Tactile and haptic perceptual organization

Kappers, A.M.L.; Bergmann Tiest, W.M.

published in
Oxford Handbook of Perceptual Organization
2015

DOI (link to publisher)
10.1093/oxfordhb/9780199686858.013.002

citation for published version (APA)
Kappers, A. M. L., & Bergmann Tiest, W. M. (2015). Tactile and haptic perceptual organization. In J. Wagemans (Ed.), *Oxford Handbook of Perceptual Organization* (pp. 621-638). (Oxford Library of Psychology). Oxford University press. https://doi.org/10.1093/oxfordhb/9780199686858.013.002

Tactile and haptic perceptual organization

Astrid M.L. Kappers and Wouter M. Bergmann Tiest

Helmholtz Instituut, Physics of Man, Padualaan 8, 3584 CH Utrecht,
The Netherlands

To appear in:
Oxford Handbook of Perceptual Organization
Oxford University Press
Edited by Johan Wagemans

1. Introduction

Tactile perception refers to perception by means of touch mediated only through the cu- taneous receptors (mechanoreceptors and thermoreceptors) located in the skin (Loomis and Lederman, 1986; Lederman and Klatzky, 2009). When also kinaesthetic receptors (mechanoreceptors embedded in muscles, joints and tendons) are involved, the term hap- tic perception is used. Four main types of cutaneous mechanoreceptors have been distin- guished: Merkel nerve endings (small receptive field, slowly adapting), Meissner corpus- cles (small receptive field, fast adapting), Pacinian corpuscles (large receptive field, slowly adapting) and Ruffini endings (large receptive fields, fast adapting). Together these are responsible for the human's large range of sensitivities to all kinds of stimulation, such as pressure, vibration and skin stretch. The kinaesthetic sense, or kinaesthesia, contributes to the perception of the positions and movement of the limbs (Proske and Gandevia, 2009). The main kinaesthetic receptor is the muscle spindle that is sensitive to changes in length of the muscle; its sensitivity can be adapted to the circumstances. Most of our everyday activities involving touch (think of handling and identifying objects, maintenance of body posture, sensing the texture of food in the mouth, estimating the weight of an object, etc.) fall into the class of haptic perception.

An interesting difference with the sense of vision is that visual receptors are restricted to a small well-delineated organ (namely the eye), whereas touch receptors are distributed all over the body. However, the sensitivity of these receptors varies widely over the body. A commonly used measure for the sensitivity is the two-point-threshold, which represents the smallest distance between two stimuli that is necessary to distinguish the stimulation from just one stimulus. Such thresholds are typically 2–4 mm for the fingertips, but can be more than 40 mm for the calf, thigh and shoulder (Weinstein, 1968; Lederman and Klatzky, 2009). Another interesting fact compared to vision is that the extremities (limbs) are not only exploratory sense organs, but they are also performatory motor organs (Gibson, 1966).

The availability of tactual information is usually taken for granted and as a consequence its importance is severely underestimated. The importance of haptics, or of touch in general, is usually illustrated by referring to its significance to those individuals that lack the use of one of the other major senses, particularly sight. Blind (or blindfolded) humans clearly have to rely heavily on the sense of touch. However, this observation disregards the fact that in daily life touch is of vital importance for everyone, not just for the visually disabled: living without the sense of touch is virtually impossible (e.g. Cole and Paillard, 1995). Patients suffering from peripheral neuropathy (a condition that deafferents the limbs, depriving the person of cutaneous and haptic touch) are unable to control their limbs without visual feedback: in the dark or when covered under a blanket, they are completely helpless. Such patients are fortunately rare, but they make us aware of our reliance on touch in basically all our daily activities.

Humans are able to perceive a wide range of properties by means of touch. Some of these are shared with vision, like, for example, shape and size, but others are specific for touch, such as weight, compliance and temperature. Properties like texture can be perceived both visually and haptically, but in quite different ways and these could contradict each other: an object might look smooth but feel rough and vice versa. In 1987, Lederman and Klatzky made an inventory of the typical hand movements humans make when assessing object and material properties. Information about weight, size, texture, shape, compliance and temperature can be obtained by unsupported holding, enclosure, lateral movement, contour following, pressure and static touch, respectively (Lederman and Klatzky, 1987). These so-called exploratory procedures do not only suffice to assess these properties, but they are optimal and often also necessary.

This chapter aims at giving a concise overview of the human haptic perception of object and spatial properties. Insight into perceptual organization can often be obtained by studying perceptual illusions, as many of these rely on tricks with perceptual organization. The theoretical basis for this idea lies in the way information from the world around us is processed. A great deal of our representation of the world is not actually perceived, but supplemented by our brain according to certain mechanisms. When this process goes wrong, as is the case with illusions, these mechanisms are laid bare and their operation can be fathomed. The topics in this chapter will therefore, where possible, be illustrated with tactile or haptic illusions (e.g. Robertson, 1902; Hayward, 2008; Lederman and Jones, 2011; Suzuki and Arashida, 1992)

2. Object properties

The question “What is an object?” or more in particular, “How do humans segregate figure from ground?”, has been investigated extensively in vision. In touch, however, only a few studies are relevant in this respect. For example, Pawluk and colleagues (2010) asked observers to distinguish between figure and ground by means of a “haptic glance”, a very brief gentle contact with all five fingers of a hand. They showed that such a brief contact is indeed sufficient for the distinction between figure and ground. A similar pop-out phe- nomenon, immediately separating different aspects of a haptic scene, has been reported for haptically relevant properties such as roughness (Plaisier et al., 2008) and compliance (van Polanen et al., 2012). Some other studies report on numerosity perception. By actively grasping a bunch of a small number objects (in this case spheres), one can rapidly deter- mine the correct number of objects (Plaisier et al., 2009), which gives clear evidence of fast object individuation by touch.

This section will focus on the haptic perception of object properties, such as curvature, shape, size and weight that have received quite some attention. It will also be shown that some of these properties are susceptible to strong illusions and these are important for our understanding of how and what aspects of objects can be perceived by touch.

2.1. Curvature

An important aspect of a smooth shape is its curvature and it is therefore of interest if and how well humans can perceive and discriminate curvature and what perceptual mechanism is used for haptic curvature perception. The first studies on curvature perception focused on the question how well humans could decide whether a stimulus was concave, straight or convex. Hunter (1954) and later Davidson (1972) presented curved strips on the horizontal plane and found that what observers perceive as straight is actually somewhat concave (the middle of the stimulus bent away from the observer). They also compared performance of blind and blindfolded sighted observers and their conclusion was that blind observers give more “objective” (that is, veridical) responses. Davidson found that if the sighted observers were instructed to use the scanning strategies of the blind, their performance improved. He concluded that the exploratory movement of an arm sweep might obscure the stimulus curvature.

Gordon and Morrison (1982) were interested in how well observers could discriminate curved from flat stimuli. Using small curved stimuli explored by active touch, they could express the discrimination threshold in terms of geometrical stimulus properties: the base-to-peak height of the curved stimulus divided by half its length is constant (see Figure 1A). This expression indicates the overall gradient of the stimulus. To exclude and investigate the possible influence of kinaesthetic perception on curvature discrimination, Goodwin et al. (1991) pressed small curved stimuli onto the fingers of observers, so that only cutaneous receptors in the finger pads could play a role. In this way, a 10 % difference in curvature could be detected. In a subsequent study (Goodwin and Wheat, 1992), they found that discrimination thresholds remained the same even if contact area was kept constant, so contact area was not the determining factor for curvature discrimination. However, dis- crimination performance increased with contact area. For stimuli with a larger contact area, the base-to-peak height is also larger, so their finding was consistent with the conclusion of Gordon and Morrison that the stimulus gradient determines the discrimination threshold (see Figure 1).

