graph. (†) Accuracy has been averaged over the single and multiple finger data. (‡) Partly based on Heller (1989); D'Angiulli et al (1998)

Study	Pictures	Material	Size (cm)	Acc. (%)
Magee and Kennedy (1980)				12.5
Heller (1989)	Own set	Swedish kit	4-11	12.9
Lederman et al (1990)	Snodgrass	Braille printer	12.7-15.2	33.5
Loomis et al (1991)	Snodgrass	Swell paper	15.9	43.8*†
Klatzky et al (1993)	Own set	Swell paper		23*†
Heller et al (1996)	Snodgrass	Swedish kit	7.5 - 10	24.7
Kennedy and Bai (2002)	Own set‡	Swedish kit	15.5-22.5	61
Thompson et al (2003)	Snodgrass	Swell paper	13-15	56*
This research (S)	Own set	Swell paper	10	77
This research (L)	Own set	Swell paper	35	84

The time that participants spent using each strategy was normalised per experimental trial to ensure that each trial would have equal weight. This resulted in $21 \times 12 = 252$ sets of three proportions. The average proportions of movement strategies per picture size can be seen in Figure 3.5. On average, during 17% of the exploration time observers used the single-hand strategy, 21% was devoted to two-handed exploration with one hand static, and for 62% of the time two hands were moving dynamically. Furthermore, it can be seen from Figure 3.5 that the one-hand strategy is used more often for small pictures but the opposite is the case for both two-handed strategies. A 2×3 repeated measures ANOVA was performed on the average data per participant with size and strategy as factors. Due to the normalisation of the exploration strategy, it is trivial that the factor 'size' yields equal means and will therefor not be reported. The degrees of freedom for strategy were adjusted with the Greenhouse-Geisser correction because the data failed to show sphericity. Both the main effect of strategy ($F(1.3, 26.1) = 25.057$, $p < 0.0005$, $\epsilon = 0.652$) and the interaction between strategy and picture size ($F(2, 40) = 7.483$, $p = 0.002$) were significant. The latter effect reflects the change in strategy use when the size of the picture changed as shown in Figure 3.5. Our results further suggest a possible relationship between two-handed exploration and accuracy since they both increase with increasing picture size. To explore this possibility we calculated the correlation between accuracy and two-handed exploration proportions per picture. We did not find any correlation between these two measures ($r = 0.06$, $p = 0.86$).

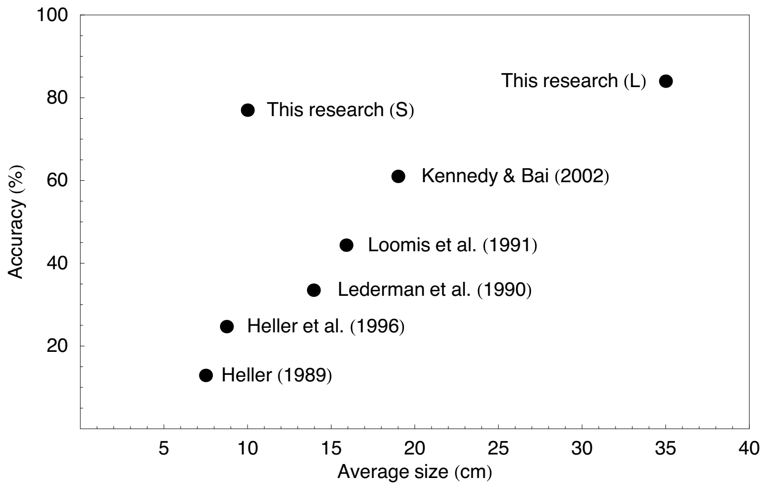

Figure 3.4: The average recognition accuracy plotted against the average stimulus size from previous studies together with the current results.

3.3.4 Delay

For 30% of the correct responses there was no record of a preceding first answer; these data points were included in the analysis and scored as a delay of zero seconds. The average time difference between the first and final correct response (standard deviation) was 11.4 (22.5) seconds which equals 23% of the average final response times. Correlating the first response time with the delay yielded $r = 0.07$ ($p = 0.23$) indicating that the delay does not depend on the initial recognition time. To investigate the relationship between delay and difficulty we calculated the correlation between all nonzero delay trials and the average accuracy obtained for the individual stimuli. We did not find a significant correlation ($r = -0.04$, $p = 0.60$).

3.4 Discussion

We have shown that picture size influences recognisability. Large pictures elicit higher response accuracy but response latency is not influenced. According to the hypothesis of Kennedy and Bai (2002) larger pictures should be recognised more easily because they contain more accurate spatial information. To investigate this issue it should first be noted that a hypothetical gain in spatial resolution can, in principle, be both cutaneous and kinaesthetic, and should thus be analysed separately.

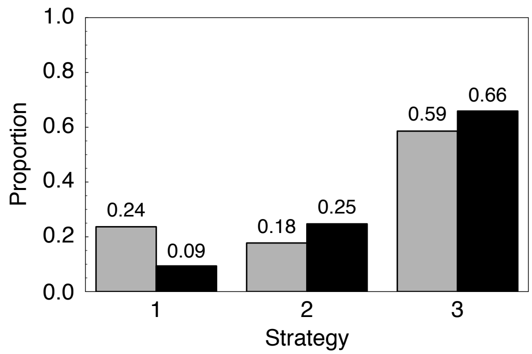

Figure 3.5: The overall proportions of movement strategies per size condition: grey bars denote small pictures; black bars denote large pictures. Strategy 1 means single-hand movement, 2 stands for using two hands one of which is static and 3 stands for using both hands dynamically. Due to rounding, the proportions in the figure do not add up to exactly one.

The minimal distances between the lines of the small pictures of our stimulus set were never less than 3 mm (the spiral lines on the bottom of the light bulb) which is above the typical tactile spatial resolution of 1 mm (Van Boven and Johnson, 1994). Although the lines can thus be distinguished during a controlled discrimination experiment, this might be different when high line density regions are only a small part of a large and spatially complex stimulus. When visually inspecting our stimulus set we realised that only a few stimuli may contain these high line density regions. Although visual inspection is speculative, this indicates that the cutaneous resolution is not the critical factor responsible for the size effect.

Assessing how the resolution of kinaesthetic input is influenced by size is not straightforward. The spatial information contained in the raised lines can be divided into positions and path elements. For the haptic encoding of position we can assume that the signal contains constant uncertainty over the whole workspace, which would mean that the relative kinaesthetic accuracy, defined by the ratio between discrimination threshold and for example length, increases with scale. This assumption about the kinaesthetic encoding position can be compared with measuring two lengths with a ruler: the measurement error of the ruler is constant and thus the relative error will decrease with increasing length. It is, however, unknown how the kinaesthetic accuracy of the path elements is related to size. A law which often applies to discrimination thresholds of quantities such as weight, brightness and sound is Weber's Law which states that thresholds increase linearly with intensity. If Weber's Law held for line lengths and curvatures this would imply that the relative accuracy is invariant with respect to scale. Since research relating spatial resolution to scale is very sparse and does not exist at all for raised line materials, it is impossible to infer whether the kinaesthetic encoding of line paths gains accuracy when larger stimuli are used. There are, however, no indications that accuracy will be negatively influenced by size.

We believe that the gain in spatial resolution is likely to be found in the kinaesthetic encoding, at least in the position information. Our conclusion is supported by Magee and Kennedy (1980) who found that the spatial information is largely kinaesthetically encoded and that the cutaneous input merely serves to guide the fingers along the lines.

Another candidate possibly responsible for the size effect is the differential hand use for the two different picture sizes. Although both two-handed exploration and recognition accuracy increase with scale, no correlation was found between these measures. Correlating the accuracy with exploration strategies, however, might not be the appropriate technique for confirming that multiple hand use has a positive influence on accuracy. Since multiple strategies are used within a trial we do not know which exploration strategy is the most informative for the observer. A study that systematically controls for hand use could resolve this matter.

A striking aspect of our results is that the overall recognition scores are so high when compared to other studies on raised line drawing recognition. As can be seen from table 3.2 it does not seem to be caused by different materials used to produce the raised line drawings. Another possible difference between our study and previous studies is the use of different observers. Since all studies, including ours, were performed on university campuses and the majority of the observers were students, we do not think that the difference depends on this factor. However, our picture set might be a realistic candidate responsible for our high recognition scores. Only three of our stimuli were used in previous studies which makes our set for the larger part new. We can thus only hypothesise that the use of different pictures is a (partial) explanation for our high recognition scores. This is surprising since, as can be seen in table 3.2, various studies have used different picture sets and never before this seemed to be an important factor. Although this issue transcends the scope of the current research, it is an interesting finding and it could be worthwhile to investigate whether our set is indeed better recognisable than that used by Kennedy and Bai (2002). Furthermore, our high recognition scores support the theory that assumes that touch is capable of accurate picture perception.

When we collected the accuracy data from literature and plotted these against the average stimulus sizes, a clear relation became present. As proposed by Kennedy and Bai (2002) and confirmed by the current research, it appears that the size effect was already present in the literature. The fact that the accuracy we found for small pictures does not fit in this trend can be explained by the overall high accuracy we found. Although the interpretation of the graph may be tentative, it certainly strengthens our finding that size affects recognisability.

The second objective of our study was to reinvestigate recent findings concerning the spontaneous behaviour observed in raised line drawing recognition. As noted in the introduction we had sufficient reason to doubt whether the findings of Symmons and Richardson (2000) were reproducible. Indeed, we found different spontaneous behaviour. As can be seen from figure 3.5, a single hand is only used in 9% and 24% of the total exploration time for large and small pictures, respectively. This conflicts with the notion of single-finger dominance. Even if Symmons and Richardson (2000) meant dynamic single finger movement, which would imply that our strategy 2 ranks as single finger use, and if we only use our small stimuli to compare our results with those of Symmons and Richardson (2000) (who used 8.5 cm stimuli) then we still observe the dominance of dynamic two-handed use (59%, see figure 3.5). One possible reason why we obtained different results is that in our study observers were seated whereas in the study of Symmons and Richardson (2000) they were standing at a table. Concluding this issue we can say that we do not share the idea of ecological validity of single-finger exploration. Not only did we find two-handed exploration to be dominant for small pictures but we also observed that single-hand exploration decreases to 9% of the total exploration time for large pictures, which were also recognised more accurately. The fact that spontaneous behaviour seems to be two-handed, does not degrade single-finger studies. Our results merely indicate that raised line drawing recognition studies should not restrict exploration when the experimenters desire an ecologically valid method.

Besides reinvestigating the previously found results from Symmons and Richardson (2000), a rationale behind studying the exploratory behaviour was inspired by the Exploratory Procedures (EP's) proposed by Lederman and Klatzky (1987). That study showed that different EP's are used for distinct object properties when exploring 3D objects. From the in total eight EP's, three might theoretically apply to the exploration of raised line drawings: lateral motion, static contact and contour following. The other five EP's are inherently connected with the three dimensionality of real objects. When we watched the videos of the experiments it occurred to us that almost all exploration would be categorised as contour following. The only clear difference was that subjects use either one or two hands and the two handed exploration can be split up in our strategies 2 and 3. Aside from the advantage that these three strategies were unequivocally rateable, we also had the impression that these strategies serve different purposes. Using two hands simultaneously (strategy 3) facilitates symmetry detection which may be cognitively efficient. Using one hand as an anchor point while exploring with the other hand (strategy 2) constitutes a different reference frame than using only a single hand. Using a reference frame with a fixed origin (strategy 2) probably encodes the spatial information more accurate than without origin (strategy 1). As one reviewer suggested, using different reference frames for the small and large pictures may also explain why larger pictures are better recognised. The use of two hands also decreases illusory percepts as was shown by Heller et al (2005): when two index fingers were used, the Müller-Lyer illusion became weaker in comparison to single finger exploration.

The third objective of our study was to contribute to an understanding of the mental process during line drawing recognition. Our finding that on average 23% of the total response latency is used to confirm the initial correct idea suggests that hypothesis-testing forms a substantial part of the recognition process. It was already mentioned by Klatzky and Lederman (1987) and Kennedy and Bai (2002) that the recognition process would resemble a hypothesis-testing procedure. Kennedy and Bai (2002) observed that the 'fit judgement' which observers made was related to accuracy. We did not find that the delay predicted the difficulty of the stimulus. It is likely therefore that relations exist which we cannot detect because we only have delay data for correctly recognised stimuli. Thus we cannot investigate delay on a trial-to-trial basis.

As for the applications in the area of tactile aids our results point in one clear direction. Larger pictures are recognised more often. It certainly is advisable to increase the size of the picture as much as possible. Combining our results with those of Thompson et al (2003) would yield a design recipe where the size is maximised and the region between the lines is also embossed, although further research is needed to investigate the interaction between these two factors. Although our study and the study of Thompson et al (2003) used sighted observers there is no reason why the effect of size would not work for blind observers. It has been theorised that similar interpretation principles underlie raised line drawing recognition (D'Angiulli et al, 1998). Furthermore, we did not find a direct relation between hand use and accuracy but taking into account that blind observers disapprove of single hand use (Heller et al, 2002a), we advise that observers should not be encouraged to use just a single finger.

CHAPTER 4

UNIDENTIFIED HAPTIC LINE DRAWINGS ARE IDENTIFIED AFTER SKETCHING

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Abstract

The difficulty that observers experience when trying to identify a raised line drawing by touch is still largely unexplained. In this article we show that observers who are unable to haptically identify a raised line drawing are suddenly able to do so after they have sketched on paper what they have in their mind. We conducted three experiments: first of all we show that this effect is robust; in the second we show that recognition–after–sketching is caused by visual inspection of the sketch, and not caused by feedback in general; and in the third we show that sketches which were identified by the observers who produced them, were also identified by completely naive viewers. These experiments demonstrate that during raised line drawing recognition the mental capacities required to interpret the stimulus seem to be inadequate: although enough pictorial information was present to produce a sketch which could even be identified by naive viewers, the stimulus could not be identified by haptic and mental processing alone. Furthermore we investigated whether increasing the haptic perceptual field by using two hands instead of one hand had an influence on identifiability. We did indeed find that using two hands significantly increased recognition. We use both results to discuss the underlying mechanisms of haptic raised line drawing recognition.

4.1 Introduction

“I bet you won’t be able to identify an embossed line drawing by touch". Most people will take on the bet, but will lose it. At first sight the task seems easy, but when a blindfold is on and the fingers are exploring the raised lines, all self-confidence collapses. As noted by Hayward (2008), this can be demonstrated easily in a do-it-yourself experiment: sketch a picture with a pencil while pressing hard on the paper which is lying on soft backing; the back will be slightly embossed and perceptible by touch. Another way to illustrate what makes haptic line drawing recognition so difficult is to cut a small hole in an opaque sheet of paper and use that as an aperture. Superimposing the aperture sheet on a line drawing serialises the normally parallel visual input. Observers can move the aperture along the lines of the drawing and experience the same kind of difficulty as they would encounter when haptically exploring an embossed version.

Better controlled versions of these two do-it-yourself examples have been used in the past to investigate tactile picture recognition. Raised line drawings are normally fabricated with a drawing kit or using swell paper. The drawing kit makes use of a pressure sensitive plastic sheet which becomes embossed when sketched on with a pen. Swell paper is made of heat-sensitive material which embosses the black, printed parts when heated. These two widely available tools have facilitated numerous studies on haptic recognition of line drawings.

Compared to visual recognition, haptic line drawing recognition is characterised by low accuracy and long reaction times. To understand these characteristics, we will briefly review recent literature. Magee and Kennedy (1980) investigated the effect of the exploration mode on recognition. In one condition observers had to explore the pictures actively, in the other condition the observers were passively guided along the lines. The authors found that guided observers identified the raised line drawings more accurately than did the active exploration group. This was attributed to interference between movement control and object recognition. If the observer does not have to continuously plan his movement in the local line direction sensed by the cutaneous receptors, then the observer can interpret the spatial layout better. The same study showed that observers can even identify a drawing when the fingertip is guided along a non-embossed line. Thus, the cutaneous information is predominantly used for movement control and not for recognition. Along the same lines, Thompson et al (2003) found that completely embossed drawings are better identified than raised line drawings. An embossed surface guides the finger more easily along the picture than only a line, thus relieving the observer partly from the exploration task. That an observer is actually performing a dual task of exploration and recognition is evidently an important factor responsible for the low recognition latencies. Another important contributor to the difficulty of haptic line drawing perception is the constraint that the fingers can only extract the spatial information in a serial manner. Loomis et al (1991) experimentally ’serialised‘ vision by constraining the field of view to match the size of a fingertip.

They found that recognition became just as difficult for vision as it was for touching with a single finger. Together, these findings illustrate two important restricting factors of raised line drawing recognition: exploration interferes with recognition and (haptic) serial information acquisition is slower than (visual) parallel processing. From these findings we can understand at least one characteristic of raised line drawing recognition: the slow reaction times. However, these findings do not explain why observers sometimes only reach 25% accuracy (e.g. Heller et al, 1996) despite unlimited exploration time. Observers seem to lack some perceptual or cognitive capabilities to identify a line drawing by touch. Intuitively this may not be surprising, since the purpose of line drawings is to communicate ideas via the visual sense. On the contrary, it may seem very surprising that line drawings can be identified by touch at all.

Two theories have been proposed to explain haptic line drawing recognition. The origins of these two ideas can be found in studies in which the role of visual experience is investigated. In these studies, three kinds of observers are compared: congenitally blind, who clearly do not have any visual experience but might have a better developed haptic sensitivity than sighted observers; late blind, who do have visual experience and also might have haptic superiority; and lastly blindfolded sighted, who have visual experience but may have a less developed haptic sensitivity. Two studies addressing the issue of visual experience contradict each other: Heller (1989) found that the performance of congenitally blind observers is similar to that of sighted observers, whereas Lederman et al (1990) found that congenitally blind observers performed more poorly than sighted observers. From this contradiction two theories emerged.

