Tactile and Haptic Illusions

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Abstract—This paper surveys the research literature on robust tactile and haptic illusions. The illusions are organized into two categories. The first category relates to objects and their properties, and is further differentiated in terms of haptic processing of material versus geometric object properties. The second category relates to haptic space, and is further differentiated in terms of the observer's own body versus external space. The illusions are initially described and where possible addressed in terms of their functional properties and/or underlying neural processes. The significance of these illusions for the design of tactile and haptic displays is also discussed. We conclude by briefly considering a number of important general themes that have emerged in the materials surveyed.

Index Terms—Touch-based properties and capabilities of the human user; hardware and software that enable touch-based interactions with real, remote, and virtual environments; tactile and haptic illusions; haptic communication.

1 Introduction

Perceptual illusions involving the haptic system have received much less scrutiny than those involving vision or audition. This may partly reflect the fact that few tactile illusions arise naturally during everyday activities and that most require a specific set of conditions to emerge [1], [2], [3]. Many of the early studies of tactile illusions focused on examining whether there were tactual analogs of commonly reported geometric optical illusions (for reviews see [1], [4]); more recent research has also been directed toward understanding illusory phenomena that arise when humans perceive the real world or virtual environments via haptic interfaces [5], [6], [7].

The definition of what constitutes an illusion ranges from the extreme that all perception is illusory to the more commonly accepted idea that an illusion is the marked and often surprising discrepancy between a physical stimulus and its corresponding percept. By studying illusions we gain insight into the nature of the cognitive processes that people normally use to perceive and internally represent their environments, and can discover the mechanisms involved in integrating intra- and intermodal sensory information [3], [8], [9]. Tactile and haptic illusions may also serve as a tool for manipulating human perception to enhance the display of information.

In the context of virtual environments, detailed analyses of both intrasensory and intersensory illusions have been advocated as their existence enables the design of many virtual environments to be simplified and thus become more cost effective [10]. Illusions have been used to enhance perception by compensating for missing components of the perceptual experience; for example, the stiffness of a virtual spring simulated visually can result in haptic sensations of physical resistance despite the absence of any haptic display [11]. Illusions have also been employed as a metric for evaluating virtual environments by measuring the relation between the strength of the illusion and the degree of realism in the display. In their study of simulated environments, Heineken and Schulte [12] used the potency of the size-weight illusion to evaluate the degree of realism/presence in a number of simulated environments and found that the strength of the illusion was correlated with the degree of realism. Similarly, IJsselsteijn et al. [13] have advocated using the strength of the rubber hand illusion as a metric to evaluate the quality of a particular media environment.

The *robustness* of an illusion refers to the percentage of people or number of trials on which the illusion is present across experimental studies. An illusion's *strength* refers to the magnitude of the change in perception. Robustness and strength are difficult metrics to calculate across experiments that vary considerably with respect to the range of stimuli presented and the measures of human perceptual performance used. In addition to issues associated with determining the robustness of an illusion, an additional problem relates to how one calculates its strength. As Ross [14] noted, when calculating the strength of an illusion the choice of denominator for representing a "control condition" is often arbitrary. This can result in estimates of illusion strength that vary by up to 40 percent [15]. Many studies lack adequate controls against which performance in the illusory condition can be compared; moreover, for some illusions the control condition has varied considerably across experiments, thus making comparisons even more difficult.

The scope of this review includes tactile and haptic illusions that are relevant to the representation of information in tactile and haptic displays, and for which there exists some scientific analysis of the underlying functional mechanisms. Previous reviews have either focused on a subset of illusions, typically geometric illusions (e.g., [1], [4]), or have considered illusions in the context of describing how to produce demonstrations of these phenomena [2].

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Manuscript received 26 Aug. 2010; revised 15 Dec. 2010; accepted 13 Jan. 2011; published online 3 Feb. 2011.
Recommended for acceptance by E. Colgate.
For information on obtaining reprints of this article, please send e-mail to: toh@computer.org, and reference IEEECS Log Number TH-2010-08-0043.
Digital Object Identifier no. 10.1109/ToH.2011.2.