Pont et al. (1997) used stimuli that were similar in curvature and size to that of Hunter (1954) and Davidson (1972), but they used these stimuli upright and performed discrimination instead of classification experiments. In various conditions, observers had to place their hand on two successive stimuli and they had to decide which of the two had the higher curvature. Figure 2A-C shows a few of their experimental conditions: stimuli could be placed along the various fingers as in (A), across the fingers at several locations as in (B), or even at the dorsal side of the hand as in (C). Consistent with the previous findings, they found that the gradient of the stimuli determined the curvature discrimination threshold. As the dorsal side of the hand contains much less cutaneous mechanoreceptors than the palmar side, worse discrimination performance with the dorsal side of the hand showed the importance of the cutaneous receptors in curvature perception. They also found that performance with statically or dynamically touching the stimuli was not significantly different (Pont et al., 1999). Possibly this is due to the important role the cutaneous receptors play in discrimination performance.

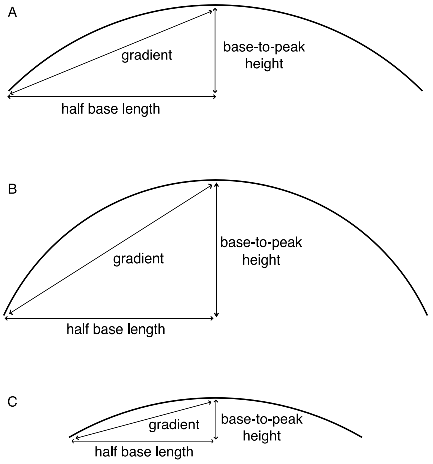

Figure 1: Illustration of the threshold expression of Gordon and Morrison (1982). A) A curved stimulus has a base-to-peak height and a length. The ratio of the two divided by 2 gives the gradient or slope. B) A stimulus with a higher curvature has a larger base-to-peak height if the length is the same as in (A). As a consequence, the gradient is also larger. C) Stimulus with the same curvature as in (A), but of smaller length. The gradient is smaller than in (A) because of the nonlinear relation between slope and stimulus length.

If the overall gradient or slope of the stimulus plays a major role in curvature discrim- ination performance, then height and local curvature are of minor importance. Pont et al. (1999) investigated this explicitly by creating a new set of stimuli in which the order of information that the stimulus contained was varied (see Figure 2D-F). The first stimulus set contained only height differences (zeroth order information), the second set contained both height differences and slopes (zeroth and first order information) and the third set contained in addition local curvature information (zeroth, first and second order information). Participants placed their fingers on the stimuli as shown in Figure 2D-F and had to decide for each stimulus pair (within a set) which of the two was more convex. All thresholds could be expressed in terms of base-to-peak height. Convincingly, the thresholds for the zeroth order set were much higher than for both the two other sets. There was no significant difference in thresholds if local curvature was added to the stimuli, so thresholds are indeed based on the gradient information.

The experiments on stimulus order by Pont et al. were necessarily done using static touch. Dostmohamed and Hayward (2005) designed a haptic device that made it possible to perform similar experiments using active touch. Participants had to place a finger on a small metal plate and when actively moving this plate, the plate followed the trajectory of a preprogrammed stimulus shape. In this way, Wijntjes et al. (2009) could compare discrimination performance with the same stimulus shapes Pont et al. used. They also included a condition directly touching the real curved shapes. Their results were consistent with those obtained for static touch: height information alone is not sufficient, but as soon as first order information (slope) is present, performance is just as good as with the curved

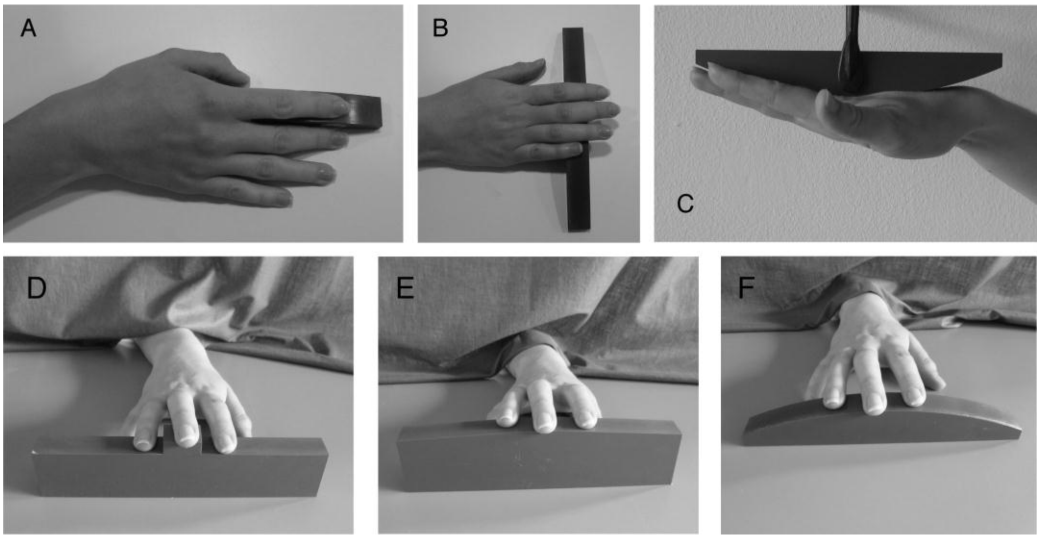

Figure 2: Illustration of some of the conditions in the experiments by Pont and colleagues (1997, 1999). A) Stimulus placed along the index finger; B) Stimulus placed across the fingers; C) Stimulus presented dorsally; D) Stimulus just containing height differences (zeroth order information); E) Stimulus containing height and slope differences (zeroth and first order information); F) Stimulus containing height, slope and curvature information (zeroth, first and second order information)

shapes. Therefore, the determining factor for curvature discrimination performance is the overall gradient in the stimulus. It is clear that the principles of perceptual organization are at work here: from just the orientation of the surface in a few locations, the entire curved surface is reconstructed according to the principle of good continuation. Not only is the surface reconstructed, its curvature can also be perceived as accurately as in the case of a complete surface.

2.1.1. Illusions of curvature

Although humans are sensitive to only small differences in curvature, their perception of curvature is not veridical. Both Hunter (1954) and Davidson (1972) reported that what is perceived as straight is actually curved away from the observer. Davidson’s explanation was that a natural hand movement also follows a curved line, obscuring the stimulus’ curvature. Vogels et al. (1996; 1997) found that a three-dimensional surface that is perceived as flat corresponds to a geometrically concave surface. In other words, an actually flat surface is usually perceived as convex. There are other, even more pronounced, curvature illusions that will be described below.

2.1.2. Anisotropy of the hand

Pont et al. (1999) not only showed that curvature discrimination thresholds decreased with increasing stimulus length, they also showed that the perceived curvature was larger for stimuli of larger length. This has an interesting implication: as human hands are usually longer than wide, perceived curvature of a sphere would be larger along the fingers than across the fingers. Pont et al. (1998) tested this experimentally and could confirm the prediction that spherial ojects are perceived as ellipsoidal.

2.1.3. Curvature aftereffects

Gibson (1933) was the first to show that touching a curved strip leads to aftereffects. He asked observers to move back and forth along a curved strip during three minutes and he reported that a subsequently touched straight strip felt as curved in the opposite direction. Vogels et al. (1996) performed extensive experiments investigating the curvature aftereffect of touching a curved three-dimensional shape. In their experiments, observers, seated behind a curtain, had to place their hand on a curved adaptation surface for only 5 s, and then decide for the next touched shape presented at the same location whether it was convex or concave. By systematically varying the curvatures of both the adaptation and the test surfaces, they established that the strength of the aftereffect was about 20 % of the curvature of the adaptation shape. Moreover, they showed that an adaptation time of only 2 s was sufficient to obtain a measurable aftereffect and after 10 s the effect was already at its maximum. On the other hand, a delay between touching the adaptation surface and the test surface of 40 s could not eliminate the aftereffect.