The first theory was outlined by Kennedy (1993) and was commented on by D'Angiulli et al (1998) and Kennedy and Bai (2002). These authors argue that no visual experience is needed to interpret the various pictorial meanings of line configurations like edges. Also, concepts such as vantage points, outlines and perspective apply to the haptic perception of raised line drawings, irrespective of the observers' visual experience. It is proposed that recognition of line drawings is an amodal process, i.e., both the visual and haptic modality can be used to interpret line configurations. The difference in recognition performance is more a matter of experience than a fundamental difference between modalities. Further evidence for this theory was found in case studies of congenitally blind observers (e.g. Kennedy and Juricevic, 2006) and more general studies on haptic perception of perspective (Heller, 2002).

Lederman et al (1990) proposed a different theory to explain raised line drawing recognition. In their study they found evidence that recognition is mediated by visual imagery, i.e., the observer translates the haptic spatial layout into a visual image which is identified using visual experience. This hypothesis explains their finding that congenitally blind observers (who do not have visual experience) perform more poorly than late blind and sighted observers (who both have visual experience). According to this theory the difference in recognition performance has a modality-specific cause. The haptic modality is unable to identify line drawings and observers need to translate the stimulus into a visual mental image in order to identify it.

Since both theories are supported by experimental evidence, the question of what mediates haptic line drawing recognition is still unsolved. In the present study we will test a hypothesis that could sharpen and even resolve this debate. Ikeda and Uchikawa (1978) reported a case in which an observer, who initially did not identify a raised line drawing by touch alone, could suddenly do so after taking off his blindfold and sketching the image on paper. This was only a single observation but the implications of such a mechanism would help us to gain a better understanding of haptic line drawing recognition. If this finding can be generalised, it would contradict the amodal hypothesis of Kennedy (1993) since it would prove that feedback of tactual information into the visual system enhances recognition. Furthermore, it would mean that the imagery process (Lederman et al, 1990) has some limitations in comparison to direct visual input. In the experiments presented in this paper, we investigated the recognition-after-sketching effect by asking observers to explore raised line drawings for a fixed time interval. After exploration first of all they had to name the object (i.e., identify the basic-category to which the object belongs), secondly they were allowed to sketch the object, and thirdly they had to name the object again. If the observation made by Ikeda and Uchikawa (1978) can be generalised, we should find a substantial increase in recognition after sketching. In three experiments we investigated the recognition-after-sketching effect in detail. In the first experiment we investigated whether this effect is robust and in the subsequent two experiments we tried to disentangle which component is crucial for the effect.

As noted above, various studies have investigated how we retrieve pictorial information from a raised line stimulus. Wijntjes et al (2008a) found that large raised line drawings are better identified than small raised line drawings. It has also been found that using five fingers instead of one finger improved recognition (Klatzky et al, 1993). In contradiction to this latter finding, Loomis et al (1991) found that the use of two adjacent fingers did not increase recognition performance with respect to a single finger. Klatzky et al (1993) also investigated the influence of manual restriction on real 3D object recognition. While material properties were blocked by the use of a glove, the object geometry could be explored under three levels of restriction: with the whole hand, with only the five fingertips and with only one fingertip. They found that recognition became increasingly difficult when the effective perceptual field was decreased. This suggests that for 3D object exploration recognition is better when the size of the perceptual field is larger. As mentioned, raised line drawing identification increased using five fingers, but not using two fingers. A possible explanation for this contradiction is that the increment in perceptual field size was too small to be measured for the two-finger condition. Our first experiment aims to resolve this issue by comparing one- and two-hand exploration. If two-handed exploration yields better recognition then it is likely that the same perceptual field size principle holds for 2D and 3D objects.

4.2 Experiment 1: Visual feedback

In the first experiment we investigated whether recognition-after-sketching is a robust phenomenon. In addition we investigated the influence of hand use on recognition.

4.2.1 Method

Participants

A total of 20 sighted observers (10 men and 10 women) participated in this study, five of which were financially rewarded. All participants were naive with respect to the purpose of the experiment and had no knowledge of the raised line stimuli.

Stimuli and materials

Twenty raised line drawings were used. The stimuli represented a wide range of objects, as can be seen in Fig 4.1. Some pictures were inspired by previous studies. The raised lines were produced with Zytex Swellpaper (http://www.zychem-ltd.co.uk/). The lines were 1 mm wide, approximately 0.5 mm high and the sizes of the pictures were scaled to fit onto a sheet of A4 (21×29.7 cm) paper with 2 cm margins. This size is relatively large with respect to other studies but we decided to use large stimuli because our previous research (Wijntjes et al, 2008a) indicated that size positively influences recognition.

Procedure

Participants received written instructions explaining the procedure. They were blindfolded when exploring the drawings haptically. The total exploration time was 45 seconds. At 30 seconds a signal was given that 15 seconds remained. At the end of the fixed exploration time of 45 seconds, the participants had to identify the object that was represented. They were told explicitly that even if they had only a vague idea they were supposed to communicate it. No feedback was given about the correctness of their responses. After their response, participants had to reproduce the picture by sketching with a pencil on a blank sheet of paper. The participants always had to draw, irrespective of the correctness of the first response. Since possible recognitions could be caused by the extra thinking time during the sketching phase, we introduced a control condition in which observers kept their blindfold on. In that way, they were performing the same motor act in approximately the same amount of time, but were not able to perceive their sketch visually. Participants could take as long as they needed to finish their drawing. After drawing, they had to name the object again. If the drawing was done blindfolded, the blindfold remained on during the naming procedure. They were told that they could repeat their initial response (i.e., the response they gave before drawing) or give a new response.

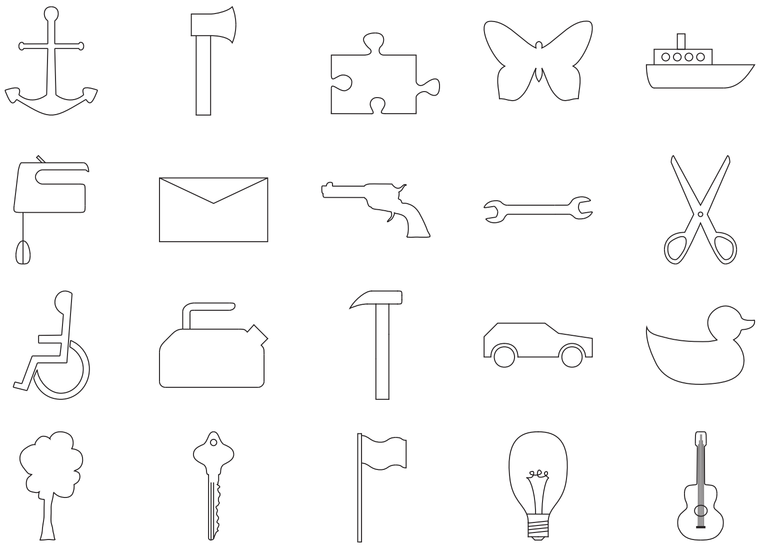

Figure 4.1: From right to left and from top to bottom: (1) anchor; (2) axe; (3) piece of jigsaw puzzle; (4) butterfly; (5) boat; (6) kitchen mixer; (7) envelope; (8) revolver; (9) open-end wrench; (10) scissors; (11) handicapped sign; (12) kettle; (13) hammer; (14) car; (15) duck; (16) tree; (17) key; (18) flag; (19) light bulb; and (20) guitar. During the experiment the stimuli were presented in this order.

Concerning our first research question, the only interesting trials are those which initially were named incorrectly. We distributed these non-identified trials equally among the conditions of sketching with and without blindfold. To do so we assigned the sketching condition depending on the responses. We designed a protocol which allowed the sketching condition to alternate independently for the correct and the incorrect trials. An example of a hypothetical series is presented in table 4.1. As can be seen, the sketching condition switches between with and without blindfold independently for the correct and incorrect responses.

Furthermore, hand use was controlled during the experiment. Half of the participants had to use only one hand during the first ten trials and two hands during the last ten trials. This order was reversed for the other half of the participants. When one hand was used, participants were instructed to use the preferred hand. Participants were free to choose how many fingers to use during exploration. In general, the number of fingers used for exploration did not seem to depend on whether one or two hands were used. Thus, the perceptual field increased with the number of hands used for exploration.

Table 4.1: Hypothetical series of the condition assignment during experiment 1. In this case the starting conditions were both *blindfolded*. As can be seen, the first two drawings were correctly identified, the third trial was incorrect, etc.

Picture		1	2	3	4	5	6	7	8	9	etc …
Correct	Blindfolded	×			×			×			etc …
	Not blindfolded		×				×				etc …
Incorrect	Blindfolded			×					×		etc …
	Not blindfolded					×				×	etc …

Analysis

The total number of trials for 20 participants and 20 drawings amounted to 400. We fixed the exploration time at 45 seconds because we estimated that approximately half of the stimuli would be correctly identified at first response (before drawing). This estimate was based on the median response latency of 37 seconds found in previous research (Wijntjes et al, 2008a). Since the median recognition latency is by definition based only on correct responses we adjusted the time limit upwards. We analysed the effect of sketching with or without blindfold by determining the z-score on the two independent proportions for the two sketching conditions. Furthermore, we tested the homogeneity of the effect by analysing whether the recognition-after-externalisation occurred both for the various participants and for multiple stimuli. This was to ensure that if there was an effect, it was not due to either specific participants or specific stimuli.

We analysed the effect of hand use independently of the sketching conditions. Only the first answer was analysed with respect to the hand use analysis. The hand conditions can only affect the sketching effect, and not vice versa. The effect of hand use was analysed using a paired t test on the average accuracy scores per participant. Since our previous research suggested that bimanual exploration may enhance recognition we used a one-tailed p-value.

4.2.2 Results

A diagram illustrating the overall results is presented in figure 4.2. Only the responses which were initially incorrect are of interest for our research question. When participants could see while they were sketching, 28 'discoveries' occurred, whereas only 2 occurred when vision was blocked by the blindfold. This means recognition occurred in 30.8% of the trials with vision, and in 2.2% of the trials without vision. This difference between the blindfold conditions was highly significant as revealed by a z-score for two independent proportions ($z = 5.6$, $p < 0.0001$). The effect was homogeneously spread over the participants and pictures: 16 participants showed at least one 'discov-

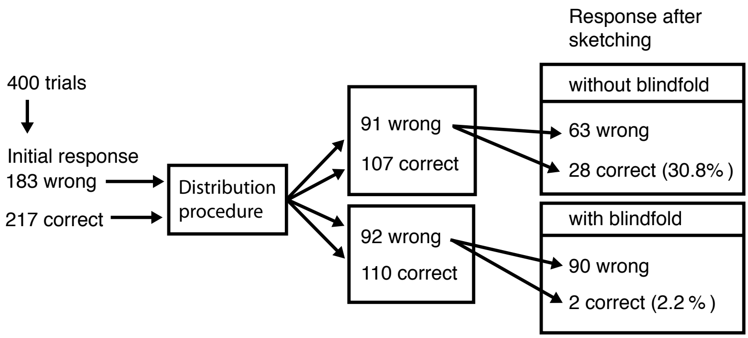

Figure 4.2: Diagram illustrating the results of experiment 1. The total number of trials was 400 (20 participants and 20 stimuli). The initially correct and incorrect trials were distributed equally among the sketching conditions as described by table 4.1. Almost one-third of the 91 initially not identified trials were identified after sketching without blindfold.

ery' and 14 pictures were identified by at least one participant after drawing with visual feedback. Of the 217 initially correct identified stimuli, none was given a new (incorrect) name after the drawing procedure; in other words, no transitions from correct to incorrect occurred after the drawing phase.

The average recognition accuracy for unimanual and bimanual exploration was 49.5% and 59.4%, respectively. We conducted a paired t test on the mean recognition accuracy of the participants. This showed that recognition was significantly better for bimanually exploration then for unimanual exploration ($t_{19} = 2.703$, $p < 0.01$, one-tailed). Furthermore, of the 28 visual 'discoveries', 17 were explored unimanually and 11 bimanually. We performed an independent proportion test which showed that this difference was not significant ($z = 0.89$, $p = 0.38$).

4.2.3 Discussion

We have shown that recognition-after-sketching is a robustly measurable phenomenon. Almost one third of the raised line drawings which were not identified initially were correctly identified when they were sketched without blindfold, whereas hardly any were identified when vision was blocked by the blindfold. Furthermore, we found that bimanual exploration leads to better recognition than does unimanual exploration. This last finding will be commented on further in the general discussion.

The recognition scores are in line with our previous research. We limited the exploration time to 45 seconds which was the (adjusted) median of the reaction latencies reported by Wijntjes et al (2008a). Thus we estimated that the recognition accuracy would lie around 50%. The average recognition accuracy we found in experiment 1 was indeed 54.5%. The accuracy rates in the present study and in Wijntjes et al (2008a) are higher than the rates normally found in the literature, which lie between 10% and 45%. As was noted by Wijntjes et al (2008a), the size of the line drawings could be partly responsible for this. The size of the stimuli used in the present study was between 17 and 25.7 cm (depending on their aspect ratio) whereas other studies often used picture sizes between 8 and 17 cm. An exception is the study by Kennedy and Bai (2002) who used pictures sizes ranging from 15 to 22 cm which resulted in a high recognition rate, namely 61%. The high accuracy in experiment 1 may also be due to the fact that our picture set differed from the set used in previous studies. Some researchers use the standardised set from Snodgrass and Vanderwart (1980) which is normally used in visual line drawing recognition and others use their own set, for instance, Kennedy and Bai (2002) and Heller et al (1996). In our previous study we used 12 pictures, 11 of which were also used in the present study. Since the present accuracy data are consistent with our previous study, it is likely that each set contains a certain inherent difficulty. Our particular set could thus be partly responsible for the high recognition rates.

Our results clearly show that the observation made by Ikeda and Uchikawa (1978) is a robust phenomenon: sketching an unidentified pictorial stimulus can result in recognition. To ensure that this effect was not caused by the extra time associated with the sketching condition we used a control condition in which the blindfold remained on during sketching. Thus, we can explain our finding by suggesting that visual feedback during sketching caused recognition. However, we cannot actually distinguish whether it is feedback in general or specifically *visual* feedback that caused recognition-after-sketching. We designed a second experiment to further investigate this distinction.

4.3 Experiment 2: Haptic feedback

In this experiment we wanted to investigate whether haptic feedback after sketching would also lead to recognition-after-sketching as visual feedback had shown in experiment 1. In order to do this, we used a raised line drawing kit as sketching equipment. The drawing kit allows immediate haptic feedback since the pencil strokes cause clearly tangible relief. This drawing kit is often referred to as the 'Swedish drawing kit'.

4.3.1 Method

Participants

Twenty observers participated in this experiment. They were naive with respect to the purpose of the experiment and had no experience with the raised line stimuli. All were paid for their participation.

Stimuli and material

We used the same stimuli as in experiment 1. We used the raised line drawing kit as sketching medium. The essential ingredient of the raised line drawing kit is the plastic sheet which deforms when sketched on. The deformations establish thin but clearly tangible lines. The sheets were attached firmly so they could not move when the participants were sketching.

Procedure

Participants received written instructions explaining the procedure. Before the experiment started, the raised line drawing kit was shown to the participants and they were asked to sketch some lines to familiarise themselves with the kit. The participants were told that they were free to explore the stimuli in the way they wanted. The sketching always took place with the blindfold on. Otherwise, the procedure was similar to that in experiment 1. Before the experiment started, one test trial (a raised line drawing of a lamp) was given in order to familiarise the participants with the procedure. During this trial the sketching procedure was also practised. As in the first experiment, recognition was measured after haptic exploration and after the sketching procedure. The observers were told explicitly that after they had finished sketching the stimulus, they should touch their own sketch again before giving their final answer.

4.3.2 Results

In total 175 of the 400 trials were initially identified correctly, i.e., an average accuracy of 43.8%. Since we found an average recognition accuracy which was substantially lower than that found in experiment 1, we performed an unpaired t-test on the mean accuracy scores of the participants from experiments 1 and 2. Since the hand use of participants in experiment 2 was not constrained we used the average accuracy scores for unimanual and bimanual exploration from experiment 1 for comparison. The t-test did not reveal a significant difference between the recognition accuracy of the two experiments ($t_{38} = 1.717$, $p = 0.094$).

Of the 225 unidentified trials, 10 (4.4%) were identified after sketching with the raised line drawing kit. This occurred for 8 different participants and for 9 different stimuli. The recognition rate of experiment 2 did not significantly differ from the 2.2%

found for the drawing with blindfold condition in experiment 1 as was revealed by a z-score for two independent proportions ($z = 1.1$, $p = 0.27$). Compared to the visual feedback condition of experiment 1 there was a significant difference between the two proportions ($z = 5.2$, $p < 0.0001$).

4.3.3 Discussion

The result of experiment 2 shows that using a raised line drawing kit does not improve the recognition of unseen sketches. This finding rules out the possibility that recognition-after-sketching is caused by a modality-independent feedback mechanism. Instead, recognition after sketching seems to be a phenomenon specifically occurring when visual feedback of the sketch is provided.

In our last experiment we wanted to investigate this visual feedback mechanism in more detail. Recognition by an observer of his or her sketch in experiment 1 could be due to several factors. Firstly, the observer had haptically perceived the original picture; secondly, the observer could see the moving, sketching hand; thirdly, the observer is seeing the emerging sketch; and lastly the observer saw the final result. In order to partly disentangle these factors we conducted a third experiment.