The aim of the present survey is to provide a comprehensive review of tactile and haptic illusions, further considering how they may impact the design and implementation of tactile and haptic displays. Illusions resulting from neurological or psychiatric disorders will not be covered.

An important requirement for inclusion in this review was evidence from a number of sources that the illusion was robust and that it was demonstrated under controlled experimental conditions, not just reported anecdotally. Some published reports of haptic illusions are suggestive of very interesting phenomena, but require further experimentation to be scientifically validated. In evaluating an illusion it is important that experimental subjects be unaware of the essential conditions responsible for the phenomenon under study, and that the instructions given do not force subjects to report on some aspect of the illusion as opposed to its presence or absence. By directing participants' attention to the illusory phenomenon rather than requiring an open-ended response, powerful biasing effects can influence perceptual judgments and inflate estimates of an illusion's robustness [16].

To date, there has been no straightforward way to categorize the richly varying world of tactile and haptic illusions. To organize most of the robust illusions addressed in the current survey rationally, we offer a conceptual framework based on current knowledge of somatosensory function [17]. Accordingly, our framework distinguishes between tactile/haptic information processing pertaining to 1) *objects and their properties*, and 2) *haptic space perception* (with respect to both the body itself and to external space).

2 Illusions of Objects and Their Properties

In this section, we consider illusions that relate to the tactile and/or haptic perception of external objects and their properties. A secondary organizing principle that we have found useful when analyzing such illusions is directed by the critical distinction that has been emphasized in touch research between the tactile/haptic processing of material (e.g., texture, stiffness, temperature) versus geometric (e.g., size, shape) properties [17], [18]. The perception of weight is considered separately as a hybrid property, inasmuch as it is influenced by both material and geometric attributes.

2.1 Illusions of Material

2.1.1 Texture

Texture-based illusions may be grouped into two categories. The first involves illusory enhancement of tactile sensitivity to the textural contours of real surfaces during manual exploration. Lederman [19] has shown that an intermediate paper held in the hand serves to enhance tactile sensitivity to the perceived roughness of a wide range of abrasive surfaces. Felt roughness was amplified by reducing the lateral shear forces between the moving intermediate paper and the stationary target surface beneath, relative to when the bare fingers were used. Lederman proposed that these lateral forces normally mask one's ability to detect surface irregularities.

The second category includes virtual textures that have been rendered using a variety of computational approaches. In a pioneering study, Minsky [20] created virtual gratings using a lateral-force gradient model implemented on a 2D force-feedback joystick. Since then, researchers have proposed numerous other computational approaches to generating virtual textures, including but not limited to the use of algorithms based on the modulation of friction force during scanning [21], use of Fourier series [22], modulation of resistive force in conjunction with a geometric texture model [23], a stochastic approach [24], a constraint surface algorithm [25], and a force model for collision response between textured surfaces [26]. Virtual textures may prove of considerable value in a multitude of virtual application domains (e.g., virtual training techniques for minimally invasive and endoscopic surgery, woodworking, and e-commerce).

2.1.2 Stiffness

The advent of virtual environments and the limitations of haptic devices in their capacity to provide the range and bandwidth of forces necessary to match the perceptual capabilities of the human haptic system have led to the exploration of multisensory displays as a means of compensating for haptic device limitations. In the context of perceiving the stiffness of virtual objects, it has been shown that changing the visual [11] or auditory [27] cues presented concurrently with haptic cues regarding the object's stiffness can result in compelling haptic illusions. Srinivasan et al. [28] showed that when the visual information presented to participants regarding the mechanical deformation of springs they were compressing was discrepant with their finger movements, visual cues dominated the perception of stiffness. In this situation, participants disregarded proprioceptive cues regarding finger displacement and attended to the visual position information and indentation forces. A similar but much weaker effect was noted by DiFranco et al. [29] who presented various impact sounds as participants tapped virtual objects using a force-reflecting haptic interface. They noted that auditory cues affected the ranking of the stiffness of virtual surfaces, although the influence of auditory cues was more variable than that of visual cues and diminished as participants became familiar with the task. It has also been possible to create an illusion of stiffness in the absence of any haptic interface, an effect that has been termed pseudohaptic feedback (for a review see [11]). In one of a number of studies, Lécuyer et al. [30] demonstrated that when participants used an isometric input device (a Spaceball) to interact with a virtual object while they perceived its deformation, visual displacement of a virtual object strongly dominated participants' perception of the displacement of their fingers. Using this pseudohaptic simulation of stiffness, Lécuyer et al. created a range of virtual stiffness values.