In a follow-up study, Vogels et al. (1997) tried to locate the origin of this curvature aftereffect. During a delay between touching the adaptation and test surfaces, observers were instructed to either keep their hand still in the air, make a fist, or bend and stretch their hand periodically. In this way, they varied the degree in which the cutaneous, joint and muscle receptors were stimulated during the decay. As they did not find differences between the three conditions, they concluded that peripheral receptors do not play a major role in causing the aftereffect. In a small experiment with only two participants, they also tested whether the aftereffect transferred to the other hand. As they did not find an indication of such a transfer, they had to conclude that the origin of the aftereffect is neither of a high level.

Van der Horst et al. (2008a) found not only a substantial aftereffect when the curved surface was just touched by a single finger, they also found a partial transfer of the aftereffect to other fingers, both of the same hand and of the other hand. Because the transfer is only partial, they conclude that the major part of the aftereffect is caused at a level where the individual fingers are represented, but that in addition a part has to occur at a level shared by the fingers. Interestingly, in another study Van der Horst et al. (2008b) found a full transfer of the aftereffect when the curved surfaces were touched dynamically. They conclude that the level of the representation of curvature apparently depends on the way the information is acquired (see Kappers (2011) for an overview of all aftereffect studies).

2.1.4. Curvature perception induced by force

Robles-De-La-Torre and Hayward (2001) designed a haptic device with which they could combine a geometric stimulus presentation with a horizontal force profile. Among others, they found that if a flat physical surface was presented together with a force profile of either a bump or a hole, observers perceived indeed a bump or a hole. Even when a virtual bump or hole was combined with a physical hole or bump, the virtual stimulus dominated the percept. They concluded that force could overcome object geometry in the active perception of curvature.

2.2. Shape

Curvature is an important property of smooth shapes, but it is also of interest to investigate the perception of shape itself. A first study was conducted by Gibson (1963), who used a set of smooth solid objects that were “equally different” from one another to perform matching and discrimination experiments. He concluded that blindfolded observers could distinguish such shapes by touch. Klatzky and colleagues (1985) used a large set of common daily life objects, such as a comb, wallet, screw and tea bag, and they established that such three-dimensional objects could be recognized accurately and rapidly by touch alone. Norman and colleagues (2004) made plastic copies of bell peppers, which they used in matching and discrimination experiments, both unimodally (touch or vision) and bimodally (touch and vision). As the results in the various conditions were quite similar, they concluded that the visual and haptic representations of three-dimensional shape are functionally overlapping.

A different approach was followed by van der Horst and Kappers (2008). They used a set of cylindrical objects with different elliptical cross-sections and a set of blocks with rectangular cross-sections. The task of the observers was to grasp (without lifting) a pair of objects and determine which of the two had the circular (for the cylinders) or square (for the blocks) cross-section. They found that an aspect ratio (i.e. ratio between the longer and the shorter axes) of 1.03 was sufficient to distinguish circular from elliptical, but an aspect ratio of 1.11 was necessary for distinguishing square from rectangular. This was somewhat surprising, since the aspect ratio is more readily available in the block than in the cylinders. They concluded that apparently the curvature information present in the cylinders could be used in a reliable manner. Using a similar set of objects, Panday et al. (2012) studied explicitly how local object properties (such as curvature variation and edges) influenced the perception of global object perception. They found that both curvature and curvature change could enhance performance in an object orientation detection task, but edges deteriorated performance.

2.3. Size

Objects are always extended and thus have a certain size. Size can be measured in one, two or three dimensions, which corresponds to length, area and volume. In this section, we will restrict ourselves to the haptic perception of length and volume.

2.3.1. Length

An object's length can basically be perceived in two ways. The first is the *finger-span method*, in which the object is enclosed between thumb and index finger. This method is restricted to lengths of about 10 cm or less, depending on hand size. The best accuracy (discrimination threshold) with which lengths can be perceived in this way is about 0.5 mm (1 %) for a 5 cm reference length (Langfeld, 1917). For greater lengths, the thresholds increase somewhat up to about 3 mm for a 9 cm reference length (Stevens and Stone, 1959).

For even larger objects, the finger-span method cannot be used and movement is required to perceive the object's length. When moving the finger over the side of an object, two sources of information are available: the distance travelled can be derived from the kinaesthetic information from muscles and joints. At the same time, it can also be extracted from the cutaneous information of the fingertip moving over the surface by estimating the movement speed and duration. Length perception with the movement method is a lot less accurate than

the finger span method. Based on kinaesthetic information, the length discrimination threshold for a 8 cm reference length is 11 mm (14 %), while based on cutaneous information, it is 25 mm (32 %) (Bergmann Tiest et al., 2011). In conclusion, haptic length perception can be done with either the finger-span method, kinaesthetic movement information, or cutaneous movement information, with varying degrees of accuracy.

Illusions of length

A well-known illusion in haptic length perception is the radial-tangential illusion, in which lengths explored in the radial direction (away from and towards the body) are perceived to be larger than lengths explored in the tangential direction (parallel to the frontoparallel plane) (Armstrong and Marks, 1999). This indicates that haptic space is anisotropic and that the perceived length of an object depends on its orientation.

Regarding the different methods, it has been found that lengths perceived by the finger-span method are judged to be shorter than by the movement method, both in a perception-and-reproduction task (Jastrow, 1886) and in a magnitude estimation task using a visual scale (Hohmuth et al., 1976). The difference in perceived length between the methods was as high as a factor of 2.5 in some cases. Furthermore, lengths perceived using the movement method with only cutaneous information were underestimated more than with only kinaesthetic information (Terada et al., 2006). When kinaesthesia and cutaneous perception yielded conflicting information, the estimate was found to be based on the greatest length.

Finally, the well-known Müller-Lyer illusion, in which the length of a line is perceived differently depending on the type of arrowheads present at the ends, has been demonstrated in touch as well as in vision (Robertson, 1902; Millar and Al-Attar, 2002). All in all, these illusions indicate that haptic length perception is not independent of the direction or the type of movements made, nor of the direct environment of the object to be perceived.

2.3.2. Volume

Although quite a number of studies focused on the perception of weight (see below), which usually correlates with object size unless different materials are compared, only a few studies investigated the haptic perception of volume. Volume is typically assessed by enclosing the object with the hand(s) (Lederman and Klatzky, 1987). Kahrimanovic et al. (2011b) investigated the just noticeable difference (JND) of spheres, cubes and tetrahedrons that fitted in the hand. They found that for the smaller stimuli of their set, the volumes of tetrahedra were significantly more difficult to discriminate than those of cubes and spheres, with Weber fractions of 0.17, 0.15 and 0.13, respectively. The availability of weight information did not improve performance.