4.4 Experiment 3: Identifiability by naive viewers

To understand why sketches led to recognition we wanted to know more about how the sketches were used by the participants. Did their haptic knowledge (i.e., the experience of having touched the stimulus) contribute to the recognition? Was it important to see the sketching hand or was merely seeing the resulting sketch sufficient for recognition? We tried to answer this question by measuring how recognisable the sketches were to naive viewers. If naive viewers are able to identify a sketch, then haptic knowledge and seeing the sketching hand are likely to be of minor importance.

In the third experiment we only used the sketches which were identified when sketched without blindfold from experiment 1. From experiment 1, video recordings were available for half of the observers who showed recognition-after-sketching. We watched the recordings to check at what moment during sketching the recognition occurred. This is relevant because it may influence the quality of the sketch: if recognition occurs during sketching it is possible that the observer uses this knowledge to improve the sketch. The video recordings revealed that most of the time recognition during experiment 1 occurred after sketching was finished (12 out of 14). This means that subjects generally completed their sketching before recognition.

4.4.1 Method

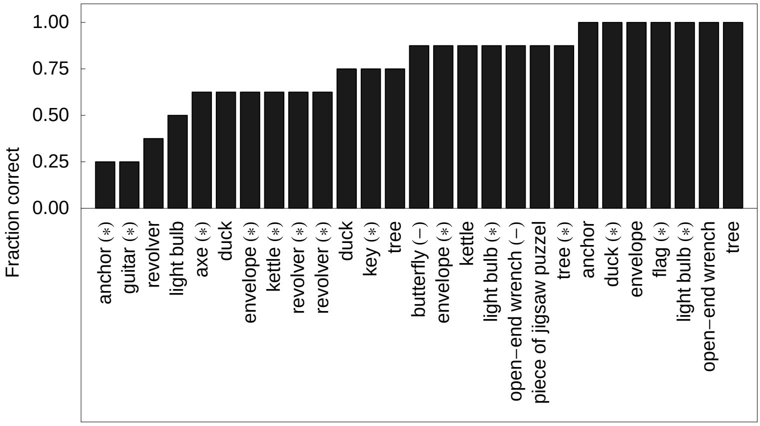

Figure 4.3: Average recognition scores for 27 sketches which led to recognition in experiment 1. The scores are ordered and the names of the original drawings are written on the x-axes. With regard to the sketches from which video recordings were available we report whether recognition occurred during the sketch (-) or after (*).

Participants

Twenty-four observers who were naive with respect to the purpose of the experiment and had seen neither the stimuli nor the sketches participated in this experiment.

Stimuli and materials

The results from experiment 1 showed that only the raised line drawing of the duck resulted in four discoveries. We randomly left out one of these 4 duck sketches and from the resulting 27 sketches we constructed three sets in which no drawing was represented more than once.

Procedure

Each set of nine sketches was shown to 8 participants. Participants were instructed to try to identify the sketch. They reported this by writing down their answers.

4.4.2 Results and discussion

The average recognition scores are presented in figure 4.3. As can be seen, the sketches are identified more often than not. Only 3 sketches were identified by less than 50% of the observers and all of the sketches were identified at least once. On average 76% of the sketches were identified by naive viewers. These results suggest that in most cases haptic knowledge or seeing the sketching hand is not necessary for recognition.

4.5 General discussion

Our experiments have shown that recognition-after-sketching is a robust phenomenon and occurs specifically when a finished sketch is being inspected visually. Of the raised line drawings which initially were not identified, 30.8% became recognisable after the spatial information was externalised by means of sketching. We have also shown that sketches of unidentified stimuli are identified only by vision, and not by touch. Furthermore, the sketches were recognisable for naive viewers, suggesting that the sketch does not serve as a supplement to the recognition task, but serves rather as an independent stimulus.

As outlined in the introduction, two theories compete for the explanation of raised line drawing recognition, namely the amodal theory of Kennedy (1993) and the modality specific theory of Lederman et al (1990). At first sight, our experiments show that raised line drawing recognition is a modality-specific problem, since recognition increases when the stimulus perceived by the haptic modality is fed back through the visual modality. Thus, our findings favour the theory of Lederman et al (1990). Since this idea is based on the assumption that a mental image can be identified (i.e., visualisation can lead to recognition), we need to understand the relation between imagery and perception. This relation is central to the so-called imagery debate about the nature of mental representations. Interestingly, researchers involved in this debate found recognition-after-sketching effects similar to the ones we found.

The ongoing imagery debate focuses on the question of whether the mental representations used in an imagery task are depictive or descriptive. Kosslyn (1994) states that the representations are depictive and he takes the view that perception of a mental image is similar to perception of the real world. On the other hand, (Pylyshyn, 2003) states that imagery is purely descriptive; the vivid visual experience humans have when visualising an object or scene is merely an illusion. To resolve this debate researchers performed experiments in which observers were asked to perceive mental images. One way of doing this is to show observers an ambiguous figure for a brief moment. If only one of the two referents is identified the task is to identify the other referent using imagery. Chambers and Reisberg (1985) presented the rabbit/duck ambiguous figure for 5 seconds. Whereas none of the participants could reinterpret the figure during imagery, all were able to identify the other referent after sketching. Since the imagery task did not cause recognition but sketching did, the results were explained as an argument against the depictive hypothesis. A different paradigm was used by Finke et al (1989) who investigated the recognition of mentally constructed images. Observers were given verbal instructions on how to manipulate and synthesise alpha-numerical symbols. For example: “Imagine a capital letter ‘D’. Rotate the figure 90 degrees counter-clockwise. Now attach a capital letter ‘J’ at the bottom." This instruction should lead to the recognition of an umbrella. They found that observers could identify most mental constructs; this evidently was used as an argument counter to the descriptive hypothesis. However, Finke et al (1989) also measured the effect of externalisation when recognition failed. In their second experiment they found that 83% of the unidentified stimuli were identified after sketching.

Although not resolving the imagery debate, these studies showed that externalising a mental image can lead to recognition. Together with our results these findings suggest that the externalisation effect is independent of the origin of the mental image: Externalisation increases recognition rates both for visually (Chambers and Reisberg, 1985), verbally (Finke et al, 1989) or haptically (our study) perceived pictures. It should be noted that externalisation is also often used in everyday life. Multiplying two numbers consisting of more than two digits causes one to reach for a paper and pencil. Physics and mathematics students need to write out the symbolic derivations in order to understand complicated equations. More formally, Verstijnen et al (1998) showed that externalisation is used when observers have a need to restructure a mental image.

Externalisation seems to be a process which can be used to restructure uninterpretable input. In the case of line drawings, it restructures the serial input into parallel input. Looking at the sketch essentially recruits the large perceptual field of vision. A similar relation between the perceptual field size and recognition was found in Experiment 1. There, we showed that two-handed exploration enhances recognition with respect to one-handed exploration. This finding complements the finding of Klatzky et al (1993) who found that five-finger exploration outperforms single finger exploration. On the assumption that the difference between one and two adjacent fingers (Loomis et al, 1991) was too small to be measurable, one is lead to conclude that increasing the perceptual field positively influences perception. A functional equivalence holds for vision: increasing the aperture size increases recognition rates. It can thus be hypothesised that the difference between visual and haptic line drawing perception is only a matter of different perceptual field sizes and is not a result of the visual system having privileged access to line drawing recognition. It is interesting to note that blindfolded observers have a natural tendency to increase their perceptual field by using multiple fingers and two hands (Wijntjes et al, 2008a).

Why do we (sometimes) need to restructure a serially acquired line drawing? It could well be that the way line drawings are explored gives rise to a representation which cannot be matched to an internal representation and thus cannot be identified. The representation which is built up when the line drawing is being explored is of such a serial nature that it does not suit the recognition system which uses parallel or simultaneous representations. Rephrasing, one could say that haptic line drawing exploration results in a one-dimensional description in which only left or right turns are coded, whereas the internal representations that are used for object recognition are two-dimensional. One-dimensional descriptions lack configural regularities such as parallelism and symmetry which may play an important role in object recognition as suggested by Panis et al (in press). As one reviewer noted, the assumption that haptically perceived pictures are encoded one-dimensionally could be tested by investigating the video recordings. If exploratory movements could predict the sketching movements, this would be evidence that observers use a one-dimensional description. This is a very interesting idea, but studying our video recordings made it clear that these could not be used for this purpose. As was noted by Wijntjes et al (2008a), observers usually explore using multiple fingers, even when using one hand only. This was also evident from the video recordings of the current experiment: since multiple fingers were exploring the drawing, we could not relate these movements to the production of the sketch. However, there is evidence from the literature that typical errors are made during the reproduction of haptically explored two-dimensional shapes. Becker (1935) investigated haptic perception of two-dimensional shapes which were composed of simple closed shapes such as circles, squares and triangles. Interesting configurations were the ones where two shapes partly overlapped. The first observation Becker made was that for two overlapping circles a large part of the observers did not detect the two circles but perceived either three non-overlapping closed shapes or they grouped the outer figure and the inner figure. He could not relate the exploration movements to the reproduction movements but he did observe that the way the stimulus is explored is at least partially responsible for the errors. In another experiment Becker (1935) showed that when vision is confined by an aperture, similar reproduction errors occur, although less frequently than with touch. Although the experiments were performed on children aged 9 to 11 years, informal observations from our lab confirm that for the two overlapping circles the typical errors were also made by adult observers: 10 out of 18 observers showed similar errors. The study by Becker (1935) shows that serial perception of two-dimensional shapes often leads to errors characterised by a failure to detect geometrical sub-components.

The failure to detect geometrical sub-components, associated with serial perception, has also been observed in a patient study by Behrmann et al (1992). They found that a patient with severely impaired object recognition (visual object agnosia) reproduced a configuration of two squares connected by a circle in a similar manner as observed by Becker (1935): instead of sketching the sub-components separately, the patient sketched the outer line connecting the three shapes. The finding of Behrmann et al (1992) strengthens the hypothesis that serial perception causes impaired object recognition. Our study has shown that the internal serial description of the stimulus can be used to sketch a recognisable drawing. Through sketching it is possible to transform the difficult-to-identify serial description into an easier-to-identify simultaneous picture. Therefore, we suggest that the difficulty of haptic line drawing perception is not caused by the privileged object recognition access of the visual system, but is caused by inherent serial perception of the haptic system. The recognition system is not well equipped to match the serial input to internal representations. There are possible ways to increase the haptic perceptual field, for instance, by using two hands, but haptic line drawings will still not be identified as accurate and fast as visual line drawings.

CHAPTER 5

LOCAL SURFACE ORIENTATION DOMINATES HAPTIC CURVATURE DISCRIMINATION

M.W.A. Wijntjes, A. Sato, V. Hayward, and A.M.L. Kappers, (submitted)

Abstract

In previous research it has been shown that local surface orientation is the dominant cue for static haptic perception. Furthermore, indirect evidence has shown that this dominance also holds for dynamic touch (Pont et al, 1999). We developed an apparatus with which we could directly test this hypothesis for dynamic touch. The haptic interface used in our experiments provided the observer with two geometric information sources: position and surface orientation. These two information sources could be set independently.

In the first experiment, we measured discrimination thresholds for the two types of shape information. We also measured whether discrimination of real shapes is better than of virtual shapes. The results confirmed the dominance of local surface orientation. We did not find differences in discrimination performance between real and virtual shapes. The isolated thresholds for the geometric information sources allowed us to calculate in which regions of exploration range these shape descriptors should be dominant. We found that local surface orientation is dominant within the range of 1.2 to 78 cm of finger movements.

In the second experiment we directly compare the perception of real and virtual shapes. We did this by investigating whether a virtual curved surface feels equally curved as a real curved surface. We found that observers did not systematically judge either of

the two kinds of stimuli to be more curved than the other. More importantly, we found that points of subjective curvedness were not influenced by the availability of height information.

5.1 Introduction

A shape can mathematically be described in many ways. A simple way of describing a two-dimensional shape is to specify its position $\mathbf{x}(s)$ along its path length s. Alternatively, the surface orientation $\mathbf{x}'(s)$ or the curvature $\mathbf{x}''(s)$ can be used to fully specify the shape. If one of these shape descriptors is known, the others can be attained by means of differentiation or integration. These shape descriptors are all available to the haptic sense, as can be seen in Fig. 5.1: If a finger explores a shape, the profiles of the height z, orientation of the surface $\mathbf{n}$ and local curvature c can all in principle be haptically encoded, although complicated transformations may be needed to acquire them from the raw sensory input. The geometric cues 'position', 'surface orientation' and 'curvature' are the zeroth, first and second order shape descriptors, respectively.

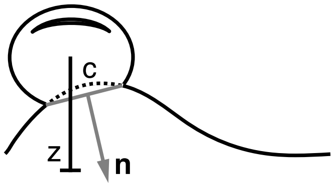

Figure 5.1: Geometric information available for an exploring finger: the height profile z (zeroth order shape); the orientation profile of the normal vector **n** (first order shape) and the local curvature profile c (second order shape).

Since each of these geometric sources is available, the shape is over-specified. In the study presented here we investigated how the haptic system takes advantage of this over-specification. We studied how haptic curvature discrimination depends on the availability of zeroth and first order shape information. Previous studies suggest that the orientation of the surface is the most important source of information for curvature. Gordon and Morison (1982) let observers explore curved strips which were 2 cm wide and found a threshold (75%) of approximately 2 m^{-1}. Pont et al (1999) performed a similar experiment but used wider strips (20 cm) and found a discrimination threshold (84%) of approximately 0.5 m^{-1}. As was suggested by Gordon and Morison (1982) this decrease of thresholds with increasing lateral motion can be explained when not curvature itself is the effective stimulus, but the total gradient of the surface. This idea was further developed by Pont et al (1999) who showed that for static touch, the effective stimulus of a curved surface is the total surface orientation difference, the first order shape descriptor. Evidence that a similar mechanism underlies dynamic touch was found after Pont et al (1999) manipulated the exploration length. In terms of curvature, the thresholds increased with decreasing exploration lengths, but in terms of orientation differences, the thresholds stayed constant.

Although literature suggests that change of surface orientation is the dominant geometric source of information, there is nothing known about the separate discrimination thresholds of zeroth and first order shape for dynamic touch. With knowledge about thresholds it is possible to predict on which stimulus scales each geometric cue is likely to dominate. To measure separate discrimination thresholds, independent presentation of height and orientation is required. Dostmohamed and Hayward (2005) designed a device that could render a haptically perceivable shape using only orientation information. The fingertip was placed on a surface which could be freely moved horizontally. The orientation of the surface was controlled such that it would be similar to the orientation of real surfaces. They found that this simplified stimulus induces curvature perception, but they did not address the contribution of multiple geometric cues. In the present study we used a similar device but improved the design such that also the height (zeroth order) could be varied systematically. We were thus able to generate three kinds of shapes: zeroth order, first order and the combination of the two. This is illustrated in Fig. 5.2 A–C.

In the experiments we conducted, second order shape information was disregarded. From literature we could estimate that the curvatures of the stimuli we used were always sub-threshold with respect to local curvature sensed by the fingertip pressure profile: Goodwin et al (1991) found that observers could not discriminate (84% level) a flat surface from a curved one when the curvature was smaller than 7.5 m^{-1}. The shapes we used as stimuli were all well below this value. This means that they were all perceived as 'flat' in terms of second order shape description.

If observers would only use geometric information, the virtual and real stimulus (Fig. 5.2 C and D) would be equally well discriminated. However, there are non-geometric differences between real and rendered shapes, which may be of influence. To account for the roles of non-geometric cues, we included real, solid shape stimuli in our investigation.

Our study serves two goals. Firstly, knowledge about the use of geometrical cues in haptic shape perception serves as a basis to the study of haptic shape perception in general. Haptic perception of shape does not only depend on geometric features of the stimulus but also on other aspects of the interaction between the body and the stimulus. It has been shown that rendering the lateral force which normally arises when a finger explores a gaussian bump, induces an illusory perception of shape (Robles-De-La-Torre and Hayward, 2001). It has further been shown that humans perceptually combine this force cue with zeroth order shape information (Drewing and Ernst, 2006). In the research presented here we investigate the sensitivities of two geometric cues which could serve as a base line for further research into cue integration models for haptic shape perception. Secondly, designers of haptic interfaces need to know which aspects of a shape to render. If for certain applications it turns out that one of these can be discarded, this can result in important cost or computational reduction. On the other hand, the use of haptic devices that only deliver zeroth order information for psychophysical experiments should be reconsidered if the haptic system shows to be much less sensitive to zeroth order information than to first order information. For example, Henriques and Soechting (2003) studied haptic perception using a manipulandum that only delivers zeroth order information. They investigated both perceptual sensitivity and biases. To generalise their findings to haptic perception of shapes, one first needs to prove that perceptual sensitivity is similar for a manipulandum and a real or at least geometrically richer stimulus.

In two experiments we tested the role of zeroth and first order shape information on haptic perception. In the first experiment we measured discrimination thresholds (Just Noticeable Differences, JNDs) for the three combinations of shape descriptors and real shapes. We used a flat reference and were thus measuring just noticeable curvedness. In the second experiment we wanted to understand whether a virtual shape felt equally curved as a real shape. To investigate this, we measured whether there is a perceptual bias between real and virtual shapes. Our particular interest was to test whether a shape rendered only by the first order shape descriptor, i.e. the orientation of the contact area surface, gives a similar bias as the combined cue configuration in which also height information is present.

5.2 Experiment 1: Thresholds for individual cues

5.2.1 Methods

Participants

Eight observers participated in the first experiment. They were recruited from the McGill campus and were reimbursed for their participation. None of the observers had previously participated in a related study and they were naive with respect to the purpose of the study. The group consisted of four males and four females, with a mean age ($\pm$ standard deviation) of 22.9 ± 5.4. According to Coren's handedness test Coren (1993) all observers were right-handed.