2.1.3 Temperature

Thermal illusions are particularly relevant to thermal displays because they demonstrate how innocuous stimuli can result in noxious or painful sensations when particular patterns of stimulation are presented [31].

Thermal grill illusion. This illusion refers to the burning pain that can result from touching interlaced warm and cool bars [31], [32]. Painful burning sensations have been reported in response to stimulation with alternating hot (36-42° C) and cool (18-24° C) innocuous temperatures on the palm of the hand, with the most elevated and consistent pain ratings occurring in response to temperature combinations of 20/40 and 18/42° C. When participants are asked to match the thermal sensation from making contact with the grill to that of a uniform thermal surface the matching temperatures selected are 45.7 and 46.6° C, respectively [32]. With more moderate differences in temperature (26 and 40° C), subjects report that the stimulus is hot but not painful, a phenomenon referred to as synthetic heat [33]. The latter has been described as a synthesis of warm and cool sensations that is qualitatively different from either of them and similar to the sensation produced when skin temperature is increased to a level just below the pain threshold.

The thermal grill illusion is a robust phenomenon, occurring in 70-90 percent of observers tested, even though no reports of pain occur when the hand is in contact with a surface of uniform temperature ranging from 18 to 42° C. Because sensations of pain and temperature result from activation of physiologically distinct sensory pathways, the thermal-grill illusion provides an interesting window into how these two systems are integrated. Green [33] has suggested that afferent activity in cold and warm sensory fibers may summate as they converge in the spinothalamic tract, resulting in sensations of pain when warm and cold stimuli are presented simultaneously.

2.1.4 Weight

The perceived weight of an object can change when other properties of the object such as its volume, shape, surface texture, temperature, or density vary [34]. Such effects may be considered illusory because variations in these object properties are not generally associated with concomitant changes in the sensory cues signaling weight. For some of these properties, such as volume, there is presumably a range of values for which the perceived weight may not be considered illusory [14]. For others, such as surface texture, information available to the central nervous system about the object's weight can change with variations in the object property and so their effects may not necessarily be illusory [35].

In this section, we will examine how the perception of weight changes as other properties of the object, both material and geometric, vary. These illusions are relevant to our understanding of the perception of objects in real and virtual environments because they provide cues about the perceptual processes underlying the haptic perception of object properties and about the limits of perceptual constancy, that is, the invariant perception of object properties. From the viewpoint of haptic interface design it is important to know that variations in object properties not directly related to weight can influence heaviness.

Size-weight illusion. One of the most well-known and robust weight illusions is the size-weight illusion first described by Charpentier [36], who noted that when two objects of identical mass but different volumes are lifted, the smaller object is generally perceived to be heavier than the larger. Over the years, numerous studies have examined how judgments of the perceived heaviness of an object change as a function of its volume [37], [38]; they have been consistent in demonstrating that the illusion is robust, that is, it occurs in the vast majority of subjects tested [39] and the greater the difference in volume between two objects with the same mass, the stronger the illusion [39], [40]. The magnitude of the illusion increases with an increase in the relative volume of the object lifted, with estimates of perceived heaviness decreasing by up to 26 percent when the volume doubles [41]. The strength of the illusion varies with the modality that is used to assess the size of the object. It is most powerful when volumetric cues are assessed haptically or using haptic and visual information (see Fig. 1), and significantly weaker when an object's volume is sensed only visually [41]. Moreover, if the visual cues about size are not concurrently available as the object is lifted, no size-weight illusion occurs [42]; however, if participants are led to believe that they are lifting an object that they have just viewed, then their estimates of weight are influenced by the size of the object they have seen [43]. These findings indicate that haptic volume information is both necessary and sufficient to produce the size-weight illusion.