As visual estimates of volume were found to be biased depending on the object geom- etry, Krishna (2006) decided to investigate this so-called “elongation bias” haptically. She found that in touch, an effect opposite to that in vision occurred: a tall glass was perceived

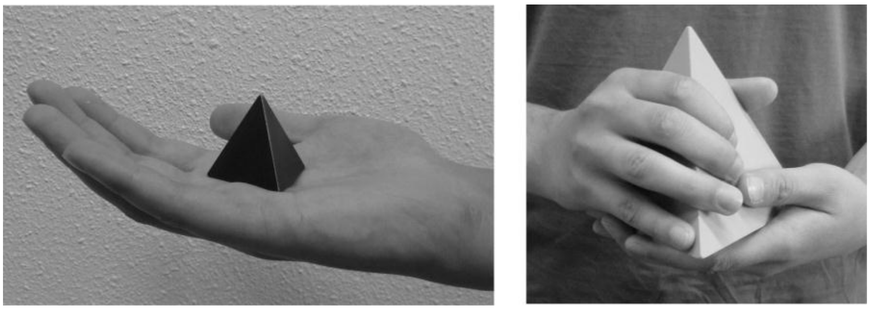

Figure 3: Examples of tetrahedral stimuli as used by Kahrimanovic et al. (2010, 2011).

as larger in volume than a wide glass of the same volume. Her conclusion was that whereas in vision “height” is a salient feature, for touch “width” would be more salient. As objects can differ along more geometric dimensions than just height or width, Kahrimanovic et al. (2010) investigated volume discrimination of spheres, cubes and tetrahedra (see Figure 3 left). These stimuli were of a size that fitted in one hand. They found substantial biases: tetrahedra were perceived as much larger than spheres (about 60 %) and cubes (about 30 %). Somewhat smaller, but still substantial biases were found when observers had access to the mass (weight) of the object (although they were not told explicitly that weight correlated with volume).

The subsequent step in the research was to investigate the physical correlates of these volume biases. If the volumes of spheres, cubes and tetrahedra are the same, then, among others, their surface area and maximal length are not identical. It turned out that for volumes that were perceived as being equal, the surface areas of the objects were almost the same (Kahrimanovic et al., 2010). If participants were instructed to compare surface area of these shapes, their performance was almost unbiased. This outcome makes sense, if one realizes that surface area correlates with skin stimulation, which is a more direct measure of object size than the more “abstract” volume. If the cue of surface area of the cubes and tetrahedrons was absent by using wire frame objects, biases increased to an average of 69 % in the cube-tetrahedron comparison. In this condition, the maximum length between two vertex points was the factor correlating with the participant’s perceived volume. Again, this can be understood by realizing that now length is the more direct stimulus compared to volume. It seems to be a general principle of haptic perceptual organization that volume is perceived on the basis of the most readily available geometric property of the stimulus.

In a follow-up study, similar shapes but of a size much larger than the hand were used (see Figure 3 right). Again a tetrahedron was perceived as larger than both the sphere (22 %) and the cube (12 %), and the cube was perceived as larger than the sphere (8 %), although the latter difference was not significant. From these smaller differences than in the previous study, it could already be seen that surface area could not be the (sole) responsible factor. This need not be surprising. The objects are larger than the hands, so the skin area stimulated when holding the objects is probably very similar (namely the whole hand surface) for all shapes. Moreover, bimanual perception necessarily takes places at a higher level than unimanual perception, so the experimental findings need not be the same.

2.4. Weight

One of the first to report on weight perception was Weber (1834/1986). Since then, quite a number of studies investigated human discriminability of weight (for an overview see Jones (1986)). The methods used to measure these thresholds are rather diverse and as a consequence the reported Weber fractions also vary over a wide range, from 0.09 to 0.13 for active lifting. Thresholds obtained with passively resting hands are higher, suggesting that receptors in muscles play a role in weight discrimination (Brodie and Ross, 1984). Jones (1986) also gives an overview of the relationships between perceived weight and physical weight and also these vary widely: most authors report power functions, but their exponents range from 0.7 to 2.0. When participants were asked to enclose the objects (sphere, cubes or tetrahedrons), Weber fractions for weight discrimination were even higher (0.29). They were also higher than volume discrimination thresholds obtained with the same objects, so apparently weight information could not be the determining factor in volume discrimination (Kahrimanovic et al., 2011a).

2.4.1. Illusions involving weight

A well-known illusion concerning weight is the size-weight illusion. The first experimental evidence was established by Charpentier in 1891 (Murray et al., 1999). In this illusion, a smaller object is perceived as heavier than a larger object of equal weight. There have been many attempts to explain this illusion, such as the “expectation theory” which uses the fact that in general there is a correlation between size and weight of an object, or the “information-integration theory” in which size is considered to be an object property that affects its perceived weight (Ellis and Lederman, 1993). The information-integration theory holds that different cues (in this case weight, volume, or density) are combined with different weight factors to form the final percept. In many of the experiments, visual inspection plays an essential role. However, Ellis and Lederman (1993) showed that just as strong an illusion occurs with blindfolded sighted and congenitally blind observers, suggesting that this illusion is a haptic phenomenon. They concluded that the existing theories were not really able to predict their results and that the illusion probably has a sensory and not a cognitive basis.

There also exists a material-weight illusion, where objects made of a heavier (higher density) material are perceived to be lighter than same-sized objects of lighter material (e.g. Ellis and Lederman, 1999). Ellis and Lederman (1999) showed that with only haptic information a full-strength illusion can be obtained, whereas just visual information caused at most a moderate illusion.

These illusions show that different cues, which may not always be relevant to the task, contribute to the final percept. This suggests the existence of a mechanism, also in haptic perception, that synthesizes the perception of an object from different information sources, possibly operating according to Gestalt laws.

3. Spatial properties

The haptic sense does not only provide us with object properties, but also the relations between these objects or parts of objects have to be perceived. The perception of such spatial relations has been studied most extensively in raised line drawings.

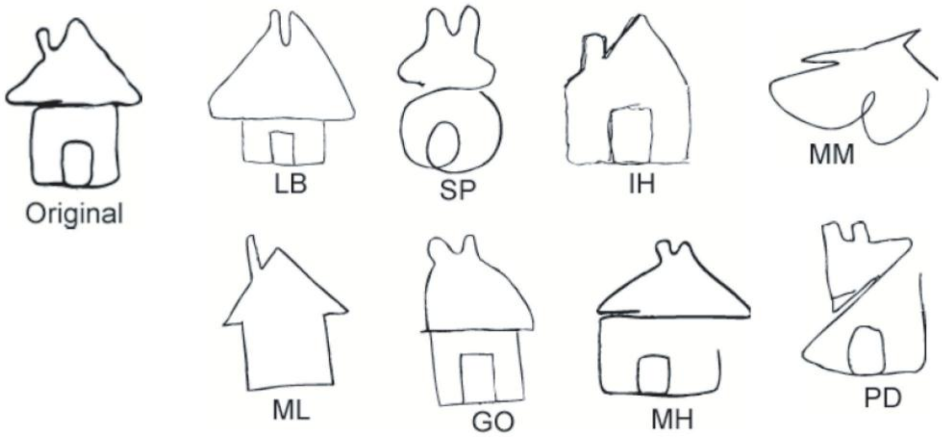

Figure 4: Result of an informal experiment. The original "house" is a wire frame placed flat on a table in the correct orientation. Blindfolded participants were asked to explore the stimulus and draw it when they felt ready to do so. Exploration time was free and usually in the order of minutes. The resulting drawings of the 8 participants are shown.

3.1. Line drawings

Although three-dimensional objects are easy to recognize by touch (see above), two- dimensional raised line drawings are very hard to recognize (e.g. Magee and Kennedy, 1980; Heller, 1989; Loomis et al., 1991; Klatzky et al., 1993; Picard and Lebaz, 2012), even with extended exploration times. To illustrate this phenomenon, blindfolded observers had to explore a wire frame stimulus of a house in an informal experiment, and when they felt confident that they could draw what they had felt, they stopped the exploration that typically took several minutes, removed the blindfold and made a drawing without seeing the stimulus. It can be seen in Figure 4, that some of the participants clearly recognized a house, but most of them missed several details, such as parts like the door, the bottom line of the roof or the placement of the chimney. Other participants had no idea of the shape and were also not able to draw it. They missed (in addition) more important aspects such as the straightness of lines, the relation between lines or the fact that many of the angles are right. Note that observer LB was only able to recognize the house after he saw his own drawing.