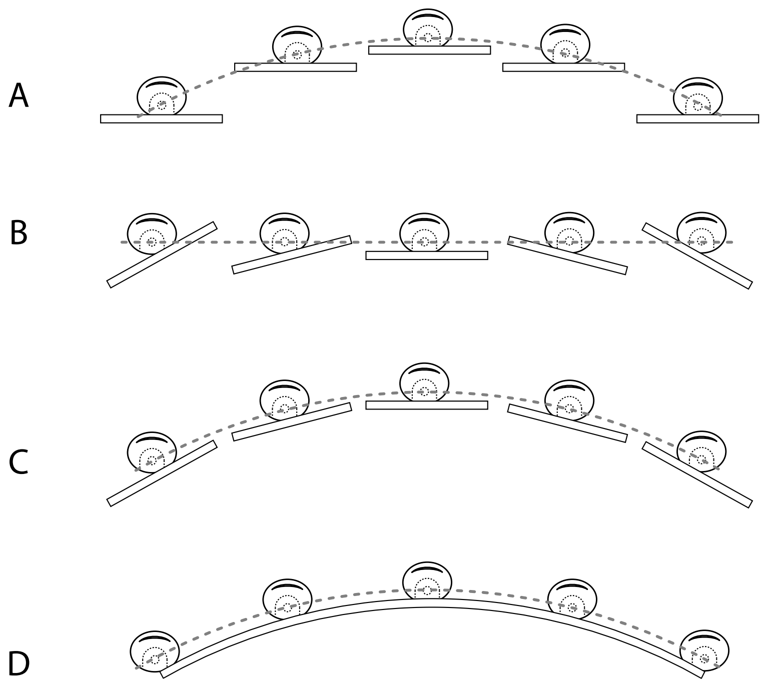

Figure 5.2: The four conditions used in Experiment 1. The upper three conditions illustrate how the device simulated certain geometric aspects of curvature. A: The height-only condition in which the orientation curvature is set to zero. The observer only experiences a curvature through the vertical displacement of the contact area. B: In the orientation-only condition the height curvature is set to zero, and the observer only experiences changes in the orientation (attitude) of the shape. C: Both height and orientation information are available to the observer. D: The solid shape contains the most information, next to zeroth (height) and first order (orientation) geometrical information is contains second order (curvature) information. Also the observer experiences slip.

Stimuli

The virtual stimuli were rendered with a device that could independently orientate and elevate a moving contact surface, as shown in Fig 5.3. By placing the fingertip on the surface, an observer could laterally move the surface. The orientation and elevation depended on the position of the surface and the value of the curvature. The two motors were controlled independently which made it possible to keep either of the two curvatures constant at zero. A detailed description of the device can be found in Wijntjes et al (2008c).

The real stimuli were previously used by Pont et al (1999). The stimuli were curved strips made from PVC. They were 20 cm long, 2 cm wide and at the midpoint had a constant height of 5 cm. Movement limiters were mounted on the stimuli to equalise the movement range of the real and virtual stimuli which was 18 cm. The movement limiters were cylindrically shaped such that contact with them could not be used as a cue by the observer.

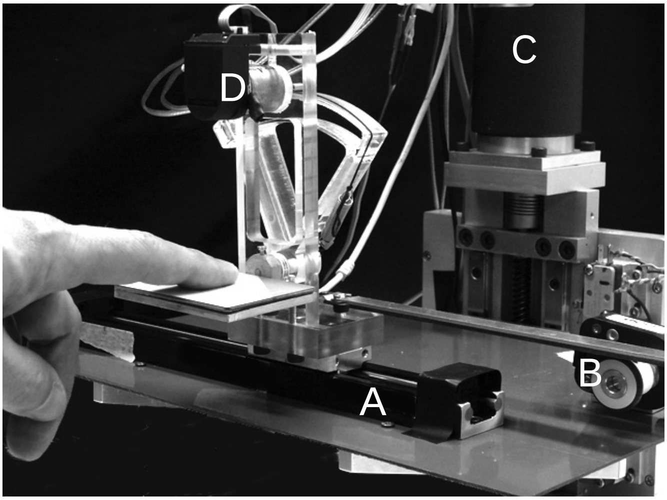

Figure 5.3: The apparatus that simulated the shape. During exploration the finger moved the contact surface laterally in the direction of the rail (A). The position encoder (B) served as input to generate the shape through a combination of the height motor (C) and the elevation motor (D).

Fig. 5.2 depicts how the stimuli were set in the four conditions. In condition A, only zeroth order shape was rendered: the height motor rendered a height profile with a constant curvature, whereas the orientation motor was set to maintain the contact area horizontal. In condition B only first order shape was rendered: the height of the finger stayed constant whereas the surface orientation varied. In condition C both shape descriptors were rendered and in condition D the real stimuli were used.

Procedure

We measured discrimination thresholds (JNDs) in such a way that possible side-effects of working with a electromechanical device could not influence the data. For example, tactile or auditory vibration produced by the device could be used as a cue for a non-flat shape. To avoid unwanted cueing we used a Two-Alternative-Forced-Choice (2AFC) task in which the observer had to judge which of two presented stimuli was more convex. In this way, unwanted detection of non-flatness could not influence the discrimination threshold because the observer was forced to indicate the *sign* of the difference. The two stimuli of a trial consisted of a reference curvature of zero (i.e. flat) and a non-zero test curvature. The order of test and reference stimulus was counterbalanced and randomised.

We used a block design in which we investigated each of the four conditions separately. The order of the conditions was semi-counterbalanced because the number of permutations of conditions (4) exceeded the number of participants. We ensured that the real shape condition was balanced among the virtual conditions. Before the experiment started the experimenter made sure that the participants understood that convex meant 'curved upward' (for the current configuration of stimuli). During the experiment an illustration was continuously visible that clarified what was meant with convex.

The participants were seated in front of a curtain behind which the stimuli were presented. They could not see the stimuli and wore a sound isolating headphone during all conditions. Participants never saw the device before the end of the complete experiment. They were informed that during three of the four conditions they would feel a virtual shape but were not informed about the details of these three virtual different conditions. At the start of each block approximately ten trials were presented. The participants familiarised with the task and received feedback on their answers. We expected that the thresholds would vary across conditions and participants. To anticipate on this variation we introduced a short break early in the session, in which the experimenter viewed the data and decided with which test stimuli to continue. The procedure was as follows. Before the break, two repetitions of the following *test curvatures* were measured in random order: $c_t = \{-2, -1.8, \ldots, -0.2, 0.2, \ldots, 1.8, 2\}$. These 40 trials were used to design the next stimulus set that consisted of 12 test values, six concave and six convex. The total number of repetitions per test stimulus was 10, making the total number of responses per discrimination threshold equal to 120.

During the experiment the solid shape stimuli were placed in a holder such that its mid-height was similar to the mid-height of the rendered stimuli: 17 cm above the table. The participants had to start their movement in the middle of the stimulus, which was at constant height for all conditions and curvatures. This means that for a convex shape the endpoints were below the mid-height and for concave shapes the endpoints were above the mid-height. After each trial the experimenter manually placed the device back in the middle. From the midpoint, participants were instructed to make two full cycle movements arriving back at the (approximate) midpoint. Within a trial, each stimulus (test and reference) was only felt once. The participant had to say which was more convex: the first or the second. In contrast with the short training period, participants did not receive feedback on their responses throughout the experiment.

Data analysis and design

For each test-reference pair the responses were transformed into fractions of 'test curvature feels more convex'. These values were fitted to a cumulative Gaussian

$$f(c) = \left(\operatorname{erf}\left(\frac{c}{\sigma\sqrt{2}} \right) + 1 \right) / 2 \tag{5.1}$$

where erf denotes the error function and $f(c)$ is the mean response for a test curvature c. The parameter σ corresponds to the 84% correct response level. A maximum-likelihood procedure was used to fit the function as described by Wichmann and Hill (2001a). The discrimination thresholds resulting from the fit procedure were analysed in a one-way repeated measures Analysis of Variance (ANOVA) with the four conditions depicted in figure 5.2 as factor.

5.2.2 Results

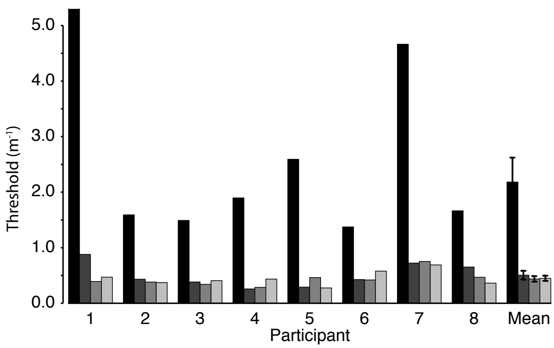

Figure 5.4: Overview of al individual discrimination thresholds. For each participant the thresholds are plotted for the four experimental conditions, from left to right: height-only, orientation-only, height and orientation, real shape. For the calculation of the mean results the threshold of the first participant for the first condition was omitted. Error bars denote for standard errors of the mean.

The individual and mean results are presented in figure 5.4. The threshold of participant 1 for the height-only condition lay far out of the stimulus range and we had to omit this threshold; thus, the rest of the data from this participant could not be included in the statistical analyses. As can be seen in the figure, the mean threshold for the height-only condition is about four times as high as the other conditions. This is confirmed by the results of the (Greenhouse-Geiser corrected) ANOVA ($F(1.036) = 15.239$, $p = 0.005$). Bonferroni corrected pairwise comparisons only revealed significant differences ($p < 0.05$) between the height-only condition and the other three conditions.

Discussion

The results clearly show that discrimination performance depends largely on the availability of orientation information. A curved shape that is only defined by a height profile is difficult to discriminate. Because of the large difference between A and B, the lack of difference between conditions B and C is not surprising.

What is furthermore interesting is that there does not seem to be a difference between rendered and real stimuli. Whatever the difference of available information is between a rendered and real stimulus, it does not seem to affect curvature discrimination.

Our thresholds for zeroth and first order shapes for dynamic touch are similar to those found by Pont et al (1999) for static touch. The orientation of the contact location seems to be the effective stimulus for curvature discrimination, irrespective of whether one uses static or dynamic touch. However, finding similar discrimination thresholds for a rendered shape and a real shape does not prove that a shape only rendered by orientation actually *feels curved*. If we can prove that an orientation-only shape feels curved, then this is an important step towards understanding haptic shape perception. Therefore, we conducted a second experiment.

5.3 Experiment 2: Points of subjective curvature

In this experiment we investigated whether an orientation-only shape (B-shape) is actually perceived as being curved. A second goal was to investigate whether a shape of which both the height and the orientation are rendered (C-shape) feels equally curved as a real shape. To answer these questions we compared rendered shapes (B and C) with real shapes. We presented observers with pairs of real and rendered shapes and measured the points of subjective equality (PSE) using the method of constant stimuli. Because we wanted the height information to be perceivable we used a reference curvature of 2 m^{-1} which is approximately the mean 84% correct threshold level found in the previous experiment (see the black bars in Fig. 5.4).

Although not the main objective of the experiment, we were also interested in how thresholds in Experiment 2 compared to those from Experiment 1. Since in Experiment 2 observers needed to compare two different stimuli (rendered and real), we hypothesised that the thresholds of this experiment would be higher than from Experiment 1.

5.3.1 Methods

Participants

For the second experiment we recruited a new group of eight (three males and five females, age 24.2 ± 5.0) participants from the McGill campus. They were naive with respect to the purpose of the study and did not participate in other studies on haptic curvature perception. They were reimbursed for their participation. According to Coren's handedness test Coren (1993) all participants were right-handed.

Stimuli

The same kinds of stimuli were used as in the first experiment. Whereas the stimuli for the first experiment were concave and convex, the stimuli in the second experiment were all concave because we used a concave curvature of 2 m^{-1} as reference stimulus. The rendered stimuli were of the types 'orientation-only' and 'height and orientation', B and C as depicted in figure 5.2.

Procedure

Participants were seated in front of a curtain behind which the stimuli were presented. In each trial the participant was presented with a stimulus pair, one of which was a real shape and one was a rendered shape. The task of the participant was to respond which of the two stimuli was more convex. When investigating points of subjective equality between two different stimuli one should be cautious that there are no other experimental differences than the one under investigation. Since the two stimuli could not be presented in the exact same location we minimised the space between them to 4 cm. The real shapes were always positioned in front of the device. During each trial the observer was instructed to explore either the stimulus 'in front' (the real shape) or 'back' (the device). When the device was explored, the real stimulus was removed to make space for exploration. Thus, the only difference between the real and rendered stimuli other than the one under investigation, was a location difference of 4 cm in the sagittal direction.

The two types of rendered stimuli, with and without height, were the two experimental conditions. These two conditions were measured in blocks and counterbalanced within the observer group. Within a block, the participant was always presented with a reference stimulus of 2 m^{-1} and a test stimulus. When the reference was a real shape, the test was a rendered shape and vice versa. After the first stimulus either the real shape was taken away or put into place and the participant could feel the second stimulus. The exploration instruction was identical to the first experiment and the participants had to respond which was more convexly curved by saying 'front' or 'back'. Before the experiment started, the experimenter made sure that the observers understood what was meant with 'more convex'. Throughout the experiment an illustration was present to remind the observer of the task.

Before each block a training set of about 10 trials were practiced. Because we were interested in the perceptual bias between two different conditions, a correct answer is not defined. Hence we did not gave feedback during the training nor during the real experiment. Furthermore, the participants were not informed about the difference between the two conditions.

For each condition the test curvatures were 2 $\mathrm{m}^{-1} \pm \{0, 0.2, 0.4, 0.6, 1.0, 1.4\}$. Each test-reference pair was measured 12 times of which the real and rendered shapes each served six times as reference curvature. Thus, each block consisted of 132 trials.

Data analysis

The 'front-back' responses were converted into 'real shape feels more convex than the rendered shape' as a function of the curvature difference between the real and rendered shape, $c_{real} - c_{virtual}$. Although the curvature of the orientation-only stimulus is not defined, we took the curvature value that described the orientation. If there would not be a perceptual bias between the real and rendered shapes, the point where the psychometric function reaches 0.5 lies at $c_{real} - c_{virtual} = 0$. If a real shape feels more curved, the bias μ would be negative and vice versa. For example, if an orientation-only shape would feel exactly flat with respect to a real shape, the bias would be $\mu = -2\ \mathrm{m}^{-1}$. To extract the bias from the data we used the same fitting procedure as in the first experiment using the cumulative gaussian with a bias μ as extra parameter: $(\mathrm{erf}\left((c-\mu)/(\sqrt{2}\sigma)\right) + 1)/2$.

5.3.2 Results

The data set of participant 6 for the condition (orientation-only) was omitted because the fitted threshold lay far out of the measurement range and was thus not reliable. Furthermore, participant 7 was accidentally measured twice in the same condition (orientation-only). There was no possibility to remeasure this participant. Because the data are still of interest they are presented together with the data of the other participants in figure 5.5.

In the left graph of figure 5.5 the individual discrimination thresholds (JNDs) are shown. To test whether there was a significant difference in discrimination performance between experiments 1 and 2, we conducted an unpaired t-test over the pooled data ($N = 24$) of conditions B, C and D from Experiment 1 (which were not significantly different from each other) against the pooled data ($N = 15$) of Experiment 2. This showed that discrimination was significantly better in Experiment 1 ($\sigma_{mean} = 0.46\ \mathrm{m}^{-1}$) than in Experiment 2 ($\sigma_{mean} = 0.79\ \mathrm{m}^{-1}$): $t_{37} = -3.35$, $p < 0.005$.

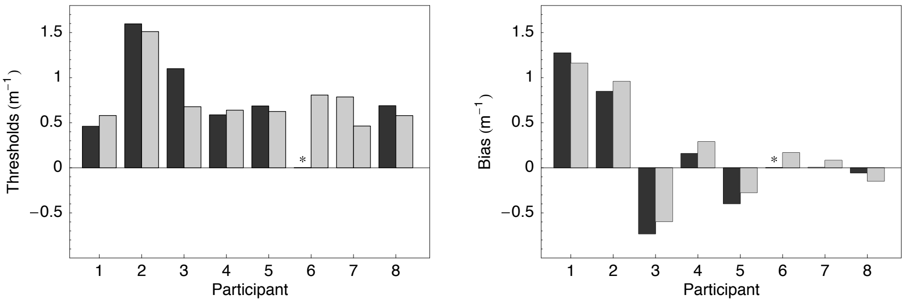

Figure 5.5: Left graph: discrimination thresholds (JNDs) per condition per participant. Right graph: the biases (PSE's). The dark grey lines denote the conditions in which both height and orientation were available, the light grey lines denote the orientation-only condition. The $\star$-sign indicates the data that were omitted, see text for details. The participants were ordered alphabetically.

As can be seen in the left graph of Figure 5.5, there does not seem to be any systematicity in the biases except a clear consistency within participants across conditions. The differences between conditions were equally balanced: half of the participants (excluding participants 6 and 7) showed positive biases for both conditions whereas the other half showed negative biases. The consistency was further supported by a high correlation between the two conditions ($r^2 = 0.99$, $p < 0.0002$). It is also important to note that all biases were well above the -2 m^{-1} level. This level indicates the point were a rendered shape would feel flat in comparison to a real shape of curvature 2 m^{-1}.

5.3.3 Discussion

This experiment shows that adding zeroth order shape to the geometry does not influence the subjective curvature perception. Irrespective of the experimental condition, the observers did not systematically judge a rendered shape to have higher or lower curvature than a real shape. Furthermore, we found that the thresholds in Experiment 2 were significantly higher than Experiment 1. In the second experiment the observers had to compare two different stimuli (rendered vs. real) and in Experiment 1 the comparison was always performed for two similar stimuli. As hypothesised, it is more difficult to compare two shapes made from different material, than shapes made from similar material.

