Haptic perception

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Fueled by novel applications, interest in haptic perception is growing. This paper provides an overview of the state of the art of a number of important aspects of haptic perception. By means of touch we can not only perceive quite different material properties, such as roughness, compliance, friction, coldness and slipperiness, but we can also perceive spatial properties, such as shape, curvature, size and orientation. Moreover, the number of objects we have in our hand can be determined, either by counting or subitizing. All these aspects will be presented and discussed in this paper. Although our intuition tells us that touch provides us with veridical information about our environment, the existence of prominent haptic illusions will show otherwise. Knowledge about haptic perception is interesting from a fundamental viewpoint, but it also is of eminent importance in the technological development of haptic devices. At the end of this paper, a few recent applications will be presented. © 2013 John Wiley & Sons, Ltd.

INTRODUCTION

In 2005 the first World Haptics Conference was organized and since then this biannual conference has attracted researchers from all over the world. In 2008, a specialized journal, the IEEE Transactions on Haptics, was launched. These two new developments clearly indicate that interest in haptic perception research is growing rapidly. The major driving force is technological progress, in particular in the field of robotics. There has been an enormous increase in the development of mobile devices and haptic displays. In order to design and create tools and devices that are meant to have a haptic perception component [think of teleoperator or remote sensing devices (see below), but also of touch screens, prosthetic hands and arms, etc.], it has been realized that fundamental knowledge about haptic perception is necessary or at least useful. Now that computer-processing power is no longer a bottleneck, visual and/or auditory feedback can be accompanied by haptic feedback.

Research into haptic perception is also progressing thanks to the surprisingly fast development of 3D printers with which very precise haptic stimuli can be created. Usually, the limits of haptic perception are investigated in terms of discrimination thresholds or matching performance. As shown below, haptic discrimination thresholds can be quite small, and to be able to investigate these, stimuli that differ only in small well-defined details are necessary. Ten years ago an expensive computer-controlled milling machine was needed to manufacture the stimuli, but now quite a number of labs possess their own 3D printer. A final important cause of the increasing interest in haptic perception is that multimodal perception is gaining in attention. Insights into certain brain mechanisms and the level of processing of information can be obtained by studying interactions or parallels between, for example, vision and touch. An increasing number of vision labs started recently to devote part of their time to haptic perception.

In daily life we manipulate, use and explore objects the whole day, so it is of scientific interest to know what kind of information about objects we can derive from just touching (see Box 1). When interacting with objects haptically, we obtain information about the object's material properties, shape, size, orientation in space, and also how many objects there are (numerosity). In what follows,

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these aspects are reviewed. There are many ways to investigate haptic perception experimentally. One promising way to study which kinds of object or material properties are salient for human perception is to employ a search paradigm (see Box 2). Although sometimes believed otherwise, haptic perception is just as vision and audition susceptible to illusions. Some illusions are discussed that provide insight in the way haptic information is processed by the perceptual system. Finally, possible applications of fundamental knowledge about haptic perception are mentioned.

BOX 1

EXPLORATORY PROCEDURES

Humans make active hand movements while haptically exploring objects. Lederman and Klatzky[1] investigated how specific certain movements belonged to the exploration of certain object features. They classified eight typical movement patterns, which they termed 'exploratory procedures' or EPs. The six EPs that can be used for all objects are the following: the EP 'Lateral motion', a quick back and forth movement, is typically used when exploring textures; 'Pressure' is used when the hardness or softness of an object has to be determined; 'Static contact' is mainly used for estimating temperature; 'Unsupported holding' is used for judging weight; 'Enclosure' is the EP typically used for estimating the size of an object; 'Contour following' is the preferred EP when the exact shape of an object needs to be determined (see Figure 1). Lederman and Klatzky[1] showed that the use of these EPs in acquiring information about a certain object property is not only sufficient, but also optimal and often even necessary.

MATERIAL PROPERTIES

The haptic sense can provide us with information about what an object is made of. The most notable aspects of an object's material properties are its roughness, compliance, coldness, and slipperiness (friction).[8] The heaviness of the object also depends on its material properties through the material's density (specific weight). For liquids, the viscosity is an important material property. This section discusses these aspects in relation to haptic perception.

Roughness

Roughness is related to the small-scale unevenness of an object's surface. When the object is pressed against


BOX 2

SEARCH PARADIGM AND SALIENCY

In vision research, a search paradigm is a useful method to investigate the saliency of features.[2] A target item is presented among distractor items and the time it takes an observer to find the target (or to decide there is no target) is a good measure of its relative saliency. If a target is very salient, the response time will not or hardly depend on the number of surrounding distractors. An example of such a salient target is a red disk among blue disks. The red disk is said to 'pop-out' and the search slope, that is the slope of the line showing the relation between the response time and the number of distractors, is rather flat, almost horizontal. As all items are assessed at the same time, this type of search is termed 'parallel'. A less salient feature, for example, a letter 'O' among letters 'Q', will be much harder to find and the response time will depend on the number of distractors (the number of letters Q). The search slope will be nonzero, as the observer has to look at all individual items to decide whether it is an O. As the items are assessed one by one, this is an example of a 'serial' search.

This search paradigm has successfully been adapted for haptic research. The items can either be pressed to the fingers,[3,4] presented on a display over which participants sweep their hands,[5,6] or presented in a bunch that participants have to grasp[7] (see also the set-up in Figure 9).

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the skin, this results in an uneven pressure distribution that can be sensed. Furthermore, when the fingers are stroked over the object, this causes vibrations that can also be picked up. The roughness of the coarser surfaces can be perceived either with or without movement.[9] However, for smoother surfaces, with surface features smaller than 30 μm, the variations in pressure are too small to be perceived. Moving over such a surface still produces vibrations that can be perceived. Therefore, movement is necessary to perceive the roughness of surfaces with features smaller than 30 μm. In this way, roughness down to a feature size of 9 μm can be perceived.[9]