One of the explanations given for the poor performance in recognizing line drawings, lies in the difficulty to integrate spatial information. In the case of the line drawings, information is acquired sequentially and has to be integrated over time into a coherent representation, a process possibly governed by Gestalt laws. Loomis et al. (1991) compared tactual performance with that of exploring a drawing visually with just a very limited field of view. If the field of view was similar in size to that of a finger pad, visual and tactual recognition performance was comparable. In an experiment where the finger of the observer was either guided by the experimenter or actively moved by the observer, performance was better in the guided condition (Magee and Kennedy, 1980). The explanation could be that in the active condition movements are much noisier, making integration of information harder.

The role of vision in recognizing raised line drawings is somewhat controversial (e.g. Picard and Lebaz, 2012). Some authors report similar performance of blindfolded sighted and congenitally blind observers (e.g. Heller, 1989), whereas others report worse perfor- mance for blind observers (e.g. Lederman et al., 1990). In any case, from several studies, notably those by Kennedy (e.g. 1993), it follows that congenitally blind observers are able to use raised line drawings to their advantage.

Based on an idea by Ikeda and Uchikawa (1978), Wijntjes and colleagues (2008) gave blindfolded observers 45 s to recognize drawings of common objects, such as a hammer, a car and a duck. After this time period, they were forced to guess what they thought the object was. Subsequently, in the case of a wrong answer (about 50 % of the cases), they had to draw what they felt. Half of the observers had to do that without a blindfold, the other half with blindfold. Those who drew without blindfold, recognized their own drawing in about 30 % of the cases; those who drew with blindfold mostly remained unaware of what the object was. These different outcomes showed that the execution of motor movements during drawing could not be the cause of the recognition. Naive observers also recognized the recognized drawings. Therefore, the authors conclude that the mental capacities required to identify the drawing are not sufficient. Externalization of the stimulus, as done by drawing on a sketchpad, seems to be a process that can be used in the identification of serial input that needs to be integrated.

3.2. Spatial patterns

Gestalt psychologists have identified a number of regularities or “laws” that can be used to explain how humans categorize and group individual items and how they perceive spatial patterns. Principles of “similarity”, “proximity” and “good continuation” can explain how humans group items that seem to belong together. Almost all research has been performed using visual experiments and only recently a few studies investigated the existence of such laws in the touch domain (Gallace and Spence, 2011).

3.2.1 Proximity and similarity

Items that are close together (close proximity) will be perceived as being related and these will be perceived as a group. Items that share some property such as colour, shape, or texture will be grouped because of their similarity. Chang and colleagues (2007b) performed an experiment comparing visual and haptic grouping principles. Their stimuli consisted of cards with elements that differed in both colour for the visual condition and texture for the haptic condition. Participants were asked how they would group the elements and why. Groups could differ in number, proximity and similarity of the elements. Depending on the stimulus organization, items were either grouped on the basis of spatial proximity or on the basis of their texture. For a large part the groupings in vision and haptics were similar, suggesting that the Gestalt laws of proximity and similarity are also valid for touch. In a rivalry experiment, Carter et al. (2008) showed that the proximity of tactile stimuli could bias the perceived movement direction of an ambiguous apparent motion stimulus. As their tactile and visual experiments yielded similar results, they suggest that this might be based on a strategy common to all modalities.

Overvliet et al. (2012) used a search task to investigate the influence of similarity and proximity on finding a target item pair among distractor pairs. Their stimuli consisted of two columns of small vertical and horizontal bars. They found, among others, that if distractors consisted of pairs of different items and the target of a pair of identical items, performance was worse (longer reaction times) than in the reverse condition. However, when searching for a different pair among identical pairs, the task can be performed by just searching for the odd-one-out in either the left or the right column. There is no need to correlate the input from the left and right fingers (although that was the task instruction). This makes the task inherently easier than the reverse task, but in our opinion, it is questionable whether this has to do with the Gestalt concept of similarity. The finding that there is no influence of proximity (between the pairs of stimuli in the two columns) can be explained in the same way.

3.2.2. Good continuation

Items that are aligned tend to be perceived as a group and will be integrated to a percep- tual whole. Chang and colleagues (2007a) also designed a “good continuation” experiment, once again comparing visual and haptic performance. They constructed 16 different lay- outs, shapes that were partially occluded. The occlusion was represented both by colour and texture, so that the same stimuli could be used in the visual and haptic experiments. They found that overall visual and haptic behaviour was nearly the same, indicating that the Gestalt principle of continuation is also applicable to touch.

3.3. Spatial relations

Helmholtz (1867/1962) was one of the first to notice that visual perception of the world around us is not veridical. Hillebrand (1902) showed that lines that appeared parallel to the eye, were not at all parallel. A few years later, Blumenfeld (1913) showed that also visually equidistant lines are not physically parallel, and, interestingly, that they are different from the “parallel alleys” of Hillebrand. In the literature, a discussion started about the concept and existence of “visual space”. Inspired by these findings, Blumenfeld (1937) decided to perform similar experiments to investigate the veridicality of haptic space. With pushpins he fixed two threads to a table and he asked blindfolded observers to straighten these threads by pulling them towards themselves in such a way that they would be parallel to each other. Blumenfeld found that these threads were not parallel: if the distance between the two pushpins was smaller than the observer’s shoulder width, the threads diverged; if the distance was larger, the threads converged. In the same year, also von Skramlik (1937) reported on the distortion of haptic space.

For a long time hardly any research on the perception of haptic space was performed. In the late nineties, Kappers and colleagues decided to investigate the haptic perception of parallelity in more detail. Their first set-up consisted of a table on which 15 protractors in a 5 by 3 grid were placed (e.g. Kappers and Koenderink, 1999). An aluminium bar of 20 cm could be placed on each of the protractors. The bars could rotate around the centre of the protractor. A typical experiment consisted of a reference bar placed at a certain location in an orientation fixed by the experimenter and a test bar at another location in a random orientation. The task of the blindfolded observers was to rotate the test bar in such a way that it felt parallel to the reference bar. In all conditions, either unimanual or bimanual, large but systematic deviations of parallelity were found. Depending on the condition, these deviations could be more than 90°. The bar at the right hand side (either the reference or the test) had to be rotated clockwise with respect to a bar to the left of it in order to be perceived as haptically parallel (e.g. Kappers and Koenderink, 1999; Kappers, 1999, 2003). These findings were reproduced in other labs (e.g. Newport et al., 2002; Kaas and van Mier, 2006; Fernández-Díaz and Travieso, 2011).