5.4 General discussion

Our experiments clearly show that first order shape information dominates haptic perception of curvature. This is in line with the study of Pont et al (1999) who proposed that the attitude difference (the change in contact area orientation) is the effective stimulus of a curved surface. The results also confirm and extend the findings of Dostmohamed and Hayward (2005). However, it could well be that first order dominance only applies for a certain movement range. Our research and that of Pont et al (1999) only investigated shapes within one order of magnitude, around 10 cm. Maybe for other orders of magnitude, the effective stimulus is not the orientation difference. Louw et al (2000) performed an extensive study on the detection thresholds of Gaussian profiles in a range of four orders of magnitude. The widths of the Gaussian shapes ranged from 0.15 mm to 240 mm, the latter resulting in a total stimulus length of 900 mm (since the stimulus itself should be longer than the Gaussian width). Although different sensory mechanisms are almost certainly to be recruited for the different shape scales, they found a single power law describing the thresholds as a function of stimulus width. Whereas Louw et al (2000) defined the scale by the (Gaussian) width of the stimulus, we will use the word scale, or rather movement range, to denote the lateral movement of the fingertip. This difference in definition becomes important later when we want to compare the data of Louw et al (2000) with our theoretical predictions. We will now show that the first order cue is dominant over a large range with respect to human movement limitations.

The stimuli used in our experiment can be characterised with two parameters. These parameters can be any combination of the four parameters relevant to our problem: the curvature c, the mid-height h, the orientation α and the horizontal position x. They are related through the equations $2hc = (xc)^2 + 1$ and $\sin(\alpha) = xc$. The exploration range is between $x = -d/2$ to $x = d/2$ and the total orientation difference is the change of α over this range. Using these equations we can express a threshold σ_c as an equivalent height threshold σ_h or orientation threshold σ_α. Pont et al (1999) measured curvature discrimination thresholds for various exploration lengths between 5 and 20 cm. They plotted the thresholds expressed with different quantities and found that the threshold expressed in orientation difference, σ_α, was invariant with respect to the exploration range d. This finding led them to conclude that orientation difference is the effective source of information for curvature. However, their model does not take into account that we can also statically discriminate curvature, namely with a second order shape cue, which was shown by Goodwin et al (1991). Because the model of Pont et al (1999) cannot account for the extreme case of $d = 0$, the question rises in which movement range their model holds.

To generalise this model, we propose that the information derived from the three shape descriptors varies in dominance across the movement range. The construction of this model is illustrated in Fig. 5.6. The rows represent the threshold of each shape

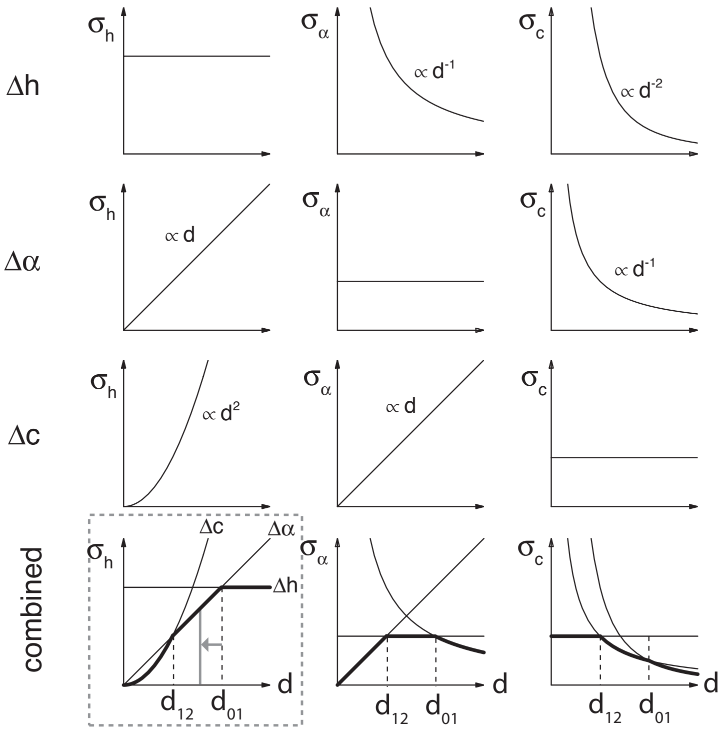

Figure 5.6: Qualitative explanation on how the different geometric information sources can be expressed with different quantities, and vary with scale. See main text for further explanation. In the bottom row the three threshold dependencies are superimposed. d_{12} and d_{01} mark the movement ranges where two cues indicated, by the indices, are equally dominant. The thick line shows the threshold dependency if the most dominant cue is selected.

descriptor where Δ means the just noticeable difference of height, orientation or curvature. The columns are the different quantities in which the individual thresholds can be expressed. Whereas Pont et al (1999) could only use thresholds for which all cues were available, Experiment 1 together with the data from Goodwin et al (1991) provide us with the isolated thresholds per shape descriptor. These isolated thresholds can be compared by expressing them with the same quantities. As can be seen in Fig. 5.6, they depend on the movement range. For example, the height threshold Δh, expressed in terms of orientation difference decreases with respect to d. On the other hand, the orientation threshold $\Delta\alpha$ expressed in height increases with increasing d.

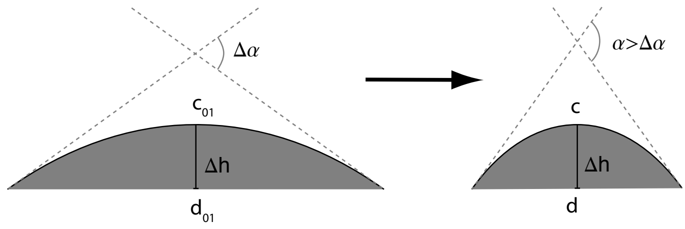

Figure 5.7: Left: illustration of the construction of a stimulus that should be equally well discriminated on the basis of two different geometric cues. Right: for $d < d_{01}$ the curvature c is adjusted to keep the shape at height threshold Δh which means it is above the orientation threshold $\Delta\alpha$.

The next step is to look at what exploration ranges the isolated thresholds are equal. An example of a shape equally well discriminated by the zeroth and first order threshold is depicted in Fig. 5.7. The curvature c_{01} and the range d_{01} specify the shape that is at threshold level for zeroth and first order shape cues. If the movement range would decrease, the shape specified by the height threshold would be above threshold for the orientation cue. On the other hand, if the movement range would increase (not illustrated) the shape specified by the height threshold would be *below* the threshold for the orientation cue. This is also illustrated in Fig. 5.6 in the dashed box at the left bottom: if the range d gets smaller than d_{01}, the first order threshold gets smaller and thus more dominant than the zeroth order threshold, as indicated by the grey line. If the range d would get larger than d_{01} the zeroth order threshold would dominate. It can also be seen that each shape cue is dominant in a different movement range, separated by d_{12} and d_{01}.

Based on our data of the isolated zeroth and first order thresholds and the second order threshold measured by Goodwin et al (1991), we calculated the parameters d_{12} and d_{01} to be 1.2 cm and 78 cm, respectively. This indicates that according to our and Goodwin's data, the orientation cue is dominant in a very large range with respect to the human body: from fingertip size up to maximal arm movements . It also shows that zeroth order information is not used since the range in which this information gets dominant lies outside the limits of human arm movements. This means that only first and second order shape contribute to the human ability to perceive a non-flat shape. It effectively means that the model of Pont et al (1999) holds for movements larger than 1.2 cm.

The superposition of geometric thresholds as shown in the bottom row of Fig. 5.6 is not yet a model since we do not know how these cues combine. A simple model would be to assume that the most dominant cue is selected, which is shown by the thick line.

To better understand the behaviour of curvature thresholds on different exploration ranges we have plotted values from literature in Fig. 5.8. The plot is similar to the combined thresholds from Fig. 5.6 expressed in units of curvature. The straight lines are the three isolated geometric thresholds that follow from our and Goodwin's data. They are not fitted, but specified by a single threshold. The data from literature were grouped into 'full-cue' conditions and 'height/position only' conditions. The former group consists of experiments performed with real stimuli, the latter were performed with robotic interfaces that only provided position cues and not local surface orientation cues. The first thing to note is that the slope of the full cue data is similar to the orientation threshold, although shifted downward. Since our model is only based on geometric cues, this shift could reflect the use of non-geometric cues by humans exploring real surfaces. For example, it is known that force acts as a cue for shape (Robles-De-La-Torre and Hayward, 2001; Drewing and Ernst, 2006).

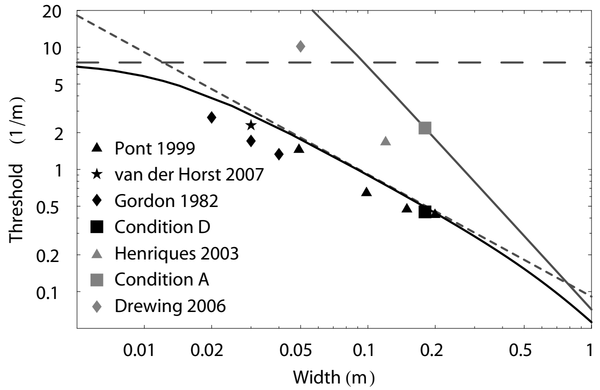

Figure 5.8: The geometric cue dominance model based on the thresholds that were found in Experiment 1 and Goodwin et al. (1991). The grey lines indicate the individual threshold characteristics for zeroth order (long dashes), first order (short dashes) and second order (continuous) shape. The values from literature were all converted to 84% thresholds described in units of curvature. The grey points indicate thresholds that were obtained in experiments where only zeroth order information was available to the participant. The black line gives an impression of the prediction based on cue integration.

Furthermore, it can be seen that stimuli of which only zeroth order information is rendered, yield consistently higher thresholds than real shapes. There is a difference between the threshold from our experiment 1A and the experiments from Drewing and Ernst (2006) and Henriques and Soechting (2003). Although the two values from literature together show a slope that would be predicted, they lie below the threshold found by us. A possible reason for this is that these two studies both used a manipulandum which was held by the whole hand. It is likely that observers are better in discriminating shapes when the whole hand is used to encode positional information, than when only the tip of the index finger is used, as in our experiment.

From Fig. 5.8 it can be seen that we can only speculate on how the cues are combined, since no data is available to verify the behaviour outside $[d_{12}, d_{01}]$. We have plotted a speculative model (black) which is the combined cue according to $\frac{1}{\sigma^2_{comb}} = \sum \frac{1}{\sigma^2_i}$. As can be seen, the predicted bends that mark the ranges where other shape descriptors become dominant cannot be verified.

Although it is difficult to compare, our model is qualitatively in line with the findings of Louw et al (2000). They found that the increase of detection thresholds with increasing Gaussian stimulus width was described by a power law. The fitted coefficient was approximately 1.3 which means that the relevant geometrical information is mostly first order (predicted coefficient=1) and to a lesser extent second order shape (predicted coefficient=2). Our model also predicts that haptic shape discrimination depends only on the first and second order cues, where the first order cue is the most dominant.

We have used a model that is based only on geometry as a framework to interpret data from literature and our experiment. We do not suggest that each geometric cue is independently processed by the central nervous system. For example, orientation can either be cutaneously encoded by the location of the contact area, or kinaesthetically by the orientation of the hand that is keeping the finger orientation constant with respect to the surface. What makes this model relevant is that it clearly shows that the range in which the orientation cue is dominant is relatively large and that the orientation cue largely accounts for the data found in literature. This makes our results relevant to future research into cue integration mechanisms: *one should be cautious that the orientation cue dominates the position cue on almost the whole range of human arm movements.* Another aspect that is suggested by our model and the literature is that there may be non-geometric cues important for haptic shape perception. Experiment 2 shows that real and rendered curved shapes are perceived differently, but not systematically. The individual differences could be caused by differential use of slip information between participants. As was shown by Pont et al (1999), the curvature of a stimulus explored over a small range is underestimated with respect to the curvature of a wide shape. If some participants used slip to estimate exploration length, this could induce curvature biases.

With respect to the design of shape simulating interfaces the message is unequivocal: perceptual sensitivity is dramatically better when contact location orientation is available. This idea has already been successfully put in practice (Provancher et al, 2005;

Solazzi et al, 2007). Not only does the addition of first order information improve discriminability, more importantly it evokes the subjective experience of feeling a curved surface as we have shown in our second experiment. For relatively flat surfaces, our data even suggest that the designer might as well leave out the zeroth order information since the biases found in Experiment 2 were very similar for shapes rendered with and without this information. Also, psychophysical experiments investigating haptic perception of shape should either be performed with real shapes, or with shapes of which at least the surface orientation is simulated. The use of haptic interfaces that provide only zeroth order (positional) information should be reconsidered. Although previous studies such as Henriques and Soechting (2003) give good insight into motor planning and control, the data do not reflect the biases and sensitivity of haptic perception of *shape*.

Chapter 6

Haptic curvature contrast

M.W.A. Wijntjes and A.M.L. Kappers (to be submitted).

Abstract

It is well known that our senses are influenced by contrast and aftereffects. For haptic perception, the aftereffect is well studied whereas little is known about perceptual contrast. In this study we show that haptic curvature perception is strongly influenced by contrast effects. When observers explore a straight and a curved shape simultaneously, the straight shape feels curved in the opposite direction. Surprisingly, this is true for both two-dimensional shapes (raised lines) and three-dimensional shapes (solid shapes). By measuring various dynamical features of the exploring hand, we investigated whether biomechanical constraints of the hand could have caused this effect. Although we did not find any evidence that biomechanical constraints cause the contrast effect, we found evidence that different mechanisms mediate curvature perception when two shapes are felt than when one shape is felt.

6.1 Introduction

The human perceptual system is better in detecting differences than in estimating absolute values. For vision, this is shown by the vast amount of illusions that depend on the interaction of the surround with a target such as the Hering and Ebbinghaus illusions. Gibson (1933) showed that a straight line surrounded by curved lines is visually perceived as curved in opposite direction (see Fig. 1.3). Because the surround (curved lines) and the target (straight line) are present simultaneously this was named "simultaneous contrast". Gibson (1933) also showed that a similar bias was present when the contrast was successive, also known as the visual "curvature aftereffect". During these visual experiments observers wore prism glasses that curved all vertical lines in the environment. Some observers noticed that the induced curvature seemed to affect their haptic perception of straightness. To investigate whether the same curvature aftereffect was present in the haptic modality, Gibson (1933) let observers haptically adapt to a convex stimulus and subsequently touch a straight stimulus. All observers reported that the straight stimulus felt concave. Whereas successive curvature contrast was shown to be present in both modalities, simultaneous curvature contrast was only investigated for vision. This asymmetry has persisted up to date. Whereas the visual curvature contrast- and aftereffect (e.g. Crassini and Over, 1975) as well as the haptic curvature aftereffect (Vogels et al, 1996) have been further investigated, no attention has been given to simultaneous contrast effects for the haptic modality. In the present study we investigated the influence of a curved 'surround' on a straight target.

To understand whether visual illusions are modality specific, their haptic counterparts have been studied extensively. An early attempt was undertaken by Robertson (1902) who found that the Müller-Lyer illusion showed a similar bias in touch as in vision. She also found an illusion that seemed (at that time) exclusive for the haptic modality. When a shape consisting of a half-circle with both ends connected by a straight line (like the capital letter D) was explored with the whole hand, the straight line seemed to be curved outward. Although she did not systematically investigate and quantify the effect (the data consisted of sketches), she was the first to report an example of haptic curvature contrast. In the current study we wanted to systematically measure the effect but also extend it to stimuli that are more natural for the haptic modality. The material used in the study of Robertson (1902) and further studies on geometrical haptic illusions (e.g. Revesz, 1934; Suzuki and Arashida, 1992; Heller et al, 2002b) consisted primarily of embossed lines, because in this way the haptic and visual stimuli are similar. However, in daily life the haptic sense is not often confronted with two-dimensional stimuli. It has been shown extensively in the literature that identification of (raised) line drawings is dramatically more difficult with touch than with sight (e.g. Lederman et al, 1990; Wijntjes et al, 2008b) whereas haptic identification of 3D objects seems to go without effort (Klatzky et al, 1985). Two-dimensional stimuli are thus more valid for vision than for touch. Sensory illusions give valuable insight in the (mal)functioning of perception. Haptic perception of two-dimensional patterns is likely to be different from perception of three-dimensional stimuli. Therefore, haptic illusions are less valuable than their visual counterparts if only measured with 2D stimuli.

In the present study we used both two- and three-dimensional stimuli to investigate the existence of curvature contrast. Observers had to explore two shapes, called 'reference' and 'test' stimulus, with two fingers of the same hand. The reference stimulus was either straight or curved (4 m^{-1}), and served to be the analogue of the surrounding curvature in visual experiments. The curvature of the test shape was varied using a

2AFC task to determine the Curvature of Subjective Straightness (CSS), analogous to the Point of Subjective Equality (PSE).

We hypothesised that a curvature contrast is at least present in the two-dimensional stimuli, since Robertson (1902) already found some evidence. This curvature contrast would be shown by a shift of the CSS towards the curvature of the reference shape, or stated equivalently, a straight test shape would feel oppositely curved with respect to the reference shape.

We also compared the slope of the psychometric function (the JND) besides the CSS. We hypothesised that the JND would be smaller for three- than for two-dimensional shapes, because a three-dimensional shape can be more easily explored by the hand (see Fig. 6.1). This can be understood by considering that errors in exploring raised lines can go either way of the line, whereas the surface of a solid shape only permits errors in losing contact in the direction of the normal.

In the first experiment we tested these hypotheses. We also measured the relative movement of the exploring fingers with respect to the hand. In the second experiment we tested the generality of the findings by using a different exploration strategy and a different stimulus configuration. In that experiment we also performed movement measurements which we directly related with the responses to investigate the influence of biomechanical constraints on the contrast effect.