Since roughness is mediated partly by vibrations, it can also be perceived when a surface is touched using a rigid probe instead of directly with the fingers. In such a situation, discrimination between different levels of roughness is not as good as with the fingers
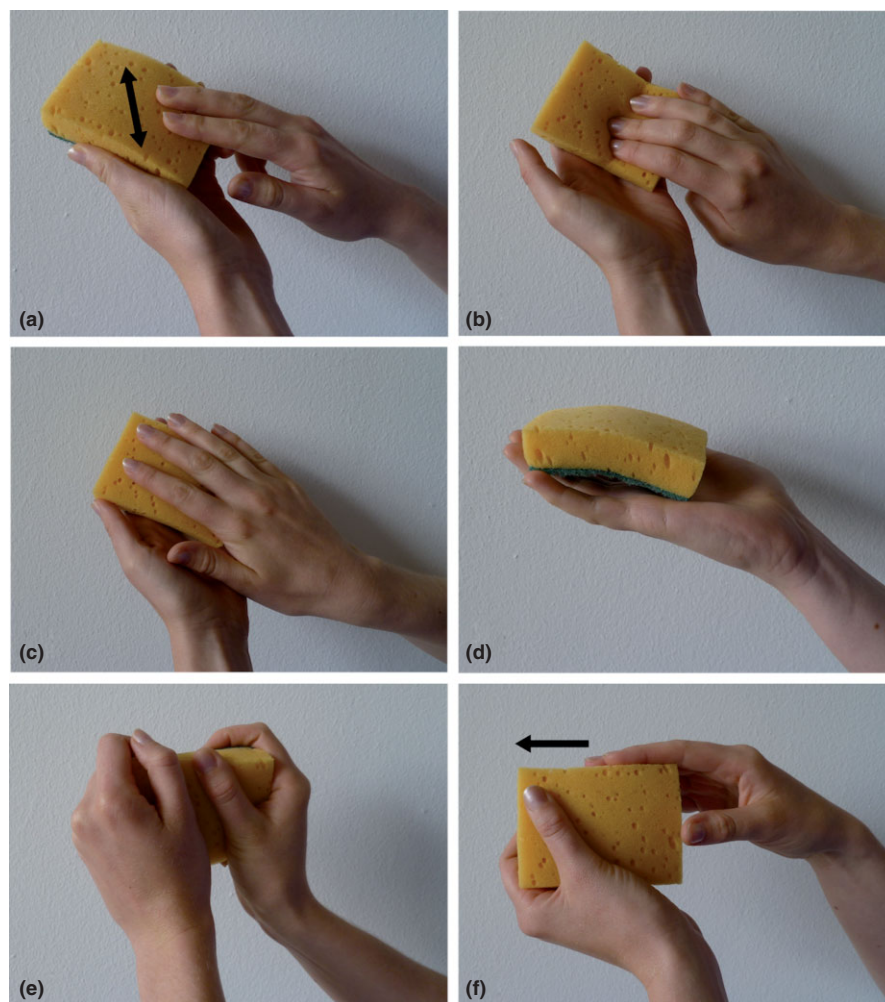
FIGURE 1 | Illustration of the six most prominent exploratory procedures, as defined by Lederman and Klatzky.[1] (a) Lateral motion; (b) pressure; (c) static contact; (d) unsupported holding; (e) enclosure; (f) contour following.

directly touching the surface, but the intensity of the perceived roughness is higher.[10] This is thought to be because the rigid probe can enter the narrow spaces between surface features that the fingers cannot enter.

The relationship between perceived roughness and physical roughness can be measured, for example, with a magnitude estimation experiment. Participants have to explore stimuli of different roughnesses and they have to rate the roughness on a certain scale (e.g., between 1 and 100, with 1 being very smooth and 100 very rough). It was found that when physical roughness is expressed as a sandpaper grit size, perceived roughness is related to physical roughness by a power function. The exponent of this power function lies around 1.5.[11] That is, when the surface's physical roughness doubles, the perceived roughness increases 2.8-fold (note that an exponent of 1 indicates a linear relationship and 2 indicates a quadratic relationship). This relationship is valid for both active touch (the

subject moves his/her finger over the surface) and passive touch (the surface is moved over the finger).[12]

Roughness perception is subject to adaptation processes. This means that after prolonged exploration of a surface of a certain roughness, the perceived roughness of a subsequent surface might be changed. The vibrational component of roughness perception, which is most important when perceiving fine textures, can be reduced in sensitivity by adapting to vibration with a frequency of 100 Hz.[13] This type of adaptation is thought to occur at the level of the mechanoreceptors in the skin. Further evidence for this role of mechanoreceptors in adaptation was found in a study where participants explored textures while holding a rigid probe.[14] In a direct touch condition in this same study, no adaptation occurred for the coarser textures, suggesting that cells at the level of the cortex are less susceptible to adaptation (or that their role in roughness perception is just minor). However,

adaptation can also occur at a higher level: a texture that is felt just after a smooth texture has been felt, feels rougher than the same texture when it is felt after a rough texture has been felt.[15] The fact that this type of adaptation *increases* the intensity of the perceived roughness suggests that it occurs not at the receptor level, but at the level of the processing of the signals in the central nervous system.

Compliance

Compliance is an object's ability to deform. This can be perceived haptically in different ways: when the object is squeezed by the fingers, the contact area and the pressure distribution change depending on the squeezing force and the object's compliance. This is mainly a cutaneous sensation, related to pressure on the skin. In addition, when force is applied to the object, the surface is displaced a certain amount, depending on the object's stiffness (spring constant). This is mainly a kinesthetic sensation, related to force and movement perception.[16,17] In this last way, compliance can be perceived without direct contact of the fingers with the object, for example, with a tool. Using that method, stimuli in the high range of hardness were perceived as softer than with direct contact.[18]

Similar to roughness perception, perceived compliance is related to physical compliance by a power law.[19] However, for compliance perception, the exponent is less than 1, namely 0.8. This means that the relation becomes less steep with increasing compliance: when physical compliance doubles, perceived compliance increases 1.7-fold.

In the normal situation, both the surface deformation and the force/displacement ratio contribute to the perception of compliance. The sizes of the respective contributions can be quantified by measuring discrimination thresholds in different situations. In such a discrimination experiment, pairs of stimuli differing in compliance are presented to the subject, who has to choose the harder stimulus in each pair, as shown in Figure 2. By changing the magnitude of the difference between the two stimuli in a pair, the just noticeable difference (JND) can be pinpointed. Srinivasan and LaMotte[20] showed that in their experiment with a set of rubber stimuli of different compliances, tactile but not kinesthetic information was sufficient for pairwise discriminations. For compliance discrimination with surface deformation and force/displacement ratio cues present, the JND is about 15% of the reference compliance value.[21] When the surface deformation cue is removed by inserting rigid steel discs between the stimulus and the subject's fingers, the threshold is about 50% of the reference value.[21] From this it can be


FIGURE 2 | A blindfolded subject compares the compliance of two silicon rubber cylinders in a discrimination experiment.

concluded that by far the most information is derived from the surface deformation cue, which is consistent with the findings of Srinivasan and LaMotte.[20]

Coldness

When two different objects are touched, one might feel colder than the other, even though they are at the same temperature (room temperature). Usually, a metal object or surface feels colder than wood, for example. This is because of differences in the rate at which heat is extracted from the skin upon touch. This rate is determined by the thermal properties of the material, the geometry of the object, and the thermal contact resistance between skin and object. The thermal properties include the heat capacity (the amount of energy needed to heat up the material 1°) and thermal conductance (the amount of heat transported per second through the material for a given temperature difference). These parameters determine the heat flow over time through the object, together with the geometry of the object: heat flows slower through a long, thin object than through a short, thick object. This heat flow, combined with the thermal contact resistance, determines the heat extraction rate when the object is touched. The contact resistance depends on the surface texture: a rough surface has a smaller contact area with the fingers, and therefore a higher contact resistance.