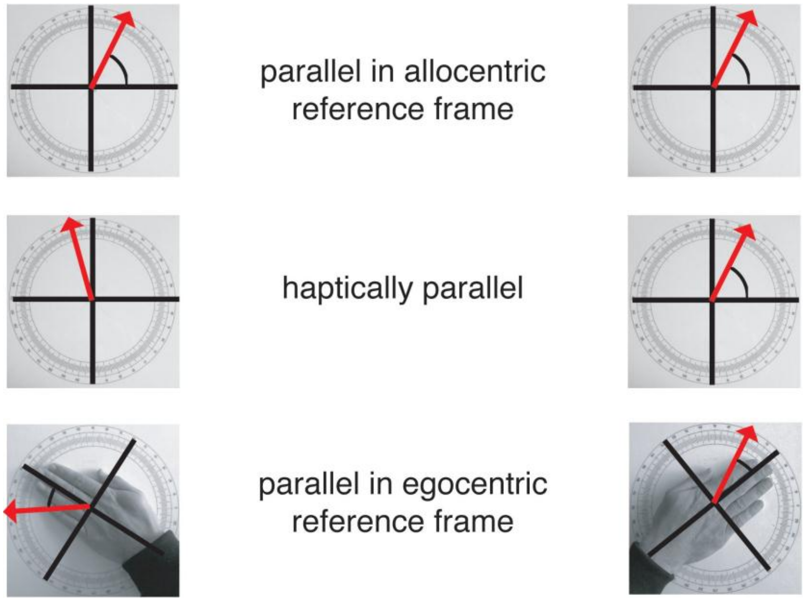

Figure 5: Illustration of different reference frames. Top: Allocentric reference frame. This reference frame coincides with a physical reference frame fixed to the table. Parallel bars have the same orientation with respect to the protractor, independent of the location of the protractor. Middle: Haptically parallel. The two bars shown are perceived as haptically parallel by one of the observers (the size of the deviations strongly depends on observer). Bottom: Egocentric reference frame, in this case fixed to the hand. The two bars have the same orientation with respect to the orientation of the hand. The orientation of the hand will depend on its location, so the deviation from veridical will directly depend on the hand. It can be seen that haptically parallel lies in between allocentrically and egocentrically parallel.

The current explanation for the deviations is that they are caused by the biasing influence of an egocentric reference frame (e.g. Kappers, 2005, 2007; Zuidhoek et al., 2003). The task of the observer is to make the two bars parallel in an allocentric (physical) reference frame, but of course, the observer only has recourse to egocentric reference frames, such as the hand or the body reference frame (see Figure 5). If the task would be performed (unintentionally) in an egocentric reference frame, the deviations would occur in the direction found. However, the deviations are not as extreme as predicted by performance in just an egocentric reference frame, but they are biased in that direction.

The evidence for this explanation is accumulating rapidly. For example, a time delay between exploration of the reference bar and setting of the test bar causes a reduction of the deviation (Zuidhoek et al., 2003), although in general a time delay would cause a deterioration of task performance. The explanation is thought to lie in a shift during the delay from the egocentrically biased spatial representation to a more allocentric reference frame, as suggested by Rossetti et al. (1996) in pointing experiments. Noninformative vision (i.e. vision of the environment without seeing the stimuli or set-up) strengthens the representation of the allocentric reference frame. It was shown that this indeed leads to a reduction of the deviations (e.g. Newport et al., 2002; Zuidhoek et al., 2004). Asking observers to make two bars perpendicular, results for some observers in almost parallel bars (Kappers, 2004). This is consistent with what would be predicted on the basis of the reference frame hypothesis. Moreover, mirroring bars in the midsagittal plane gave almost veridical performance (Kappers, 2004; Kaas and van Mier, 2006). This is to be expected as performance in both an egocentric and an allocentric reference frame would lead to veridical settings. Moreover, the deviations obtained on midsagittal (Kappers, 2002), frontoparallel (Volcic et al., 2007) and three-dimensional set-ups (Volcic and Kappers, 2008) can all be explained with this same hypothesis.

The nature of the biasing egocentric reference frame originates most probably in a combination of the hand and the body. Kappers and colleagues (Kappers and Viergever, 2006; Kappers and Liefers, 2012) manipulated the orientation of the hand during the exploration of the bars and they showed that the deviation was linearly related to the orientation of the hand, that is, the orientation of the hand reference frame. However, even when the two hands were aligned, a small but significant deviation remained and this is consistent with influence of the body reference frame.

3.3.1. Illusions of orientation

The above-described investigations on the non-veridicality of haptic space, already show that perception of orientation is apt to yield illusions. Another class of illusions concerns the so-called oblique effect (e.g. Appelle and Countryman, 1986; Lechelt and Verenka, 1980; Gentaz et al., 2008). This effect, also reported in vision, shows itself in more variable performance for oblique orientations (usually 45◦ or 135◦) than for horizontal and vertical orientations (0◦ and 90◦). Gentaz and colleagues (Gentaz et al., 2008) attribute the haptic oblique effect to gravitational cues and memory constraints that are specific for haptics.

4. Concluding remarks

We focused this chapter on the haptic perception of objects and spatial properties and left out all mentioning of the perception of material properties. Using haptic perception, our mind creates a representation of the world around us based on observed curvatures, shapes, sizes, weights, and orientations of objects. It remains to be seen whether all these elements fit together into a consistent representation governed by rules similar to those formulated by Gestalt psychologists for visual perception. As we have seen, the perception of these elements is fraught with illusory effects. The perception of size, orientation, shape, and weight all interact with each other, producing different results in different situations. It is these interactions that may be very instructive in the deconstruction of the haptic perceptual system, and it is for this reason that, in addition to studying the elements in isolation, the interactions between them should be studied and their mechanisms fathomed.

5. References

Appelle, S. and Countryman, M. (1986), 'Eliminating the haptic oblique effect: influence of scanning incongruity and prior knowledge of the standards'. *Perception* 15(3): 325–9.

Armstrong, L. and Marks, L. E. (1999), 'Haptic perception of linear extent'. *Perception & Psychophysics* 61(6): 1211–1226.

Bergmann Tiest, W. M., van der Hoff, L. M. A., and Kappers, A. M. L. (2011), 'Cutaneous and Kinaesthetic Perception of Traversed Distance', in Basdogan, C., Choi, S., Harders, M., Jones, L., and Yokokohji, Y. (eds.), *Proc. IEEE World Haptics Conference*, 593–597 (Istanbul, Turkey: IEEE).

Blumenfeld, W. (1913), 'Untersuchungen über die scheinbare Grösse im Sehraume'. *Zeitschrift für Psychologie* 65: 241–404.

Blumenfeld, W. (1937), 'The relationship between the optical and haptic construction of space'. *Acta Psychologica* 2: 125–174.

Brodie, E. E. and Ross, H. E. (1984), 'Sensorimotor mechanisms in weight discrimination.' *Perception & Psychophysics* 36(5): 477–481.

Carter, O., Konkle, T., Wang, Q., Hayward, V., and Moore, C. (2008), 'Tactile rivalry demonstrated with an ambiguous apparent-motion quartet'. *Current Biology* 18(14): 1050–1054.

Chang, D., Nesbitt, K. V., and Wilkins, K. (2007a), 'The Gestalt principle of continuation applies to both the haptic and visual grouping of elements', in *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)*, 15–20.

Chang, D., Nesbitt, K. V., and Wilkins, K. (2007b), 'The Gestalt principles of similarity and proximity apply to both the haptic and visual grouping of elements', in *Proceedings of the Eight Australasian Conference on User Interface*, volume 64, 79–86 (Darlinghurst, Australia: Australian Computer Society, Inc.).

Cole, J. and Paillard, J. (1995), 'Living without touch and peripheral information about body position and movement: Studies with deafferented patients', in J L Bermudez, N. E., A Marcel (ed.), *The body and the self*, 245–266 (Cambridge, MA: MIT press).

Davidson, P. W. (1972), 'Haptic judgments of curvature by blind and sighted humans'. *Journal of Experimental Psychology* 93(1): 43–55.

Dostmohamed, H. and Hayward, V. (2005), 'Trajectory of contact region on the fingerpad gives the illusion of haptic shape'. *Experimental Brain Research* 164(3): 387–94.

Ellis, R. R. and Lederman, S. J. (1993), 'The role of haptic versus visual volume cues in the size-weight illusion'. *Perception & Psychophysics* 53(3): 315–324.