6.2 Experiment 1: Thresholds and biases

In the first experiment we measured curvatures of subjective straightness (CSS) in case of straight and curved reference stimuli. We used a hybrid form of the staircase method and the method of constant stimuli to measure the psychometric curve.

6.2.1 Methods

Participants

Eight right handed observers volunteered to participate in the first experiment. They were paid for their participation and were naive with respect to the purpose of the experiment.

Material

For the 2D stimuli we used raised lines produced with Zychem swellpaper, which is often used for tactile pictures and maps for the blind. Raised line stimuli were printed upon the paper after which it was threaded through an infrared heater. The black lines of the print absorb the radiation and the microcapsules of alcohol embedded in the paper burst and make the black parts embossed. We printed 1 mm wide lines which resulted in an embossed height of approximately 0.5 mm. To render the two-dimensional stimuli we plotted circular arcs with the software package Mathematica. Each stimulus consisted of two lines: a reference curvature which could either be straight ($C_r = 0\ \mathrm{m}^{-1}$) or curved outwards ($C_r = 4\ \mathrm{m}^{-1}$) and a test curvature that differed from the reference in steps of $0.2\ \mathrm{m}^{-1}$. The distance between the endpoints of a line was 20 cm, irrespective of the curvature. The distance between the end points of the reference and test stimulus was 5 cm. The raised line stimuli were placed in a stainless steel holder which blocked lateral movement.

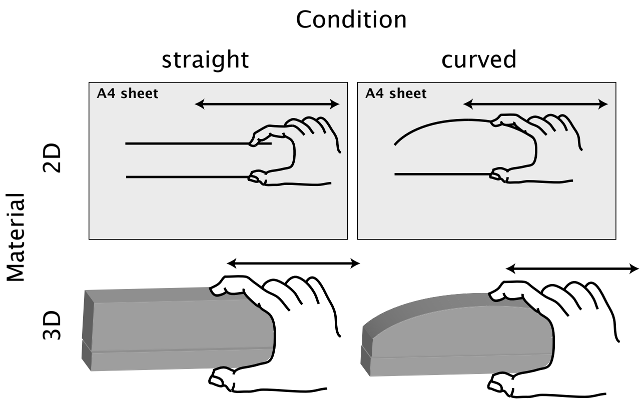

Figure 6.1: Scheme of the different stimulus materials and experimental conditions. The shape at the index finger is the reference stimulus that is either straight or curved. On the thumb a test stimulus was presented that varied in curvature. Observers were instructed to attend to the shape on their thumb and judge the direction of that curvature.

The three-dimensional stimuli were made from PVC. The dimensions of these solid shapes were the same as for the raised lines except that the endpoint distance for the straight reference of the solid shapes was 8 cm instead of 5 cm. Furthermore, the solid shapes were 2 cm thick. These stimuli have been previously used and described by Pont et al (1999). The solid shapes were placed in moulds made of cardboard in which they were fixated. Fig. 6.1 shows the two kinds of stimuli and the two kinds of reference shapes.

Procedure

Participants were seated on a chair and were visually shown example stimuli while the experimenter explained the task. A sheet was attached between the neck of the participant and two approximately 1 meter high poles that were standing on the table, as can be seen in Fig. 6.2. The purpose of the sheet was to block vision of the stimuli while the participant could use a computer to respond.

In all conditions, the participants had to explore both curves simultaneously (see Fig. 6.1). The exploration started on the left and comprised of two full cycle movements. The subjects were instructed to keep both index finger and thumb on the line or surface. The index finger was always touching the reference stimulus, and the thumb the test stimulus. The task was to attend to the curvature they felt on their thumb and judge the sign of that curvature. To overcome possible confusion about the words normally used for the curvature sign, i.e. convex and concave, we graphically presented two choices on a monitor. In Fig. 6.2 an example instance is shown: after the participant has felt a stimulus with a curved reference, he or she needs to decide whether the curvature felt with the thumb was curved away or towards the observer. The reference stimulus shown on the screen (the top curves) was similar to the reference stimulus they had just felt, straight or curved. The choices appeared on the screen after the exploration was finished. The order of the two choices was randomised. The participant had to respond by pressing with the left hand the left or right arrow on a keyboard. The key press was registered and a software program provided the experimenter with information about the next stimulus value to present. The software was written in Matlab, using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997)

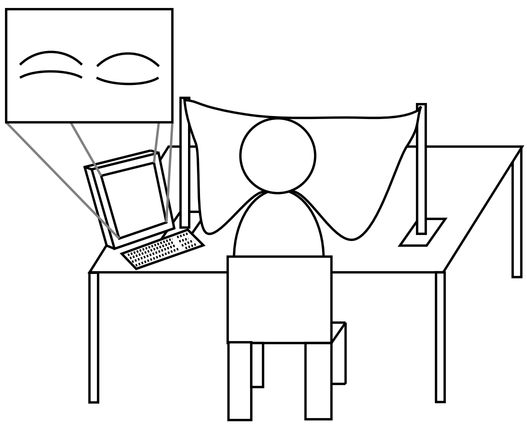

Figure 6.2: Observer during the experiment, viewed from behind. On the other side of the table the experimenter was situated (not depicted) who presented the haptic stimuli. The observer could see the monitor but not the haptic stimuli. The test stimulus on the left is defined to have a *positive* curvature.

In Fig. 6.1 the experimental design is illustrated. The design with respect to stimulus materials was blocked whereas the curved and straight reference conditions were mixed. The order of the blocks was counterbalanced among participants. Each block consisted of 3 separate sessions. In Fig. 6.3 the data collection procedure is illustrated. In the first session a 1-up-1-down staircase procedure was used to estimate the CSS. For each reference (straight and curved) a staircase started at both $+1.4\ m^{-1}$ and $-1.4\ m^{-1}$. Thus, 4 staircases were running simultaneously which were selected randomly per trail. Each staircase consisted of 20 trials. An example of staircase data for a curved reference stimulus can be seen in Fig. 6.3 A. The staircase data were transformed to psychometric data which can be seen in Fig. 6.3 B. In that figure the number of actual repetitions per test curvature is shown (light grey bars). The psychometric data were fitted to a cumulative Gaussian with the maximum likelihood estimation in which the binomial distributions per data point were taken into account (Wichmann and Hill, 2001a). From this fit the bias (CSS) and the 84% thresholds (JND) are estimated. The bias is the estimated stimulus intensity for which the mean responses are 50%. With the estimate of the CSS of each individual subject, a method of constant stimuli was designed around this point. The repetitions per test stimulus were chosen such that the total number of repetitions for the first and second session added up to 10. The additional trails are illustrated by the dark grey bars in Fig. 6.3 B. The psychometric function was fitted to the data that were taken together from the first and second sessions, as illustrated in 6.3 C. The data in the figure are from a condition in which the reference stimulus was curved. We defined a positive curvature to point in the direction of reference stimulus, i.e the left stimulus in Fig. 6.2. This is important to remember because in case of the solid shapes, this means that a positive value is assigned to a concave curvature. The example shows that if a test stimulus has a certain curvature in the direction of the reference stimulus, it is perceived as straight. Equivalently, it means that a straight line feels curved away from the reference stimulus.

The third session of a block consisted of kinematic measurements of the hand using an Optotrak Certus system (NDI, Waterloo, Ontario). The reason for this measurement was to gain insight in how the index finger, thumb and metacarpus (the hand region connecting the fingers and thumb) are moving with respect to each other. We were interested in whether the position of the metacarpus followed an intermediate curved trajectory or that it followed either that of the index finger or the thumb. To measure this we placed three sensors on the hand: one on the index finger, one on the thumb and one on the metacarpus. We measured 20 trials, 10 per reference stimulus, 2 repetitions for each of the five test stimuli which were distributed around zero in steps of $0.8\ m^{-1}$ and $0.6\ m^{-1}$ for the raised lines and solid shapes, respectively. We instructed the participants that it was a similar experiment and that they had to respond verbally because this measurement took place in a different location where the setup used for sessions 1 and 2 was not available. We recorded the position of the sensors with a sample frequency of 100 Hz. The responses were not further analysed.

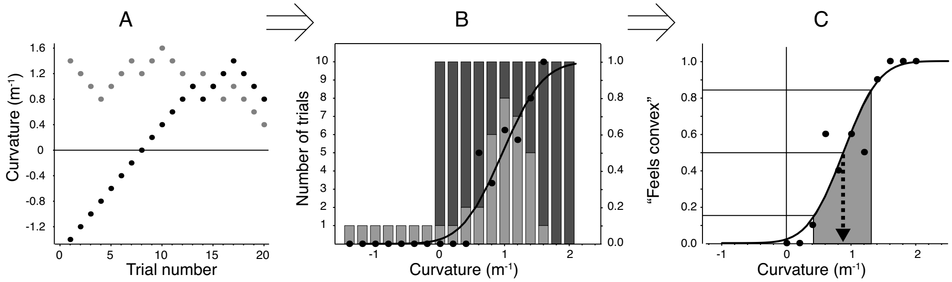

Figure 6.3: A: Raw data of a 1-up-1-down staircase used to estimate the CSS. B: The staircase data converted to psychometric data. The light grey bars denote the repetitions from the staircase. The dark grey bars denote the number of repetitions used to measure the remaining trials in the second session. C: From the final data the Curvature of Subjective Straightness (dashed arrow) and the Just Noticeable Difference (half of the width of the grey area) were extracted.

Data analysis

We fitted the psychometric data using the maximum likelihood estimation model as described in Wichmann and Hill (2001a). To estimate the variability in the parameters we used bootstrap simulations as described in Wichmann and Hill (2001b). We defined curvature contrast as the difference between the biases for straight and curved reference shapes: $\mu_{contrast} = \mu_{curved} - \mu_{straight}$. From the bootstrap simulations 95% confidence intervals were calculated. The resulting confidence interval of the curvature contrast was then calculated from the two bootstrap variabilities: $\Delta\mu^2_{contrast} = \Delta\mu^2_{curved} + \Delta\mu^2_{straight}$. We calculated per subject whether the resulting 95% confidence interval enclosed zero, in which case the curvature contrast effect would not be significant.

For the statistical group analysis we used a 2-by-2 repeated measures ANOVA. The factors were reference stimulus and stimulus material. The thresholds and biases were analysed separately (univariate analysis) since no correlation was found between them.

The Optotrak data were fitted to parabolas of the form $\frac{1}{2}c(x-a)^2 + b$ in which a and b are translation parameters and c is for small ranges approximately equal to the curvature. We only analysed the curvature parameter and compared these with respect to the stimulus values.

6.2.2 Results

Response analysis

The average values (and standard errors) of the thresholds and biases for all conditions are plotted in Fig. 6.4. As can be seen, the discrimination thresholds (JND's) for raised line stimuli are larger than for solid shapes. This is confirmed by the ANOVA which showed a significant main effect of stimulus material ($F(1,7) = 10.9$, $p = 0.013$). There was no significant main effect of reference stimulus ($F(1,7) = 0.8$, $p = 0.4$) but the interaction between stimulus material and reference stimulus was significant ($F(1,7) = 8.8$, $p = 0.021$). This interaction reflects that for solid shapes the JND is more influenced by the reference stimulus than for raised lines.

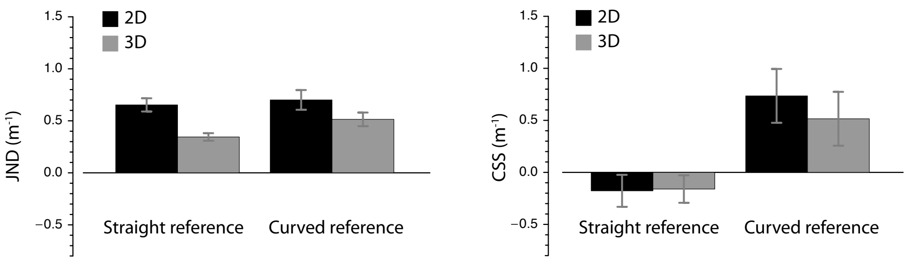

Figure 6.4: Average data of the JND and CSS, averaged over subjects. Error bars denote standard errors.

On the right hand side of Fig. 6.4 the CSS is plotted, the parameter that indicates the existence of haptic curvature contrast. The CSS is clearly affected by the reference stimulus. In the curved reference condition the test stimulus should be curved in the direction of the reference to be perceived as straight. Equivalently and possibly more intuitive, if the test stimulus is straight it is perceived as being curved oppositely to the reference curvature. The ANOVA confirmed that the main effect of reference was significant ($F(1,7) = 18.293$, $p = 0.004$). Furthermore, neither the factor material ($F(1,7) = 0.6$, $p = 0.470$) nor the interaction ($F(1,7) = 3.0$, $p = 0.128$) were significant.

We were also interested in the individual contrast effects. In Fig. 6.5 the individual contrast effects $\mu_{contrast}$ are plotted. The error bars denote the 95% confidence intervals, which only enclosed zero for participant 8. Thus, for seven subjects the individual data showed a significant curvature contrast effect. Furthermore, we correlated the 16 biases from the raised lines with the 16 biases from the solid shape condition and found a high correlation ($r = 0.82$, $p < 0.0001$).

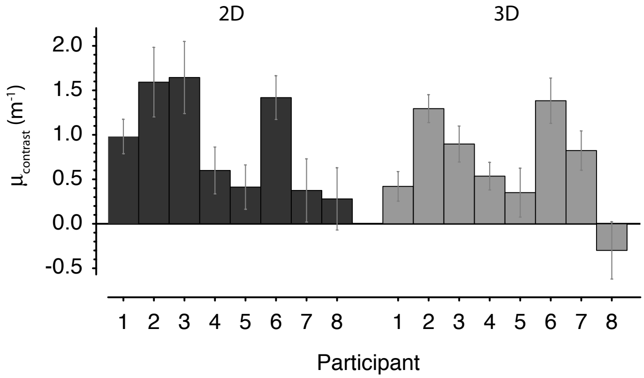

Figure 6.5: Individual biases plotted per reference shape. Error bars are 95% confidence intervals from bootstrap simulations.

Movement analysis

From the movement data we calculated the curvature of the paths taken by the thumb, metacarpus and index finger. Ideally, the curvature of the thumb path would be identical to the curvature of the test shape and the index finger path would be identical to the curvature of the reference shape. As can be seen from Fig. 6.6 this is roughly the case. Each triplet of bars denotes index finger, thumb and metacarpus, respectively. As can be seen, the average hand position represented by the metacarpus movement follows an intermediately curved path with respect to both fingers. This is especially clear in the movement data for the curved reference stimulus. Furthermore, it can be seen that the thumb follows the test stimulus path in a linear fashion.

6.2.3 Discussion

The main results show that haptic perception of curvature is subject to contrast effects. We found that curvature contrast is present for both two-dimensional and three-dimensional stimuli. The question arises whether the origin of the contrast effect is peripheral or central. It has been shown that the haptic after effect seems to be of central origin Vogels et al (1997). However, it remains to be seen how much successive and simultaneous haptic contrasts have in common. With simultaneous curvature contrast the finger exploring the reference shape can directly influence the finger exploring the test stimulus. The biomechanical constraints of the hand make simultaneous contrast a likely candidate to be partly of peripheral origin. We will discuss three possible explanations based on the role of biomechanical constraints. These explanations are not mutually exclusive and could in principle all be true.

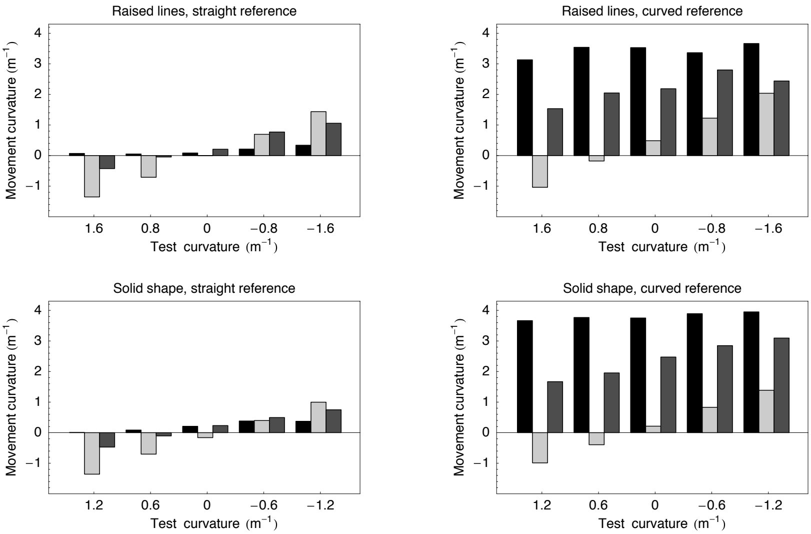

Figure 6.6: Movement curvature for the index finger (black), thumb (light grey) and metacarpus (dark grey) as a function of stimulus curvature. On the left the reference shape is straight as can be seen by the straight (no curvature) path of the index finger. On the right the index finger follows the curved reference. The thumb follows the test stimulus and the metacarpus seem to follow an intermediate path.

Firstly, when the index finger runs over a curved reference, the thumb is pulled towards the reference. In case of the raised line stimulus, this can cause a displacement of the thumb as illustrated in Fig. 6.7 A. The hypothetical path of the thumb is denoted by the grey dashed line. Whereas this path is curved, this may not be detected by the kinaesthetic sense. It has been shown in chapter 5 that curvature thresholds are in the range of 2 m^{-1} when only positional information is present. The local displacement of the line on the finger can induce a curvature percept, as illustrated on the right side of Fig. 6.7 A.

Secondly, the local line orientation on the thumb may be influenced. As participants reported, they sometimes had the feeling that they turned their hand such that the index finger was aligned with the reference stimulus. This would mean that the thumb also rotates, as is illustrated in Fig. 6.7 B. The shape that would satisfy this local orientation function (the spatial derivative) is shown on the right hand side in Fig. 6.7 B. Again, this shape has the same direction as the contrast effect.