The heat extraction rate can be perceived and used to obtain information about the object's material, as illustrated in Figure 3 (bottom row). In an experiment with six different materials, subjects could reliably discriminate between copper, bronze, and stainless steel on the one hand, and epoxy, plastic, and foam, on the other, based on thermal cues.[22] Foam and epoxy could also be discriminated. In addition to the material's thermal properties, the role of
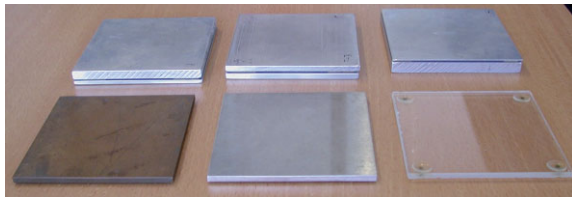
FIGURE 3 | Top row: aluminum blocks with different thickness can be distinguished based on their thermal behavior. Bottom row: different materials (from left to right: copper, aluminum, and acrylic glass) with the same surface texture can be distinguished if their thermal properties differ sufficiently: copper and aluminum are easily distinguished from acrylic glass, but not so easily from each other.

object geometry was shown to be important in an experiment with blocks of aluminum of nine different thicknesses (1–9 mm).[23] Subjects touched only the top surface of the blocks and could discriminate between blocks differing 6 mm in thickness, just based on perceived coldness. In general, differences in heat transfer rate of approximately 43% can be discriminated.[24] This makes the perception of coldness a useful tool in discrimination and recognition of object materials.

Friction

Friction is the resistance against movement over a surface. When the fingers are moved over such a surface, friction can be perceived through forces experienced in the limbs (kinesthetic cues) and through skin stretch (cutaneous cues). A correlation coefficient of 0.85 was measured between physical and perceived friction using four different materials.[25] Discrimination experiments regarding friction perception have not yet been performed with real materials. In a friction discrimination experiment with simulated stimuli using a force-feedback device, thresholds between 18 and 27% were found.[26] This is based on purely kinesthetic perception. When the authors introduced skin stretch, perceived friction increased significantly. This indicates the importance of this cutaneous cue for friction perception.

Viscosity

The material properties discussed so far all relate to solid objects. For *liquids*, the most important haptic material property is the viscosity, or 'thickness' of the liquid. Similar to friction, viscosity causes resistance against movement, in this case to a rod or finger moving through the liquid. Viscosity can be perceived kinesthetically by sensing the movement velocity and resistive force. Again, a power law was found relating physical to perceived viscosity, with an exponent of

0.43.[27] This means that perceived viscosity 'levels off' with increasing physical viscosity.

Discrimination experiments were performed using a large number of different silicone liquids, as shown in Figure 4. For the highest viscosity (thickest liquid), the discrimination threshold for stirring with a spatula was about 30% of the reference viscosity.[28] For lower viscosities (thinner liquids), this fraction increased up to 100% for liquids as thin as water, meaning that it is relatively harder to distinguish thinner liquids from each other than thicker liquids.

Density and Weight

Although object heaviness (weight) is not a material property, it is discussed in this section because it is used to estimate an object's density, which is an important cue for haptic material perception. Heaviness can be perceived in two ways: when an object is held statically, the gravitational force can be sensed. In addition, when an object is moved about, the inertial force (the resistance against a change in speed or direction) can also be used.[29] However, heaviness based on this inertial force alone is perceived as half of that based on gravitational force alone.[30] This is remarkable, and suggests that accelerated or decelerated objects are perceived as lighter than objects of the same physical weight held in the hand. Regarding weight discrimination, thresholds were around 12% of the reference weight when just inertial forces were present,[31] and went as low as about 8%[31] or even 6.6%[32] with both inertial and gravitational forces available.

There are a large number of different relationships found between perceived heaviness and physical weight, as reviewed by Jones.[33] Mostly, power functions were found, but their exponents range between 0.7 and 2.0. These disparate findings might be because of the many different ways of judging weight. For instance, the perceived weight of an object lying on the hand depends on the contact area[34]: the smaller the contact area, the larger the perceived weight. This might be related to the well-known size–weight illusion, in which a smaller object of equal weight is perceived as heavier than a larger one. Although primarily known from the visual domain, this illusion has also been demonstrated in a purely haptic situation.[35]

SPATIAL PROPERTIES

The haptic sense does not only provide us with knowledge about the material properties of an object, but also about its spatial properties, such as shape, size, and orientation. An important aspect of many smooth objects' shape is local curvature, which has been

FIGURE 4 | Cups with silicone oils ranging from very thin to highly viscous, used for viscosity discrimination experiments.

studied in detail. Length and volume are important aspects of size. In this section, the haptic perception of shape, curvature, length, volume, and orientation will be presented. What we do not cover in this section is the perception of two-dimensional shape. For the interested reader we refer to, for example, Refs 36–41.

Shape

Shapes of objects are not only recognized by vision, but also by means of touch. In clinical practice, a stereognosis (haptic perception of objects) test has since long been used to investigate the sensory functions of various types of patients. Typical times for the recognition of common objects in normal subjects are about 2 s.[42] One of the first to investigate the haptic perception of shape in a quantitative way was Gibson.[43] He gave a sculptor the instruction to create a set of hand-sized objects that were equally different in shape from each other, contained six smooth protuberances and had a regular convex backside.[44] He concluded that observers were well able to distinguish such objects by touch alone. In 1985, Klatzky et al.[45] published an experiment that looks like a game on a children's birthday party: blindfolded observers had to recognize as fast as possible three-dimensional familiar objects. This paper showed once again that human observers are indeed very well able to recognize quickly and accurately such objects by touch. Both these studies provided important information about haptic shape perception, but as the stimuli used in these studies were not well-described, they did not lead to insights on how shape is perceived.