Ellis, R. R. and Lederman, S. J. (1999), 'The material-weight illusion revisited'. *Perception & Psychophysics* 61(8): 1564–1576.

Fernández-Díaz, M. and Travieso, D. (2011), 'Performance in haptic geometrical matching tasks depends on movement and position of the arms'. *Acta Psychologica* 136(3): 382–389.

Gallace, A. and Spence, C. (2011), 'To what extent do Gestalt grouping principles influence tactile perception?' *Psychological bulletin* 137(4): 538–61.

Gentaz, E., Baud-Bovy, G., and Luyat, M. (2008), 'The haptic perception of spatial orientations'. *Experimental Brain Research* 187(3): 331–348.

Gibson, J. J. (1933), 'Adaptation, after-effect and contrast in the perception of curved lines'. *Journal of Experimental Psychology* 16(1): 1–31.

Gibson, J. J. (1963), 'The useful dimensions of sensitivity'. *American Psychologist* 18: 1–15.

Gibson, J. J. (1966), *The senses considered as perceptual systems* (Boston: Houghton Mifflin Company).

Goodwin, A. W., John, K. T., and Marceglia, A. H. (1991), 'Tactile discrimination of curvature by humans using only cutaneous information fron the fingerpads'. *Experimental Brain Research* 86(3): 663–672.

Goodwin, A. W. and Wheat, H. E. (1992), 'Human tactile discrimination of curvature when contact area with the skin remains constant'. *Experimental Brain Research* 88(2): 447–450.

Gordon, I. A. and Morison, V. (1982), 'The haptic perception of curvature'. *Perception & Psychophysics* 31: 446–450.

Hayward, V. (2008), 'A brief taxonomy of tactile illusions and demonstrations that can be done in a hardware store'. *Brain Research Bulletin* 75(6): 742–752.

Heller, M. A. (1989), 'Texture perception in sighted and blind observers'. *Perception & Psychophysics* 45(1): 49–54.

Helmholtz, H. v. (1867/1962), *Treatise on physiological optics*, volume 3, (English trans: Southall JPC) for the Optical Society of America (1925) from the 3rd German edition of Handbuch der physiologischen Optik edition (New York: Dover).

Hillebrand, F. (1902), 'Theorie der scheinbaren Grösse bei binocularem Sehen'. *Denkschriften der Wiener Akademie. Mathematisch-Naturwissenschaftliche Klasse* 72: 255–307.

Hohmuth, A., Phillips, W. D., and VanRomer, H. (1976), 'A discrepancy between two modes of haptic length perception'. *The Journal of Psychology* 92(1): 79–87.

Hunter, I. M. L. (1954), 'Tactile-kinaesthetic perception of straightness in blind and sighted humans'. *Quarterly Journal of Experimental Psychology* 6: 149–154.

Ikeda, M. and Uchikawa, K. (1978), 'Integrating time for visual pattern perception and a comparison with the tactile mode'. *Vision Research* 18(11): 1565–71.

Jastrow, J. (1886), 'The Perception of Space by Disparate Senses'. *Mind* 11(44): 539–554.

Jones, L. A. (1986), 'Perception of Force and Weight: Theory and Research'. *Psychological Bulletin* 100(1): 29 – 42.

Kaas, A. and van Mier, H. (2006), 'Haptic spatial matching in near peripersonal space'. *Experimental Brain Research* 170: 403–413.

Kahrimanovic, M., Bergmann Tiest, W. M., and Kappers, A. M. L. (2010), 'Haptic perception of volume and surface area of 3-D objects'. *Attention, Perception & Psychophysics* 72(2): 517–527.

Kahrimanovic, M., Bergmann Tiest, W. M., and Kappers, A. M. L. (2011a), 'Characteriza- tion of the haptic shape-weight illusion with 3-dimensional objects'. *IEEE Transactions on Haptics* 4(4): 316–320.

Kahrimanovic, M., Bergmann Tiest, W. M., and Kappers, A. M. L. (2011b), 'Discrimina- tion thresholds for haptic perception of volume, surface area, and weight'. *Attetion Perception & Psychophysics* 73(8): 2649–2656.

Kappers, A. M. L. (1999), 'Large systematic deviations in the haptic perception of paral- lelity'. *Perception* 28(8): 1001–1012.

Kappers, A. M. L. (2002), 'Haptic perception of parallelity in the midsagittal plane'. *Acta Psychologica* 109(1): 25–40.

Kappers, A. M. L. (2003), 'Large systematic deviations in a bimanual parallelity task: Further analysis of contributing factors'. *Acta Psychologica* 114(2): 131–145.

Kappers, A. M. L. (2004), 'The contributions of egocentric and allocentric reference frames in haptic spatial tasks'. *Acta Psychologica* 117(3): 333–340.

Kappers, A. M. L. (2005), 'Intermediate Frames of Reference in Haptically Perceived Par- allelity', in *Proc. 1st Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 3–11 (Pisa, Italy: IEEE Computer Society).

Kappers, A. M. L. (2007), 'Haptic Space Processing - Allocentric and Egocentric Reference Frames'. *Canadian Journal of Experimental Psychology* 61(3): 208 – 218.

Kappers, A. M. L. (2011), 'Human perception of shape from touch'. *Philosophical Transactions of the Royal Society of London B* 366: 3106–3114.

Kappers, A. M. L. and Koenderink, J. J. (1999), 'Haptic perception of spatial relations'. *Perception* 28(6): 781–795.

Kappers, A. M. L. and Liefers, B. J. (2012), 'What Feels Parallel Strongly Depends on Hand Orientation', in Isokoski, P. and Springare, J. (eds.), *Haptics: Perception, Devices, Mobility, and Communication*, volume 7282 of *Lecture Notes on Computer Science*, 239–246.

Kappers, A. M. L. and Viergever, R. F. (2006), 'Hand orientation is insufficiently compen- sated for in haptic spatial perception'. *Experimental Brain Research* 173(3): 407–414.

Kennedy, J. R. (1993), *Drawing & the blind: Pictures to touch* (New Haven, CT: Yale University Press).

Klatzky, R. L., Lederman, S. J., and Metzger, V. A. (1985), 'Identifying objects by touch: an "expert system".' *Perception & Psychophysics* 37(4): 299–302.

Klatzky, R. L., Loomis, J. M., Lederman, S. J., Wake, H., and Fujita, N. (1993), 'Haptic identification of objects and their depictions'. *Perception & Psychophysics* 54(2): 170–8.

Krishna, A. (2006), 'Interaction of Senses: The Effect of Vision versus Touch on the Elongation Bias'. *The Journal of Consumer Research* 32(4): 557–566.

Langfeld, H. S. (1917), 'The differential spatial limen for finger span'. *Journal of Experimental Psychology* 2(6): 416–430.

Lechelt, E. C. and Verenka, A. (1980), 'Spatial anisotropy in intramodal and cross-modal judgments of stimulus orientation: the stability of the oblique effect'. *Perception* 9(5): 581–589.

Lederman, S. J. and Jones, L. A. (2011), 'Tactile and Haptic Illusions'. *IEEE Transactions on Haptics* 4(4): 273–294.

Lederman, S. J. and Klatzky, R. L. (1987), 'Hand movements: A window into haptic object recognition'. *Cognitive Psychology* 19(3): 342–368.

Lederman, S. J. and Klatzky, R. L. (2009), 'Haptic perception: A tutorial'. *Attention, Perception & Psychophysics* 71(7): 1439–1459.

Lederman, S. J., Klatzky, R. L., Chataway, C., and Summers, C. D. (1990), 'Visual mediation and the haptic identification of 2-dimensional pictures of common objects'. *Perception & Psychophysics* 47(1): 54–64.