Thirdly, the force exerted by the fingers to maintain contact with the solid shape can cause illusory curvature perception. It is known that the motor system behaves like

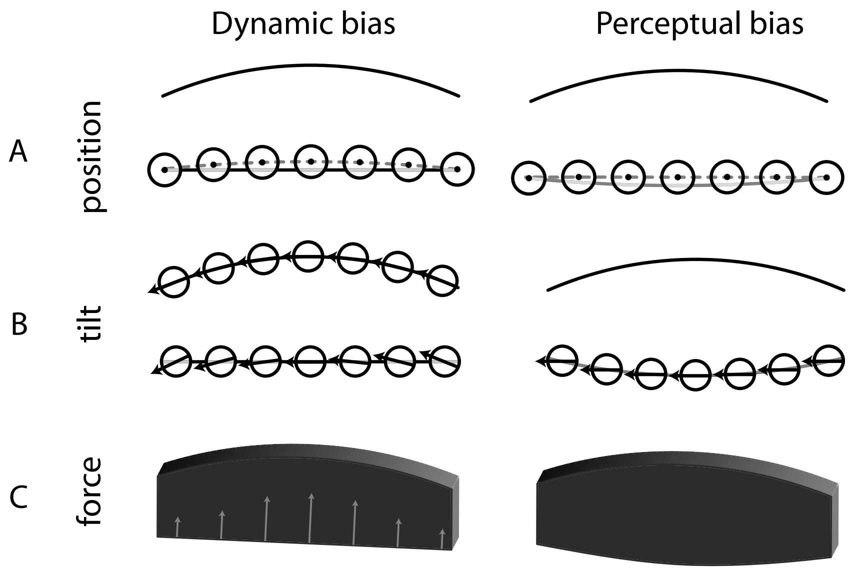

Figure 6.7: Possible biomechanical constraints responsible for the contrast effect. A: The circle denotes the contact area of the exploring finger (thumb in case of Experiment 1), the path of the contact area is distorted as depicted. B: The finger on the test stimulus follows the direction of the reference stimulus (i.e. the whole hand is rotated during the movement as to align the index finger with the reference).C: For the 3D stimuli, a force field in the normal direction can be generated by the mechanics of the hand.

a spring (Feldman, 1986). This can lead to a changing normal force on the fingers when exploring a stimulus with a curved reference, as illustrated in Fig. 6.7 C. It has been shown that force fields are used to infer shape (Robles-De-La-Torre and Hayward, 2001). As illustrated on the right hand side of Fig. 6.7 C, the normal force would elicit a convex shape, the same direction as the contrast effect. Whereas the first two explanations can only hold for raised lines, the third explanation can hold for both materials. However, a lateral force exerted on a raised line is difficult to measure.

6.3 Experiment 2: Biomechanical constraints

In this experiment we addressed the role of biomechanical constraints for curvature contrast. We measured the distortions in position, tilt and force and analysed whether either of these three dynamic characteristics could predict the response of the observer. Observers do not have difficulty (although their judgement may be completely unveridical) with a 2AFC task when the stimulus value lies far outside the JND range. Since we wanted to relate responses to dynamic characteristics, it is necessary that these responses show some variability, i.e. are equivocal. To establish this we used a rather long staircase method, that was estimated to arrive at the CSS after approximately half of the trials. In the second part of the trials, the variability of the responses is the largest and would thus give us the best opportunity to relate them to movement characteristics.

Besides studying the role of biomechanical constraints, we wanted to investigate the generality of the curvature contrast effect found in Experiment 1. To do so we employed a different experimental configuration. Observers had to touch the stimulus with their index- and ring-fingers. The biomechanical constraints causing distortions in position, tilt and force are not altered by this new configuration. If we find similar contrast effects this would strengthen the generality of the curvature contrast effect.

6.3.1 Methods

Participants

Eight observers volunteered to participate in the experiment. This group was split in half, each doing either the experiment with two-dimensional (raised lines) or with three-dimensional stimuli (solid shapes). The participants were (under-) graduate students working at the same lab as the authors. They were aware of the outcomes of the previous experiment but were not explicitly informed about the purpose of the second experiment.

Materials

The same stimuli were used as in Experiment 1, although configured differently (see Fig. 6.9). The raised line sheets were rotated in the horizontal plane and the surfaces of the solid shapes were oriented upward. The end point heights of the solid shapes were 8.8 cm above the table, for both the reference and test shapes.

To measure the force exerted on the test stimulus we made use of a construction that allowed small vertical displacements of the stimulus on a spring system, which can be seen in Fig. 6.8. The parallel spring blades ensured that the stimulus would stay horizontal when pressed upon. An Optotrak sensor was attached to a plate that was fixed to the stimulus holder. The positional resolution of a sensor is 0.01 mm. The spring constant of the construction was measured to be 0.45 N/mm. We found that during a typical exploration, the force variation was maximally 0.6 N, causing in a vertical displacement of the test stimulus that was sub-threshold.

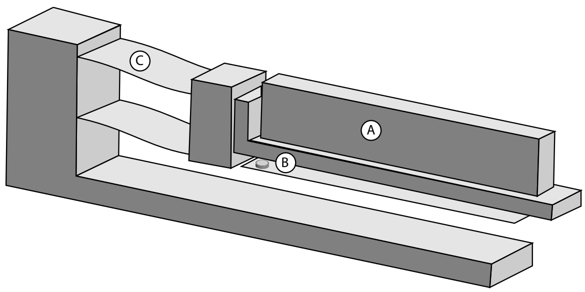

Figure 6.8: Force measurement construction. A: The test stimulus is fixed in the mould. B: An Optotrak sensor is attached to the moving part of the construction. C: Blades with a linear spring constant.

Procedure

The experiment comprised of a single session in which a mixed 1-up-1-down staircase procedure was followed. The total number of trials was 120: 60 per reference shape (flat or curved) which in turn consisted of two staircases starting at $+1.4\ m^{-1}$ and $-1.4\ m^{-1}$ of 30 trials. The subjects were instructed to explore the stimuli with their index and ring fingers, as depicted in Fig. 6.9, and move two times back and forth. The index finger touched the test stimulus and the ring finger the reference.

The response procedure was similar to Experiment 1 although in this experiment they did not view a CRT screen, but instead looked through a mirror that was halfway between their eyes and the haptic stimulus. Through this mirror they could look at a screen on which the two choices were projected. With their left hand the observers pressed keys to make a response. The observer could not see the haptic stimulus.

Four sensors were attached to the exploring hand, two on each distal phalanx. From these sensors the position and orientation of the part of the finger that was used for exploration could be calculated.

Response analysis

The staircase data were converted to psychometric data similar to Experiment 1 (see Fig. 6.3). From these data the CSS and 95% confidence intervals were calculated using the same procedure as in Experiment 1.

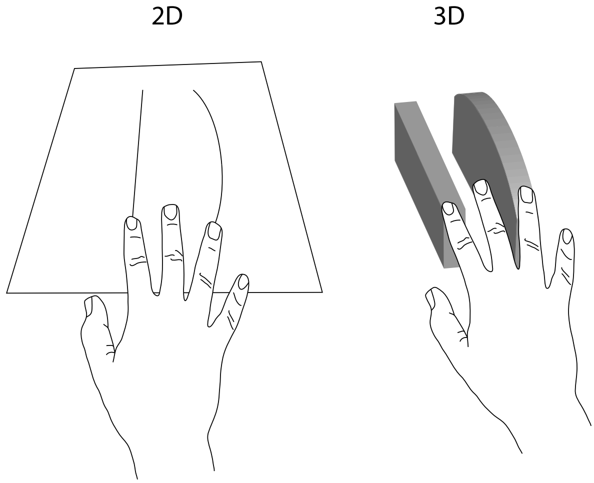

Figure 6.9: Exploration procedure and stimulus configuration of the second experiment. The observers were instructed to move back and forth two times, with their index finger on the test stimulus and the ring finger on the reference. The sheets and solid shapes were positioned on a table.

Movement and force analysis

We wanted to test the three possible explanations illustrated in fig 6.7. The first two were tested on the raised line stimulus, the third on the solid shape. We wanted to relate responses to dynamic biases and had thus to quantify the latter. For the positional bias we fitted the data to a parabola, $y(x) = \frac{1}{2}c_p(x-a)^2 + b$, where y is the deviation from a straight line, x is the position in the direction of the flat reference line and c_p reflects the curvature of the path taken by the finger. We did not fit the parameter a which was the midpoint of the stimulus. For the tilt bias we used a linear fit $\tau(x) = a_\tau x + b$. This allowed us to quantify the rate of change of the tilt (a_τ). Tilt is defined to be the angle of the contact area with respect to the stimulus, in the clockwise direction. A tilt change as illustrated in 6.7 would lead to $a_\tau < 0$. For the force bias we again used a parabola because we hypothesised that the force profile would be similarly symmetric as the stimulus, $F_n(x) = \frac{1}{2}c_f(x-a)^2 + b$, where only c_f and b were fitted and a was the midpoint of the stimulus. A force profile as depicted in Fig. 6.7 would result in $c_f > 0$.

To relate responses to dynamic biases, we grouped the dynamic parameters with respect to response and reference stimulus. We performed a 2-by-2 ANOVA on the pooled data of the last 60 trials of all subjects. For the position bias there is clearly a relation between test stimulus and bias, so we corrected for this: we calculated the difference between the test curvature and the movement curvature. As will be seen in the results, no clear relation was found between the other two dynamic biases and the curvature of the test stimuli. Therefore we performed the ANOVA on uncorrected dynamic biases.

6.3.2 Results

The perceptual biases resulting from the staircase procedure are plotted in figure 6.10. The biases are grouped with respect to the reference stimulus. As can be seen, the contrast effect is again present for both the raised lines and the solid shapes. Bootstrap analyses show that each subject showed a significant contrast effect.

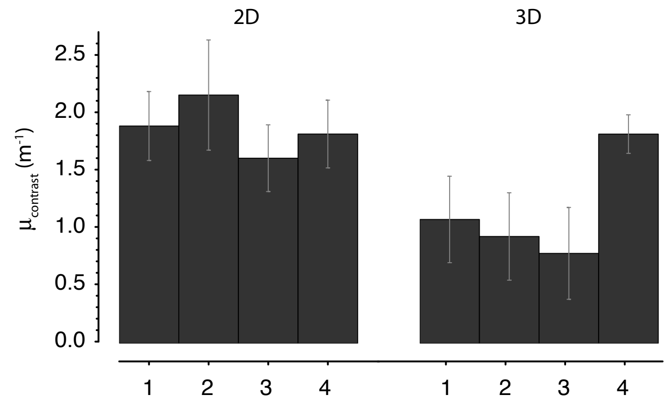

Figure 6.10: Results of experiment 2. Error bars denote 95% confidence intervals.

The average results of the dynamic bias parameters can be seen in Fig. 6.11 A, C and D. The data have been grouped in four groups: The triangles denote the averages of the curved reference data, the squares are averages of straight reference data. The important grouping is with respect to the responses. Dark grey symbols denote responses in which the observer judged the test shape to be positively curved, i.e towards the reference stimulus, which is written as "$c_t > 0$". The light grey symbols denote the opposite response. Since we analysed only the last half of the staircase data, the data are distributed around the CSS along the x-axis (curvature of the test stimulus).

In Fig. 6.11 A, the curvature of the movement (c_m) is plotted against the movement of the stimulus. The black line denotes $c_t = c_m$ and the data seem to fit this line very well. However, a clear difference can be seen between the movement curvatures for the different responses. To test whether this grouping was significant, we performed an ANOVA on the difference between the movement curvature data and the stimulus curvature, $c_m - c_t$, with Reference and Response as factors. The means are plotted in Fig. 6.11 B. The main effects of Reference ($F(1,236) = 22.3$, $p < 0.0001$) and Response ($F(1,236) = 68.4$, $p < 0.0001$) were both highly significant. Also the interaction was found to be significant ($F(1,236) = 9.8$, $p < 0.005$). A positive movement curvature means curved towards the reference stimulus. As can be seen from Fig. 6.11 B the main effect of Reference reflects what we had hypothesised (see Fig 6.7): the finger is pulled towards the curved reference stimulus. However, the main effect of Response is opposite to what we expected. If the movement curvature is positive (i.e. towards the reference curvature), observers tend to perceive it as curved in that direction. In other words, perception seems to depend on the actual curvature of the hand movement, instead of the opposite, as we hypothesised.

In Fig. 6.11 C the changing tilt is plotted. To get an idea of the unit on the y-axis: 0.2 radian per meter equals 2.3 degrees per 20 cm (stimulus length). It can be seen that the tilt change is fairly constant and near zero for the straight reference, whereas the tilt changes for the curved reference seem to follow some nonlinear trend. An ANOVA on the data only revealed a significant effect of Reference $F(1,236) = 6.0$, $p < 0.05$), reflecting that the curved reference on average shows more negative tilt change. As can be seen in Fig. 6.11 C, the triangular data points denoting the curved reference show a nonlinear trend in combination with a consistently appearing difference between the responses. In almost all pairs, the response "$c_t < 0$" (curved away from the reference) is associated with a more positive tilt change. Whereas this response is in the direction of the curvature contrast, the positive tilt change is opposite to what we had hypothesised in Fig. 6.7.

The last dynamic characteristic is plotted in Fig. 6.11 D. The parameter on the y-axis can be read as 100 times the force difference between the mid and end points: on average the force in the middle of the stimulus was 0.4 N higher than at the end points, as can be deduced from the formula we used for the fitting. As can be seen, all force parameter are negative. This mean that the force profiles were convexly shaped. Although this direction would have been predicted in Experiment 1 (as seen in Fig. 6.7), in the second experiment we used a different stimulus configuration (Fig. 6.9) and thus hypothesised a different force profile. The ANOVA did not show any significant effect.

6.3.3 Discussion

The psychophysical findings strengthen the generality of the haptic curvature contrast effect. For the two-dimensional raised line stimulus, the difference with Experiment 1 was only the way of exploration. For the solid shape condition also the stimulus configuration was altered.

Although none of our possible explanations concerning the biomechanical constraints were confirmed, we did find an unexpected relation between the curvature of the movement and the response. Apparently, if the finger moves with a curvature larger

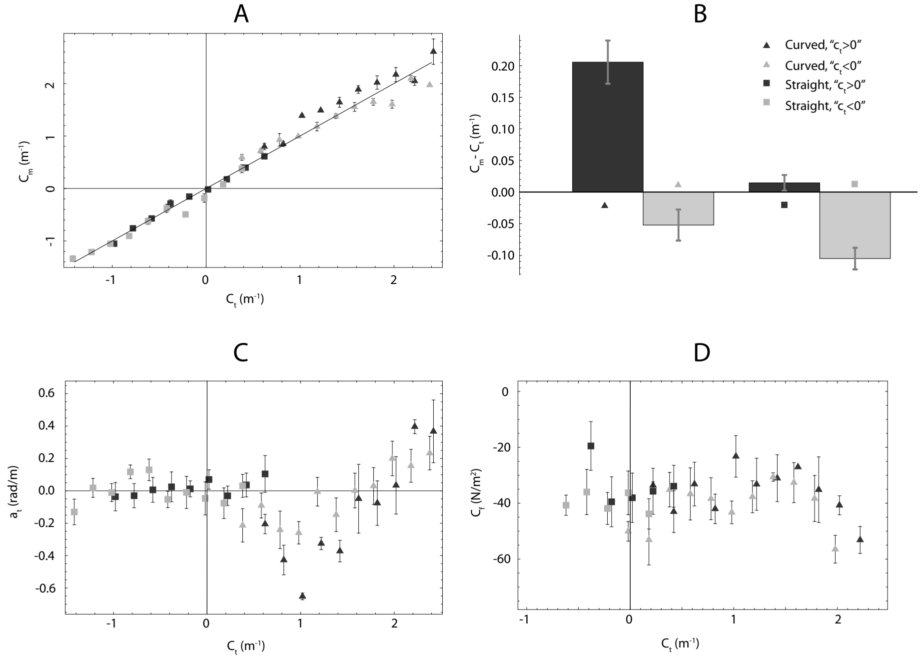

Figure 6.11: Dynamic biases overview. Errorbars denote standard deviations except B where they denote standard errors. For clarity, the data pairs per x-axis value are slightly shifted in the horizontal direction.

than the actual stimulus curvature, the stimulus is also perceived as having a larger curvature. It is important to note that this cannot explain the contrast effect. The movement curvature is generally biased towards the reference stimulus (see Fig. 6.11 B), which would predict that if an observer explores a straight test stimulus and a curved reference, the movement bias would predict that the straight line is perceived as curved *towards* the reference. This is opposite to the contrast effect in which the straight line is perceived as curved *away* from the reference stimulus.

6.4 General discussion

Our study complements the findings of Gibson (1933): visual and haptic perception are subject to both successive and simultaneous curvature contrast effects. Our experiments show that the contrast effect is clearly present in both two-dimensional and three-dimensional shapes and does not depend on a particular way of exploration. In Experiment 1, the contrast effect was as much as 20% of the reference curvature and in Experiment 2 the effect even reached 47% for the two-dimensional stimuli and 29% for the three-dimensional stimuli. Since the contrast effect reported by us has no predecessors we cannot directly compare our results with literature. However, we can compare it with the haptic after effect. Vogels et al (1996) measured the static curvature after effect using spherically curved surfaces and found that the subjective straightness was biased by about 20% of the adaptation curvature. They used different stimuli (spherically curved) and a different exploration method (static) but found an effect that was about as strong as we found. Van der Horst et al (In press) studied the dynamic after effect and used exactly the same stimuli as we did. The after effect they found was about 7% of the adaptation curvature, a substantially smaller effect than our simultaneous contrast effect.