Roland and Mortensen[46] designed a set of aluminum stimuli that were fully quantified, such as spheres, ellipsoids, and parallelepipeds of different sizes and they all had the same weight (the spheres were hollow) and surface properties. Moreover, the ellipsoids and parallelepipeds also had the same volume. They performed various shape discrimination experiments, for example, discriminating the size of spheres or the oblongness of ellipsoids or parallelepipeds and studied the way participants explored the shapes. In this way, they got information about

which geometrical aspects of the stimulus were used most. They made a start at modeling somatosensory detection, but clearly there was need for further quantitative research. Kappers et al.[47] created a set of convex and concave, elliptic and hyperbolic paraboloids of different sizes. Participants were first made familiar with the Shape Index scale[48] and subsequently, they had to classify the shapes. The curvedness, that is a measure of the curvature of the stimuli, was systematically varied. They found that hyperbolic shapes were slightly more difficult to classify than elliptic ones. Increasing the curvedness, increased the number of correct classifications.

Norman et al.[49] created a set of 'natural' shapes by making plastic copies of 12 bell peppers. With this set they performed several unimodal (vision or touch) and bimodal discrimination and matching experiments. As the results obtained in the various modality conditions were overall quite similar, their main conclusion from this study was that haptics and vision have functionally overlapping (but not necessarily identical) representations of 3D shape. In another study using the same stimuli, they found that blind observers (early and late blind, but not congenitally blind) performed better in a haptic discrimination with these 3D shapes than blindfolded observers. They suggest that visual experience may play a role in haptic shape discrimination.[50] Recently, Gaissert and Walraven[51] used real natural objects, namely a set of sea shells, in their experiments. Participants had to either rate the similarity of pairs of shells, or to categorize the stimulus set in 2, 3, or 6 groups. Different participant groups did the experiments either visually (without touching the stimuli) or haptically (while being blindfolded). Their main conclusion was that haptic and visual similarity perception are linked by the same cognitive processes.

Curvature

Curvature is one of the geometric shape properties that have been studied extensively. Hunter[52] and later Davidson[53] studied what they termed the 'objective' perception of curvature in both blind and sighted
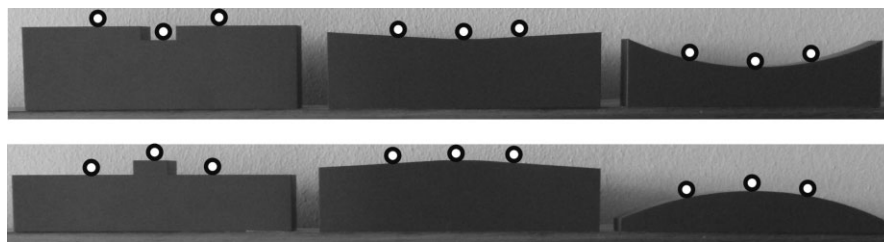
FIGURE 5 | Examples of the stimuli used in the study by Pont et al.[58] Upper row: concave stimuli. Bottom row: convex stimuli. In the experiments, the fingers are placed at the locations indicated by the circles. From left to right the stimuli contain just zeroth order information (height), zeroth and first order (height and slope) and zeroth, first and second order (height, slope and curvature). In order to discriminate two stimuli, the height difference in the zeroth order stimuli has to be much higher than the height difference in the stimuli that also contain first order information. For clarity, all stimuli in these examples are above threshold.

observers. In each trial, their observers had to judge whether a stimulus was convex, concave or straight. Both studies concluded that blind observers gave more objective judgments than sighted observers, by which they mean that the blind classified more stimuli correctly. However, Davidson[53] also showed that if sighted observers were instructed to use the scanning strategies used by blind observers, their performance improved. A more quantitative study was performed by Gordon and Morrison.[54] Using small plano-convex lenses as stimuli, they measured curvature detection and discrimination thresholds. A threshold is a measure of what observers can discriminate and it is important to investigate which aspect(s) of the stimuli determine the threshold. Gordon and Morrison found that the base-to-peak height of the threshold stimulus divided by half its length is more or less constant. This means that the overall gradient of the stimulus determines the curvature discrimination threshold.

Whereas the previous studies used active touch, Goodwin et al.[55] pressed small, highly curved stimuli to the fingers. In this way, only cutaneous receptors were stimulated and the possible influence of kinesthetic perception on curvature perception was excluded. They found that a 10% difference in curvature could be discriminated. In another condition, observers had to estimate the curvature. It turned out that estimated curvature directly correlated with contact area. To investigate the influence of contact area, this was kept constant in a subsequent study.[56] Discrimination thresholds remained the same, so observers do not (have to) use contact area to discriminate curvature. However, a larger constant contact area resulted in better performance. As the gradient increases when curvature remains the same and contact area is larger, this finding is consistent with that of Gordon and Morrison[54] for active touch.

Pont and colleagues[57] measured curvature discrimination thresholds for much larger stimuli (curved strips), which were aligned along or across the fingers. In line with the previous findings, they also found that discrimination thresholds decreased with increasing length of the stimuli and therefore, they concluded that the local slope determines the curvature discrimination threshold. In a follow-up study, they investigated this more specifically by using stimuli that contained only height differences (zeroth order information), height and slopes (first order information) or height, slopes and local curvature information (second order information)[58] (see Figure 5). Blindfolded observers had to place three fingers on the stimuli and again discriminate between two stimuli. It turned out that performance with the stimuli that just contained height information was much worse than with those that also contained slope information. Therefore, the height difference in the curved stimuli could not be the determining factor for the curvature discrimination threshold as the height differences were below threshold. On the other hand, slope information was sufficient because the addition of local curvature information did not change or improve the thresholds. In their first study,[57] they also compared performance with the palmar side of the hand to that with the dorsal side. Performance with the palmar side was significantly better, indicating again that cutaneous receptors play an essential role in curvature discrimination, as the density of these receptors is much lower on the dorsal side of the hand.

Increasing the length of the stimuli not only causes a decrease of the curvature discrimination threshold, but it also increases the perceived curvature of the stimulus.[58] This has an interesting implication: since most hands are longer than wide (see Figure 6), a spherical object would not feel spherical but ellipsoidal. Pont et al.[59] tested and could confirm this prediction.