Loomis, J. M., Klatzky, R. L., and Lederman, S. J. (1991), 'Similarity of tactual and visual picture recognition with limited field of view'. *Perception* 20(2): 167–77.

Loomis, J. M. and Lederman, S. J. (1986), 'Tactual Perception', in Boff, K. R., Kaufman, L., and

Thomas, J. P. (eds.), *Cognitive Processes and Performance*, volume 2 of *Hand- book of Perception and Human Performance*, Chapter 31, 31.1–31.41 (New York: John Wiley & Sons).

Magee, L. E. and Kennedy, J. M. (1980), 'Exploring pictures tactually'. *Nature* 283: 287–288.

Millar, S. and Al-Attar, Z. (2002), 'The Müller-Lyer illusion in touch and vision: Implications for multisensory processes'. *Perception & Psychophysics* 64(3): 353–365.

Murray, D., Ellis, R., Bandomir, C., and Ross, H. (1999), 'Charpentier (1891) on the size-weight illusion'. *Attention, Perception & Psychophysics* 61: 1681–1685.

Newport, R., Rabb, B., and Jackson, S. R. (2002), 'Noninformative vision improves haptic spatial perception'. *Current Biology* 12(19): 1661–1664.

Norman, J. F., Norman, H. F., Clayton, A. M., Lianekhammy, J., and Zielke, G. (2004),'The visual and haptic perception of natural object shape'. *Perception & Psychophysics* 66(2): 342–51.

Overvliet, K., Krampe, R., and Wagemans, J. (2012), 'Perceptual grouping in haptic search: The influence of proximity, similarity, and good continuation.' *Journal of Experimental Psychology. Human Peception and Performance* 38(4): 817–821.

Panday, V., Bergmann Tiest, W. M., and Kappers, A. M. L. (2012), 'Influence of local properties on haptic perception of global object orientation'. *IEEE Transactions on Haptics* 5: 58–65.

Pawluk, D., Kitada, R., Abramowicz, A., Hamilton, C., and Lederman, S. J. (2010),'Haptic figure-ground differentation via a haptic Glance', in *IEEE Haptics Symposium*, 63–66.

Picard, D. and Lebaz, S. (2012), 'Identifying Raised-Line Drawings by Touch: A Hard but Not Impossible Task'. *Journal of Visual Impairment & Blindness* 106(7): 427–431.

Plaisier, M. A., Bergmann Tiest, W. M., and Kappers, A. M. L. (2008), 'Haptic pop-out in a hand sweep'. *Acta Psychologica* 128: 368–377.

Plaisier, M. A., Bergmann Tiest, W. M., and Kappers, A. M. L. (2009), 'One, two, three, many - Subitizing in active touch'. *Acta Psychologica* 131(2): 163–170.

Pont, S. C., Kappers, A. M. L., and Koenderink, J. J. (1997), 'Haptic curvature discrimination at several regions of the hand'. *Perception & Psychophysics* 59(8): 1225–1240.

Pont, S. C., Kappers, A. M. L., and Koenderink, J. J. (1998), 'Anisotropy in haptic curvature and shape perception'. *Perception* 27(5): 573–589.

Pont, S. C., Kappers, A. M. L., and Koenderink, J. J. (1999), 'Similar mechanisms underlie curvature comparison by static and dynamic touch'. *Perception & Psychophysics* 61(5): 874–894.

Proske, U. and Gandevia, S. C. (2009), 'The kinaesthetic senses'. *The Journal of Physiology* 587(17): 4139–4146.

Robertson, A. (1902), 'Studies from the Psychological Laboratory of the University of California VI 'Geometric-optical' illusions in touch'. *Psychological Review* 9: 549–569.

Robles-De-La-Torre, G. and Hayward, V. (2001), 'Force can overcome object geometry in the perception of shape through active touch'. *Nature* 412(6845): 445–8.

Rossetti, Y., Gaunet, F., and Thinus-Blanc, C. (1996), 'Early visual experience affects memorization and spatial representation of proprioceptive targets'. *Neuroreport* 7(6): 1219–1223.

Stevens, S. S. and Stone, G. (1959), 'Finger span: ratio scale, category scale and JND scale'. *Journal of Experimental Psychology* 57(2): 91–95.

Suzuki, K. and Arashida, R. (1992), 'Geometrical haptic illusions revisited - Haptic illusions compared with visual illusions'. *Perception & Psychophysics* 52(3): 329–335.

Terada, K., Kumazaki, A., Miyata, D., and Ito, A. (2006), 'Haptic Length Display Based on Cutaneous-Proprioceptive Integration'. *Journal of Robotics and Mechatronics* 18(4): 489–498.

van der Horst, B. J., Duijndam, M. J. A., Ketels, M. F. M., Wilbers, M. T. J. M., Zwijsen, S. A., and Kappers, A. M. L. (2008a), 'Intramanual and intermanual transfer of the curvature aftereffect'. *Experimental Brain Research* 187(3): 491–496.

van der Horst, B. J. and Kappers, A. M. L. (2008), 'Using curvature information in haptic shape perception of 3D objects'. *Experimental Brain Research* 190(3): 361–367.

van der Horst, B. J., Willebrands, W. P., and Kappers, A. M. L. (2008b), 'Transfer of the curvature aftereffect in dynamic touch'. *Neuropsychologia* 46(12): 2966–2972.

van Polanen, V., Bergmann Tiest, W. M., and Kappers, A. M. L. (2012), 'Haptic search for hard and soft spheres'. *PLOS One* 7(10): e45298.

Vogels, I. M. L. C., Kappers, A. M. L., and Koenderink, J. J. (1996), 'Haptic aftereffect of curved surfaces'. *Perception* 25(1): 109–119.

Vogels, I. M. L. C., Kappers, A. M. L., and Koenderink, J. J. (1997), 'Investigation into the origin of the haptic after-effect of curved surfaces'. *Perception* 26: 101–107.

Volcic, R. and Kappers, A. M. L. (2008), 'Allocentric and egocentric reference frames in the processing of three-dimensional haptic space'. *Experimental Brain Research* 188(2):199–213.

Volcic, R., Kappers, A. M. L., and Koenderink, J. J. (2007), 'Haptic parallelity percep- tion on the frontoparallel plane: the involvement of reference frames'. *Perception & Psychophysics* 69(2): 276–86.

von Skramlik, E. (1937), *Psychophysiologie der Tastsinne* (Leipzig: Akademische Verlagsgesellschaft).

Weber, E. H. (1834/1986), *E.H. Weber on the tactile senses*, H. E. Ross and D. J. Murray edition (Erlbaum (UK) Taylor & Francis).

Weinstein, S. (1968), 'Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality', in Kenshalo, D. (ed.), *The skin senses*, 195–222 (Springfield, IL: Thomas).

Wijntjes, M. W. A., Sato, A., Hayward, V., and Kappers, A. M. L. (2009), 'Local surface orientation dominates haptic curvature discrimination'. *IEEE Transactions on Haptics* 2(2): 94–102.

Wijntjes, M. W. A., van Lienen, T., Verstijnen, I. M., and Kappers, A. M. L. (2008), 'The influence of picture size on recognition and exploratory behaviour in raised-line drawings'. *Perception* 37(4): 602–14.

Zuidhoek, S., Kappers, A. M. L., van der Lubbe, R. H. J., and Postma, A. (2003), 'Delay improves performance on a haptic spatial matching task'. *Experimental Brain Research* 149(3): 320–330.

Zuidhoek, S., Visser, A., Bredero, M. E., and Postma, A. (2004), 'Multisensory integration mechanisms in haptic space perception'. *Experimental Brain Research* 157(2): 265–268.