In the second experiment we have searched for possible causes of the contrast effect. Of the three possibilities we formulated, only the force model could potentially explain the effect for both the two-dimensional and three-dimensional case. We could not find evidence that supported either of these explanations; we even found an opposite effect for one of them. These findings, together with the high correlation between the biases for raised lines and solid shapes that we found in Experiment 1 suggest that similar mechanisms underlie the contrast effects for both materials. To explain the contrast effect, we should thus look for similarities in perceiving raised lines and solid shapes.

The shape cues of the stimuli used in our experiments can be divided in positional and orientational cues: the observer receives kinaesthetic input about the trajectory of the fingers and cutaneous input about the changing surface orientation. It has been found previously that curvature discrimination thresholds are four times higher when only positional information (2 m^{-1}) is available than when only orientation information (0.5 m^{-1}) is available (Wijntjes et al, Submitted). This means that the orientation difference cue is four times stronger and is effectively the only cue for curvature, as was already proposed by Pont et al (1999).

However, it is not known whether the orientation cue is equally relevant for a two-dimensional stimulus. It is certainly possible to perceive the local orientation of the raised line by cutaneous input, but it is unknown whether this is similarly processed and weighted as the surface orientation cue in case of three-dimensional shapes. The positional (kinaesthetic) cue, on the other hand, is very similar in the two- and three dimensional shapes. Therefore, this cue seems a more likely candidate to underlie curvature contrast. But then there should be an explanation why this cue suddenly gets dominant during a haptic curvature contrast task.

A large difference between studies on haptic curvature discrimination and the present study on haptic curvature contrast, is the availability of a reference. Although the movement measurements in Experiment 2 did not explain the contrast effect, they gave us an unexpected but interesting insight. In case of raised lines, the perception of curvature is biased towards the actual trajectory described by the finger. The mean curvature difference between the different responses was not more than 0.25 m^{-1} as can be seen in Fig. 6.11 B. This value contrasts dramatically with the discrimination threshold of 2 m^{-1} found for a stimulus of which only positional information was available (Wijntjes et al, Submitted). We hypothesise that this difference can be attributed to the availability of a reference shape. If two shapes are touched simultaneously, the complexity of the kinaesthetic encoding is much reduced. Only the relative distance needs to be encoded instead of the absolute trajectory. It could be that the brain automatically changes encoding strategy when two shapes are touched simultaneously. The difference between a useful (straight) and useless (curved) reference shape can possibly not be distinguished.

We propose that for shapes simultaneously explored with one hand, the relative distance between the fingers is used as an important cue, whereas for shapes touched with one finger, the surface attitude is the dominant cue. For shape perception in general, the task of the brain is to solve the inverse problem of which shape could have caused a certain sensory signal. Since the information to solve this task is often not complete, assumptions are made that depend on the statistics of prior experience. If the brain needs to solve which shape caused two fingers to move away and towards each-other, it will choose the most likely solution: a symmetric convex shape. There is more information than the interfinger distance. The average position of the hand takes a curved path, although from Fig. 6.6 it can be seen that the curvature of this path is at the positional threshold level of 2 m^{-1} (Wijntjes et al, Submitted). Furthermore, from the attitude cue, the observer certainly knows that the curved reference is more curved than the test stimulus. All may be taken into account, but it does not solve the problem completely. The contrast effect thus results from the inability to reconstruct the absolute trajectories of the fingers and a bias towards symmetry.

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SUMMARY

In **chapter 2**, we studied what underlies angle discrimination performance for raised line stimuli and found a large dependence on how the angles are explored. For relatively small angles it is possible to move the finger between the lines along the imaginary bisector. This enhances discriminability by a factor of two with respect to a line following strategy. Furthermore we found that both the angular extent (global property) and the apex (local property) influenced how well two angles could be discriminated. We did not find an influence on whether the angle is made from a raised line or a raised surface.

As is commonly reported in the literature, identification of haptic line drawings is a very difficult task. In **chapter 3**, we started to investigate this topic by studying three subjects: picture size, hand movements and 'thinking-out-loud' data. We found that larger drawings were identified more often than small drawings. This finding has some practical relevance since many studies use rather small stimuli. It is therefore advisable for future research to increase the size of the stimuli as much as the paper allows (typically A4). Furthermore, we found that, contrary to what was previously reported by Symmons and Richardson (2000), line drawings are *not* spontaneously explored with a single finger. Instead we found that in 83% of the total exploration time two hands were used for exploration. We also found that observers used a hypothesis testing strategy. By letting them think out loud, found that on average 23% of the exploration time was used to confirm their hypothesis. It has been proposed earlier that perceptions resemble hypotheses (Gregory, 1980). It is interesting that in our case observers are literally tested hypotheses in order to perceive the drawing.

Why visual identification of line drawings is so much easier than haptic identification was studied in **chapter 4**. We found that if observers were allowed to sketch a drawing that they could not identify by touch alone, they were suddenly able to identify their own sketches in 31% of the cases. For some participants it was a startling experience: after they had haptically explored a line drawing for 45 seconds, they had no idea what it was. After they were allowed to sketch and view the result, they were surprised to recognise their own drawings. The explanation of this effect can be found in the mechanisms underlying object identification. As mentioned in the introduction of this thesis, an object can be recognised because similar objects have been experienced previously. From this previous experience an internal representation (prototype) has been built in our memory. Lederman et al (1990) proposed that at an early stage, visual

and haptic object identification are two separate processes that only share a common processing in a later stage. Both senses extract different physical properties from the environment; the structure of the representations likely reflects this difference. A line drawing is easily processed with vision, but if the input is made sequential instead of simultaneous, then identification becomes very difficult as shown by Loomis et al (1991). This is because the structure of the input has changed and cannot be used to match the internal representations. Similar to sequential vision, if a line drawing is explored by touch, then the structure of the percept is what could be called 'one-dimensional'; that is, a sequential description. Observers experience difficulty in mentally switching between these two structures. What can be done, is restructuring the representation from sequential to simultaneous by producing a sketch. This explains the recognition-after-sketching-effect.

In **chapter 5**, we studied real, solid shapes and virtual shapes generated by a robotic interface. The purpose was to study whether there were differences between the perception of real and virtual shapes and the contribution of two isolated geometric cues. As previously proposed by Pont et al (1999), we found that the surface orientation ($\mathbf{x}'(s)$ from Fig. 1.1) is a much more dominant cue than the position ($\mathbf{x}(s)$). We calculated in which regions of human arm movement each of the three cues mentioned in the Introduction is dominant and found that the orientation cue is dominant in the range from 1.2 and 78 cm. Besides measuring the discrimination thresholds, we also measured whether a virtual stimulus would feel as curved as a real stimulus. We did not find a systematic difference and even found that it did not matter whether or not zeroth order information was available when observers compared the curvedness of real and virtual stimuli.

In **chapter 6**, we studied both the perception of both raised lines and solid shapes. We found that if a curved shape is touched with one finger, it will induce an illusory curvature on the other finger. Interestingly, this phenomenon was present for both raised lines and solid shapes. We also found evidence that the underlying mechanism was similar for both types of stimuli, since there was a high correlation between the material types. In a subsequent experiment we wanted to investigate whether the biomechanical constraints of the hand were responsible for the effect, but we did not find evidence for this hypothesis. Whereas in chapter 5 we found that the surface attitude is the important cue for curvature, we propose that the curvature *contrast* illusion is mainly caused by a shift of dominance from the attitude cue to the positional cue.

SAMENVATTING

In **hoofdstuk 2** onderzochten we de haptische waarneming van hoeken, geprint op reliëfpapier. We hebben gemeten hoe goed proefpersonen twee hoeken van elkaar konden discrimineren. De resultaten lieten zien dat de discriminatiedrempels sterk beïnvloed werden door de manier van exploratie. Bij relatief kleine hoeken is het mogelijk de vinger tussen de twee lijnen, langs de imaginaire bisector, te bewegen. Als proefpersonen dit mochten doen was hun drempel twee keer zo klein als wanneer ze de lijnen moesten volgen. Verder vonden we dat zowel de grootte van de hoek (een globale eigenschap) als de aanwezigheid van de apex (lokale eigenschap) van invloed was op het discriminatievermogen. Dit resultaat laat zien dat zowel proprioceptieve als cutane informatie van belang is voor het verwerken van hoekinformatie. We onderzochten ook of een hoek die uit een reliëfoppervlak bestond makkelijker te discrimineren was dan een lijnhoek. Uit eerder onderzoek is gebleken dat tekeningen makkelijker op de tast te herkennen zijn als ze van reliëfoppervlakken zijn gemaakt dan van lijnen (Thompson et al, 2003). De resultaten van ons onderzoek tonen aan dat die bevinding waarschijnlijk niet wordt veroorzaakt door een nauwkeuriger hoekwaarneming.

Het is een veelbeschreven fenomeen, dat het op de tast herkennen van een reliëflijntekening een uiterst moeilijke taak is. In **hoofdstuk 3** begonnen we dit fenomeen te onderzoeken door drie aspecten te bestuderen: de tekeninggrootte, handbewegingen en "hardop-denken"data. We vonden dat grote tekeningen beter worden herkend dan kleine. Deze bevinding heeft enige praktische relevantie omdat veel studies in het verleden werden uitgevoerd met vrij kleine stimuli. In de toekomst is het gebruik van grotere tekeningen dus aan te raden. Verder vonden we, in contrast met wat eerder gerapporteerd is in de literatuur (Symmons and Richardson, 2000), dat spontane exploratie van lijntekeningen vaak (83% van de exploratietijd) met twee handen wordt uitgevoerd. We denken dat er twee redenen zijn waarom proefpersonen deze strategie gebruiken. Enerzijds kan één hand worden gebruikt als referentiepunt, terwijl de andere hand exploreert. Op deze manier is mogelijk de spatiële informatie makkelijker te verwerken. Anderzijds kunnen met twee handen makkelijk de symmetrie-eigenschappen van een tekening worden gedetecteerd. De "hardop-denken"data brachten inzicht in het cognitieve proces dat ten grondslag ligt aan de herkenningstaak. Het bleek dat proefpersonen een hypothesegedreven strategie gebruikten. Gemiddeld werd 23% van de totale tijd gebruikt om de uiteindelijke hypothese te testen. Deze bevinding lijkt op de stelling van Gregory (1980), namelijk dat waarneming in het algemeen een hypothesegedreven proces is.

Waarom er een zo groot verschil zit tussen het visueel en haptisch herkennen van lijntekeningen, werd bestudeerd in **hoofdstuk 4**. We kwamen erachter dat als proefpersonen een niet-herkende lijntekening mochten natekenen, ze in 31% van de gevallen hun eigen tekening herkenden. Voor sommige proefpersonen was het een vreemde gewaarwording: na 45 seconden tasten hadden ze geen idee wat het was. Maar als ze mochten tekenen werden ze soms verrast door hun eigen schets, die ineens herkenbaar werd. De verklaring voor dit effect kan gevonden in de theorie van voorwerpherkenning. Een voorwerp kan worden herkend doordat (een variatie van) het voorwerp eerder is waargenomen. In het geheugen worden gedurende lange tijd prototypebeschrijvingen opgebouwd van voorwerpen. Deze prototypebeschrijvingen worden dan weer gebruikt om een waarneming mee te vergelijken. Lederman et al (1990) stellen dat visuele en haptische voorwerpherkenning in beginsel twee afzonderlijke processen zijn die pas op een laat corticaal niveau overeenkomsten vertonen. Beide zintuigen extraheren verschillende eigenschappen van de omgeving. Waarschijnlijk is dit verschil in structuur terug te vinden in de structuur van de interne representaties (prototypes). Een lijntekening wordt moeiteloos verwerkt door het visuele systeem als het in het geheel, in één oogopslag (simultaan), kan worden waargenomen. Als deze simultaneïteit echter wordt vervangen door een sequentieel proces, waarbij telkens maar een klein gedeelte van de lijntekening zichtbaar is (of gevoeld kan worden), dan wordt herkenning van de lijntekening voor beide zintuigen even moeilijk (Loomis et al, 1991). De verklaring hiervoor is dat de structuur van de waarneming veranderd is en niet meer gebruikt kan worden voor het interne vergelijkingsproces met de prototypen. Blijkbaar zijn mensen niet in staat deze sequentiële structuur mentaal te transformeren (visualiseren) naar een bruikbare, simultane structuur. Maar de sequentiële waarneming is van voldoende kwaliteit om achteraf een tekening te produceren die in een derde van de gevallen ineens herkend wordt: de proefpersoon bleek een potlood en papier nodig te hebben om de sequentiële waarneming te transformeren naar een simultane structuur.

In **hoofdstuk 5** hebben we haptische vorm perceptie bestudeerd, waarbij de vorm zowel een echte vaste vorm kon zijn als een door een robot gegenereerde "virtuele"vorm. Het doel van deze studie was ten eerste het vergelijken van de waarneming van echte en virtuele vormen, en ten tweede het meten van de sterkte van verschillende geïsoleerde geometrische "cues". Deze cues zijn geïllustreerd in figuur 1.1 en bestonden uit positie-informatie (nulde orde cue), lokale oriëntatie-informatie (eerste orde cue) en lokale kromming (tweede orde cue). Het eerste experiment toonde aan dat de oriëntatiecue het meest dominant was, waarmee het eerder werk van Pont et al (1999) bevestigd werd. Op basis van een model berekenden we op welke schaal van armbewegingen deze oriëntatiecue dominant zou zijn: tussen de 1.2 en 78 cm. In het tweede experiment onderzochten we of de kromming van een virtuele vorm even sterk word waargenomen als de kromming van een echte, vaste vorm. Voor de virtuele vorm gebruikten we twee condities: in de eerste conditie was alleen de oriëntatiecue aanwezig, in de tweede conditie was zowel de oriëntatie- als de positiecue aanwezig. De resultaten lieten zien dat proefpersonen de echte en virtuele vormen verschillend waarnamen, maar dat in deze verschillen geen systematiek zat. Een opmerkelijke uitkomst was dat de twee virtuele condities geen enkel verschil opleverden. Dit betekent dat een kromme vorm waarbij de vinger alleen maar de lokale oriëntatie kan waarnemen even krom aanvoelt als een vorm waarbij de vinger ook daadwerkelijk op en neer beweegt en de positie van de kromming volgt.

In **hoofdstuk 6** bestudeerden we de haptische waarneming van tweedimensionale (reliëflijnen) en driedimensionale (kunststof) vormen. Onderwerp van deze studie was een nieuwe haptische illusie: krommingscontrast. Als meerdere krommingen tegelijkertijd worden waargenomen beïnvloeden die elkaar. Dat dit het geval is voor visuele waarneming is al lang bekend (zie ook figuur 1.3 in de Introductie), maar voor haptische waarneming was dit nog niet aangetoond. De resultaten van dit onderzoek lieten zien dat krommingscontrast in beide gevallen een rol speelt. De hoge correlatie die gevonden werd tussen de twee condities (tweedimensionaal en driedimensionaal) suggereert dat de onderliggende mechanismen voor beide condities overeenkomsten vertonen. Om de generaliseerbaarheid van het effect te bestuderen deden we een tweede experiment waarbij we ook metingen verrichtten aan de vingerbewegingen. We wilden onderzoeken of biomechanische eigenschappen van de hand en de interactie met een stimulus verantwoordelijk waren voor het effect. We vonden dat het effect nog steeds sterk aanwezig was als de stimuli op een andere manier werden geëxploreerd, wat de generaliseerbaarheid van het effect ondersteunt. We vonden echter geen aanwijzingen dat biomechanische factoren een rol spelen in haptisch krommingscontrast. Op basis van bevindingen uit hoofdstuk 5 bediscussieerden we dat het effect waarschijnlijk wordt veroorzaakt door een verschuiving van dominantie van de oriëntatiecue naar de positiecue. Dit wordt veroorzaakt door een grotere gevoeligheid voor relatieve vingerbewegingen dan absolute vingerbewegingen.

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Acknowledgements

It is written in the 'Suggestions to PhDs' (at least in the Dutch version, for some reason it is not mentioned in the English version) that the PhD candidate should understand that his thesis will be published online and will thus be available to everyone with an internet connection. It is therefore recommended that the acknowledgements are written with some 'distance'.

This formal way of communicating is one of the aspects of science I had quite some trouble with. How many times in writing a paper did I first write a funny version which I finished in a few minutes. But then I had to delete it all and write the official, formal draft which took me months. Nevertheless, it is for good reasons that scientists should write formal, and by now I fully agree with it.

But in this section it is especially difficult. I had such a good time here that I would have liked to write a multiple page tribute to everyone and everything that made this project so great. But it is good that the 'Suggestions to PhDs' protects me from that sentimental nonsense. I could have produced obnoxious sentences like *How can I write with 'distance' when the people around me were so 'close'?*. And that would, among other things, really have ruined my reputation. However, I hope that the implicit message of this rather unclear section is understandable to everyone it concerns. THANKS!

Curriculum vitae

Maarten Willem August Wijntjes was born in Utrecht (the Netherlands) on the 1st of November, 1977. He grew up in Nieuwegein but went to high school in Utrecht (Christelijk Gymnasium). After high school he started to study Astronomy at the Rijksuniversiteit Groningen. During his study he switched to Theoretical Physics in which he graduated in September 2003 on a thesis about photonic crystals. After his graduation he moved to Amsterdam and worked for half a year as a team-leader at an in-flight catering company. In August 2004 he got an appointment as a PhD student at the Physics of Man group of the Utrecht University. There, he worked for four years under the supervision of professor Astrid Kappers. During that time he also worked for a short period at McGill University, Montréal (Canada), under the supervision of professor Vincent Hayward. From August 2008 he works as a post-doc with Sylvia Pont on the topic of Ecological Optics.