The experiments with the zeroth, first, and second order information in the stimuli could necessarily only be done with static touch using three fingers, but
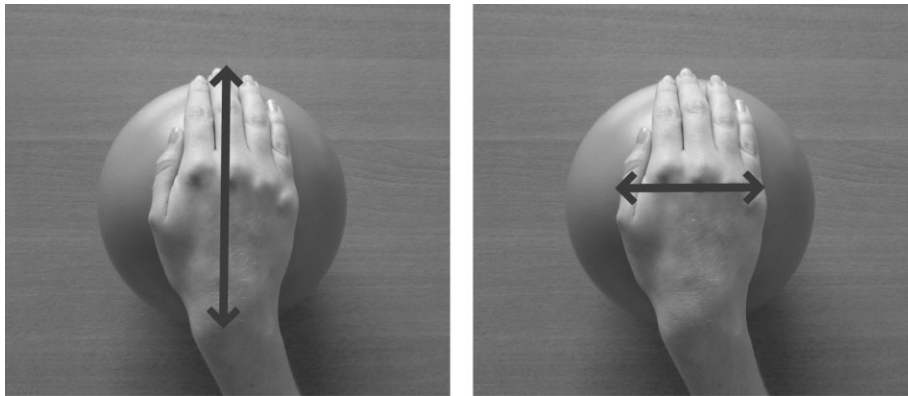
FIGURE 6 | For most hands the length is larger than the width. This has repercussions for the perception of curvature. As length of the stimulus has a direct influence on perceived curvature, a spherical surface will feel more curved along the fingers than across the fingers.[59]

the intriguing question was whether the importance of the slope information also holds for judging curvature dynamically. Wijntjes et al.[60] used a device which made such research possible. The observer had to place a finger on a small metal plate, which could move along a trajectory as if the finger moved along a curved surface. Orientation of this plate could vary consistently with the local slope of the simulated surface, or could remain horizontal, so that only height information and not slope was available to the observer. They compared curvature discrimination performance for a number of conditions: just height (zeroth order) information, just slope information (first order), height and slope, and real stimuli. They showed that curvature discrimination thresholds were the same as soon as first order information was available; stimuli containing just height information led to much higher discrimination thresholds. So the importance of local slope for the perception of curvature has been demonstrated for both static and dynamic touch.

Length

The size of objects and more in particular their length, can be assessed with several methods. For relatively small objects, the so-called finger-span method is suitable.[61,62] The object's length is estimated by grasping it between thumb and index or middle finger. It has been found that estimated length is monotonically but not linearly related to physical length.[62] The threshold for discrimination of length using this method lies around 1 mm.[63] For objects of larger size, this method can no longer be used and it becomes necessary to move a finger or hand over the whole length of the object. The former method is mainly based on kinesthetic information (information from the muscles and joints), whereas in the second method, cutaneous information provided by the

mechanoreceptors in the skin is added. This latter method is less accurate than the finger-span method.[64] By moving a stimulus under a fixed fingertip, length perception using only cutaneous information could be tested.[65] Performance in such an isolated condition is much worse than when kinesthetic information (the finger tip moves over the surface) is also present.

Volume

A three-dimensional measure of an object's size is its volume. Recent studies show that the haptic perception of volume is influenced by the shape of the object.[66,67] Krishna[66] investigated participants' judgment of the volume of plastic cylindrical glasses. She found that wider glasses were estimated to have a larger volume than taller glasses, even though their actual volume was the same. Interestingly, this effect is opposite to that found in vision or in bimodal perception. She argued that the more salient dimension influenced the judgment; for vision this is height, whereas for haptics this is width. Kahrimanovic et al.[67] compared haptic volume perception of spheres, cubes and tetrahedrons. They found that for objects to be perceived as having the same volume, a sphere has to be more than 60% larger than that of a tetrahedron and about 30% larger than that of a cube. As the total surface area of a tetrahedron is larger than that of a sphere (49%) and a cube (20%), they tested the hypothesis that participants (unconsciously) used surface area instead of volume to perform this task. Indeed, when participants were explicitly instructed to discriminate the surface area (and not the volume) of the various shape combinations, the biases almost disappeared. Finally, they wondered what would happen if surface area of the objects was removed. This was not possible for the spheres, but wire frame stimuli of cubes and tetrahedrons could be

constructed. Volume discrimination experiments with the wire frame stimuli led to even larger biases than with the solid stimuli. In this condition, the biases correlated with the maximum distance between two vertex points within an object. Like in Ref 66, these authors also conclude that salient object properties have a large influence in haptic perception of volume.

Orientation

Inspired by interesting effects in visual perception, Blumenfeld[68] was one of the first researchers investigating the haptic perception of orientation. Using two needles fixed on a board symmetrically to the median plane and two threads attached to these needles, he asked blindfolded observers to pull the threads in such a way that they felt parallel to each other and to the median plane. He reported systematic deviations: when the two needles were close to each other, the threads diverged towards the shoulders, but when the two needles were far apart, the threads converged towards the shoulders (see upper panel of Figure 7).

Kappers and colleagues set up a new line of research investigating these systematic deviations in orientation perception in a much more detailed way.[69–72] A typical task is to match the orientation of two bars: the orientation of one of the bars (the reference bar) is fixed by the experimenter and the blindfolded participant has to rotate a test bar at another location in such a way that it feels parallel to the reference bar. This task can be performed unimanually, moving one hand from the reference bar to the test bar,[69] or bimanually.[70,72] In the latter case, the hands can touch the bars simultaneously[70] or sequentially.[72] In all conditions, the deviations found are substantial and systematic: for two bars to be perceived as haptically parallel, the right bar has to be rotated clockwise with respect to the left bar (see lower panel of Figure 7 for an example).

The deviations can be explained in terms of reference frames. The task of the observers is to make two bars parallel in a physical (allocentric) reference (see Figure 8). However, observers have to use their own body to decide what is parallel and thus they make use of egocentric reference frames. As can be seen in Figure 8, parallel in an egocentric reference frame fixed to the hand is not necessarily equal to parallel in an allocentric reference frame. In practice, what is perceived as parallel lies in between egocentrically and allocentrically parallel.[71] That is, the orientation settings are biased in the direction of the egocentric reference frame. In the example

FIGURE 7 | Illustration of the parallelity tasks. Above: The task used by Blumenfeld. The participant has to straighten the two threads in such a way that they feel parallel both to each other and to the median plane. Below: The task used by Kappers and colleagues. The participant has to rotate the right bar in such a way that it feels parallel to the left bar.

of Figure 8, the egocentric reference frame is hand-centered, but also a reference frame fixed to the body might play a role.[71] The deviations are strongly subject-dependent, which suggests that the degree of reliance on egocentric reference frames varies from person to person.

The evidence for the frame of reference explanation is rapidly accumulating. Some of the most convincing arguments follow here: First, a delay between touching the reference and test bars counterintuitively reduces the deviations.[72] The hypothesis is that a time delay induces a shift from egocentric to more allocentric reference frames.[73] Second, when participants are not blindfolded, but are allowed to look around in the experimentation room (without seeing the stimuli), their performance improves.[74,75] Here the hypothesis is that non-informative vision provides sensory awareness for a more allocentric reference frame, thus reducing the biasing influence of
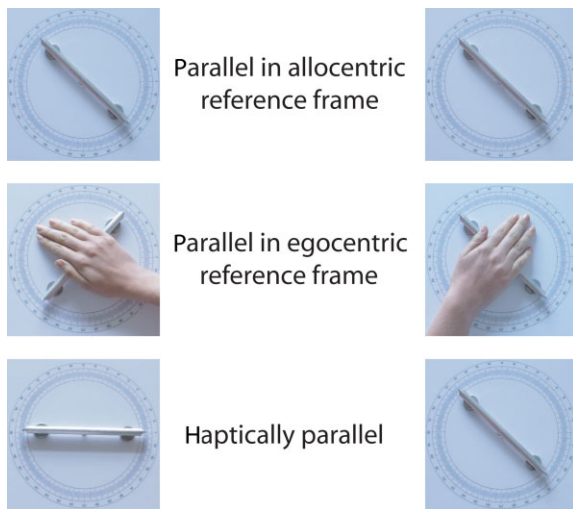
FIGURE 8 | Illustration of the reference frames. The right column shows the reference bar, which has the same orientation in all cases. The left column shows the test bar. Top: Allocentric reference frame; the test bar has the same physical orientation as the reference bar. Centre: Hand-centered egocentric reference frame; the test bar has the same orientation with respect to the hand as the reference bar. Bottom: Haptically parallel; what observers perceive as parallel bars lies in between allocentrically and egocentrically parallel.

the egocentric reference frame. Third, when participants are requested to hold their hands in a prescribed orientation, the deviations clearly change with hand orientation.[76,77] Thus, by rotating the orientation of the egocentric hand reference frame, the size of the deviations can be manipulated. Finally, if participants have to adjust a table full of bars making them all parallel, the resulting pattern is far from veridical, but again corresponds with deviations in the direction of the local hand orientation.[78]

Another finding concerning orientations is the so-called 'haptic oblique effect': in matching or discrimination tasks, performance is better with cardinal (i.e. horizontal and vertical) orientations than with oblique orientations.[79,80] Gentaz and colleagues have investigated this effect in great detail.[81] They found that also blind observers[82] and children[83] are susceptible to this effect. Interestingly, they report that the haptic oblique effect can be absent in some conditions, which is unlike the visual oblique effect. In conditions where gravity plays a role, the oblique effect is observed, but gravity is not necessary for its occurrence. They conclude that the haptic oblique effect originates at a high level in the brain.

A final topic of interest with respect to orientations is the discrimination of two-dimensional angles. This becomes relevant in the understanding of human shape discrimination, as angles are an important aspect of many shapes. Voisin et al.[84]

made a set of Plexiglas angles of 91–103°which the participants had to discriminate from an angle of 90°. They showed that for this reference angle, the discrimination threshold (75% correct) was 4.7°. Similar thresholds were found by Levy et al.,[85] who also found that the thresholds for static and dynamic exploration of the stimuli was not significantly different. Using raised line drawings of angles, Wijntjes and Kappers[86] report for more acute angles (20°) an even smaller threshold of 2.9°. They also showed that thresholds do depend on exploration strategy.
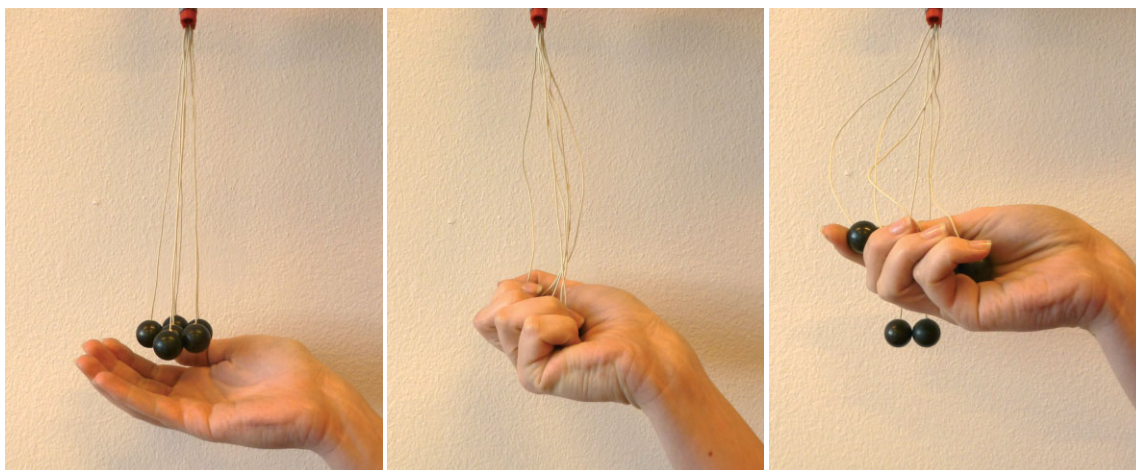
NUMEROSITY

Subitizing is the phenomenon that observers can rapidly and accurately (i.e., error-free) judge the quantity of a (small) number of items. For larger numbers of items (above three or four), observers are slower and more error-prone. This phenomenon has mostly been studied in vision, but recently a few studies were published showing that subitizing also occurs in touch.[87,88] In a passive tactile experiment, Riggs et al.[87] stimulated a varying number of fingers of observers with small metal rods and observers had to respond as quickly as possible the number of fingers stimulated. They report faster responses and higher accuracies for up to three fingers. Plaisier et al.[88] let observers actively grasp bunches of spheres (see Figure 9) and also in this situation enumeration of up to three items is more efficient than for larger number of items. In additional experiments, they could show that the relatively good performance with lower numbers of items was not due to the larger relative differences between the numbers of items. Moreover, these authors could also rule out that mass or volume estimation was the cause of this enhanced performance with lower numbers of items. The finding that subitizing not only occurs in vision, but also in tactile and haptic perception suggests that this is a modality-independent process.

Not all studies in the touch domain show subitizing. Gallace et al.[89] presented various numbers of vibrotactile stimuli over the body surface, but they did not find a discontinuity of performance between lower and higher numbers of stimuli. However, it should be noted that in this particular task error rates were extremely high (up to 90%), so apparently, observers are not really able to do the task in this way.

ILLUSIONS AND AFTER-EFFECTS

It is well known that vision is susceptible to illusions and it is often thought that touch provides the observer

FIGURE 9 | Illustration of stimuli and procedure in a numerosity judgment experiment. Left: An observer is ready to grasp a bunch of six items. Centre: An observer grasped the bunch and determines the number of items. For low numbers (up to three) the observer can subitize and knows the number right away; for higher numbers the observer has to count. Right: The observer counts the number and this is usually done by throwing items out of the hand. This same set-up is also used for haptic search experiments.

with veridical information about the environment. However, also in touch strong illusions can occur. Some examples have already been mentioned: the size–weight illusion, the fact that a curved surface along the finger feels more curved than the same surface across the fingers, and that what observers perceive as haptically parallel is far from physically parallel. In this section we will describe a few other prominent examples. For a more extensive overview of touch illusions, we refer the reader to Refs 90 and 91.

Geometric Optical Illusions in Touch

Many well-known geometrical illusions exist in visual perception. As geometrical aspects of an object (such as length) can also be observed by touch, it is an interesting question, whether such illusions are modality independent. One of the first to study this in detail was Robertson in 1902.[92] She investigated many visual illusions in the tactile domain. She reported marked tactual illusions for, among others, the Müller–Lyer and the Poggendorff illusions (see Figure 10). For the Müller–Lyer illusion she found that the tactual illusion was even stronger than for vision. The existence of such a tactual Müller–Lyer illusion was confirmed in later studies.[93–95] In the latter study, it was shown that both in vision and in haptics the illusion could be reduced to almost zero, if observers were explicitly instructed to use body-centered reference cues. Given these similar effects in vision and haptics, they suggest that an egocentric reference may be a common factor in the integration of sensory inputs from different modalities.
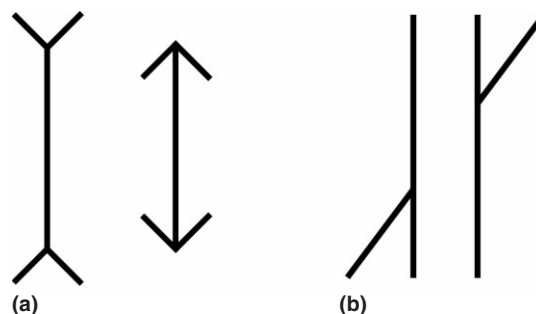
FIGURE 10 | Illustration of two well-known visual illusions. (a) Müller–Lyer illusion. The two vertical lines are of equal length, but usually the left line is perceived as longer for both touch and vision. (b) Poggendorff illusion. The oblique line segments lie on the same line, but the right line segment is perceived as shifted upwards in the visual illusion, but downwards in the tactual illusion.

Interestingly, for the Poggendorff illusion, Robertson[92] found an effect in a direction opposite to that in vision: the left line segment seems to be shifted upwards (see Figure 10(b)). This inversion was also found by Lucca et al.[93] However, Wenderoth and Alais[96] argue that this outcome is an artifact of the method used. According to their findings, there exists no evidence for a tactual Poggendorff illusion. Clearly, this issue remains to be resolved.

Curvature After-Effect

The first, rather informal, study of a curvature after-effect was described by Gibson.[97] Blindfolded observers were asked to run their fingers along a curved edge for about 3 minutes. Directly after this adaptation period, they were asked to run their fingers

along a straight edge and they had to report what they felt. Most of them commented that the straight edge felt curved in a direction opposite to that of the adaptation curvature. Much more controlled studies were performed by Vogels et al.[98,99] They asked observers, seated behind a curtain, to place their hand for five seconds on a curved adaptation surface. After the adaptation period, they had to lift their hand and put it on a test surface of which they had to decide whether it was convex or concave. By systematically varying the curvature of the test surfaces, the authors could determine the curvature that felt as flat. The curvature of this phenomenally flat surface depends linearly on the adaptation curvature and is about 20%. Interestingly, an adaptation period of 2 seconds was already sufficient to give rise to significant after-effects and after 10 seconds of adaptation, the phenomenal flatness reaches a saturation level, so the build-up of the after-effect is quite fast. On the other hand, the decay of the after-effect takes much longer. Even after a delay of 40 seconds or more after touching the adaptation curvature, a significant after-effect could be measured. Moreover, even if the hand makes active movements during the delay, the after-effect persists.[99] Van der Horst et al.[100] showed a similar curvature after-effect if the surfaces are just touched by a single finger and not with the whole hand (see Figure 11). Interestingly, these authors also showed that if a curved surface is actively explored with the index finger, the after-effect also transfers to the other hand[101,102] (see Figure 11). This suggests that the after-effect resulting from actively obtained curvature information occurs at a high level in the brain.

Temperature Illusions

A famous example was already mentioned by the philosopher John Locke in 1690.[103] First, put one hand in a bowl of cold water and the other hand in a bowl of hot water. Next put both hands in a bowl of lukewarm water. Although now both hands are immersed in water of the same temperature, the water will feel cold to the hand first exposed to hot water and warm to the other. This shows that we do not have an absolute perception of temperature. This is in essence an after-effect of having been exposed to water of a certain temperature.

Another illusion is intriguingly termed the 'thermal grill illusion'. When a grill consisting of alternating warm and cold bars, all of a temperature far removed from the pain threshold, is pressed on the hand or another body part, not an average or intermediate temperature is perceived, but a rather painful sensation of strong heat.[91,104,105] One of the most recent hypotheses of the explanation of this illusion comes from Green.[105] He suggests that the sensation of heat might result from summation of afferent activity of cold and warm fibers converging on neurons in the spinothalamic tract.

Location Illusion

Accidentally, Geldard and Sherrick[106] discovered that if a number of brief pulses were given at only three different locations, these pulses could be perceived as uniformly distributed between the two extreme locations. In their example, they presented five 2-millisecond pulses near the wrist, five on the arm located 10 cm towards the elbow, and finally five a further 10 cm away. This stimulation was perceived as a smooth progression of taps on the arm. Hence this illusion is aptly called the 'cutaneous rabbit', as it gives the observer the impression as if a small rabbit hops over the arm. In Ref 107 the cause of the illusion was studied in detail. The authors suggest that the illusion arises from the spatiotemporal integration of the stimuli within an early tactile map.

APPLICATIONS

The experiments on fundamental haptic perceptual processes as described in the preceding sections are of great importance for applications in haptic devices, remote handling, and telesurgery. The opposite is also true: the rapidly growing fields of robotics and mobile devices stimulates fundamental research on haptic (and tactile) perception, as it is recognized that such knowledge is essential for the field. Although

FIGURE 11 | Experimental set-ups for curvature after-effect measurements. Left: A blindfolded observer touches an adaptation surface with his index finger. Right: The same observer dynamically explores the curvature of a surface. Both conditions give rise to curvature after-effects. The dynamic case even transfers to the other hand.

applications are not really the topic of this overview paper, in this section, we will give a few interesting examples.

Familiar examples of haptic and tactile technology implemented in devices are the vibrations and touchscreens of smartphones. In gaming, joysticks and steering wheels with haptic force feedback augment the sense of immersion. Haptic feedback has also been implemented in graphical user interfaces (GUIs). For example, Leung et al.[108] found that haptically augmented progress and scroll bars on GUI touchscreens led to a significant improvement in terms of time to complete a task. Moreover, also the subjective experience of participants was positive.

Navigating through the world is very important for humans and other animals, but in many situations, help is welcome. Maps are obvious tools, but using these is hard to combine with other activities. GPS devices with spoken instructions are popular nowadays, but in noisy environments, these may not be optimal. Van Erp et al.[109] introduced a vibrotactile waist belt in which eight tactors were implemented. Vibration rhythm and vibration location provided information about distance and direction, respectively. They confirmed the usefulness of this display in helicopter and fast boat environments. Gleeson et al.[110] opted for a very small device that could be fixed to the finger. Tangential skin displacement at the fingertip gave reliable information about directions.

Another interesting development is the concept of contact at a distance. Modern communication systems allow persons to speak to and even see each other independent of distance. However, direct contact is a very important aspect of human relations (think of 'keeping in touch'). Prattichizzo and his team[111] developed a device they termed 'RemoTouch'. The idea of this device is that a person at one end wears a glove equipped with force sensors and in this way collects tactile information about an object (in one of their examples, a baby). This information is then transmitted to the person at the other end, which could be a valuable addition to visual and auditory information. Another device aimed at enriching social interaction at a distance is the 'HaptiHug'.[112] Persons wear a garment with 'hands' on the back, that by providing pressure simulates a 'hug'.

In telesurgery, a surgeon works at a console, remotely controlling robotic arms that perform an operation on a patient. At this moment, the feedback to the surgeon is mainly visual, while there is hardly any or no haptic feedback. By means of stereoscopic video cameras, the surgeon gets a sense of remote 'presence'. Although the surgeon can *see* what s/he is doing, s/he cannot *feel* it. This is recognized

FIGURE 12 | CyberForce: haptic device with exoskeleton. A virtual environment can be interacted with haptically. Image courtesy of CyberGlove Systems LLC.

as a clear disadvantage, as the haptic input might convey important information about the condition of, for example, an organ. The advantages are that the robotic arms can be made smaller than the surgeon's hands, making the operation less invasive. In addition, the movements can be scaled, in such a way that the surgeon can make comfortable, normal-sized hand movements, which are translated into tiny, very precise movements, necessary for microsurgery.

The fact that haptic information is lacking is considered a problem that should be solved in order to improve performance with such remote devices or at least make the use of them more intuitive. A general approach to combat this problem in recent research is to introduce *haptic feedback*. This means that touch sensations are displayed to the user by means of a haptic device.[113] In aircraft control, for example, a force-feedback joystick enables the pilot to make more precise movements, because the effects of the movements are fed back directly by means of the displayed forces. However, as we have seen, the sense of touch registers so much more than just forces: material properties such as roughness, compliance, coldness, and friction, spatial properties such as curvature and orientation, and, numerosity. These additional sources of information help with, for example, an increased

spatial awareness. Having this extra information available in a telesurgery scenario would probably contribute greatly to the success of the operation.

Improved haptic feedback will also be very beneficial in areas such as remote handling of dangerous materials or remote exploration of hostile or humanly inaccessible areas. For example, maintenance operations in nuclear installations can be performed much more efficiently if the operators get accurate feedback not only about the forces their tools encounter, but also other information, such as the material and shape of handled objects, or whether tools are slipping.

Lastly, in areas of training and simulation, *virtual reality* is used increasingly. Here, a user is immersed in and can interact with a virtual world, receiving visual, auditory and haptic feedback, as illustrated in Figure 12. For the benefit of increased realism, haptic feedback that goes beyond just force feedback or vibrations is desirable.

For these reasons, much effort is being put into developing devices that are able to display some of these tactual aspects.[114] For example, different compliant materials can be simulated by dynamically changing the size of the contact area when a virtual object is touched.[115] Subjects interacting with the integrated haptic display described in that paper are able to discriminate softness better than with either a purely kinesthetic or a purely cutaneous display. By way of another example, cutaneously perceived texture can be simulated by using lateral skin displacement.[116] The device described in that paper is able to record the lateral vibrations of the skin moving over different textures, and can replay them to subjects who were able to successfully identify the textures. These examples illustrate an ongoing trend of fundamental knowledge about haptic perception being employed in the development of improved haptic displays.

CONCLUSION

In this paper an extensive overview is given of the human haptic perceptual capabilities. It is shown that humans are able to haptically perceive a wide variety of material properties, such as roughness, compliance, viscosity, friction and coldness, and spatial properties, such as shape, curvature, size and orientation. For these properties, the limits of haptic perception are presented in terms of discrimination thresholds or matching performance. Often these thresholds are quite low, showing the sensitivity of human touch. Humans assess these properties by a using a set of stereotypical movement patterns, such as lateral movement for texture, unsupported holding for weight and enclosure for size. Humans are also able to judge the number of items in their hand. For small numbers (up to three) they can subitize, that is, assess the number rapidly and error-free without counting; for larger numbers they have to count the individual items. Like vision, touch is susceptible to illusions: what feels parallel is often far from physically parallel; estimated volume depends on shape; weight estimates depend on size; touching a curved surface influences the perception of the surface touched next; etc.

The importance of knowledge of haptic perception is increasing, among others, because the development of haptic devices or applications with a haptic component is growing. Prominent examples are telesurgery and remote sensing. As haptic research is gaining more and more attention from other perception researchers (often vision scientists), often in combination with research of other modalities (multimodal perception and interaction), it is to be expected that our fundamental knowledge about the haptic system will be expanded rapidly in the near future.

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