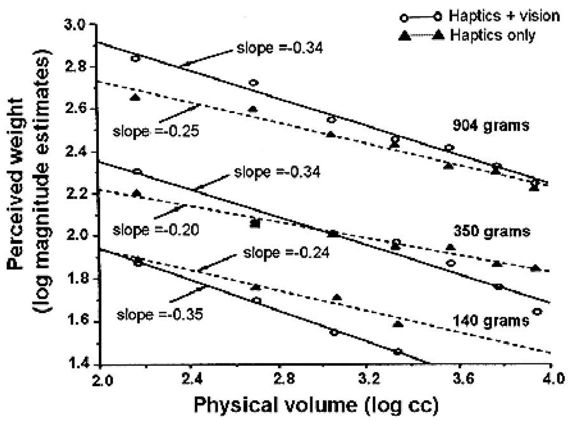

Fig. 1. Mean magnitude estimates of weight as a function of volume using haptics only or haptic and visual cues. Redrawn from [41] with permission of the Psychonomic Society.

A number of hypotheses have been proposed to explain the size-weight illusion, ranging from theories based on the idea of perceptual set or expectation [14], to those that focus on the importance of sensory information specific to the modality used to derive information [41], [42]. Expectation theories emphasize the role of previous experience in judgments of weight, with people expecting that the larger of two objects will be heavier. This results in different rates of force being applied to objects as a function of their size. However, the persistence of the illusion even when subjects have learned to scale their forces to the weight of objects indicates that expectation theories cannot adequately explain the illusion [44], [45], [46]. The latter finding suggests that there is a separation of the sensorimotor and perceptual systems in determining object mass. Unlike the sensorimotor system that uses feedback signaling a mismatch between the predicted and actual sensory signals to modify the dynamics of lifting and grasping, the perceptual system does not recalibrate itself based on sensory feedback during the initial lifting trials [43], [46]. However, perceptual recalibration can occur with experience, but on a different time scale than that seen in the sensorimotor system. Flanagan et al. [47] showed that when the size-weight relationship was artificially inverted so that after extensive training participants learned that large objects were extremely light and small objects very heavy, changes in perceived weight occurred gradually whereas the sensorimotor system rapidly adapted to the weights of the anomalous objects.

The neural mechanisms responsible for the size-weight illusion have been studied using fMRI adaptation techniques and appear to involve the ventral premotor area in the frontal cortex. This higher order cortical area integrates sensory information about the size of objects and their weight after they have been lifted [44].

Shape-weight illusion. The perception of weight has also been shown to be influenced by the shape of the object. The shape-weight illusion was first described by Dresslar [48] who noted that objects that appeared visually to be the smallest were judged haptically to be the heaviest. The shape-weight illusion is therefore a specific type of size-weight illusion. In a more recent study, Kahrimanovic et al. [49] had participants manually explore tetrahedrons, spheres, and cubes of varying volume and discriminate between them based on their perceived volume. They found that a tetrahedron was perceived to be larger in volume than either a cube or a sphere of the same physical volume, and that a cube was perceived to be larger than a sphere. In a further experiment with the same objects in which participants were required to indicate which of two objects was heavier (mass ranged from 16.8 to 117.6 g), Kahrimanovic et al. [50] found that the weight of a tetrahedron was consistently underestimated compared to the weight of a cube of the same physical mass and volume, with the average bias being -18 percent. These results indicate that an object's shape can affect its perceived heaviness, although the exact cues that participants use to relate shape to weight await further investigation. The challenge here is in determining how a single physical weight can give rise to many perceived weights and how objects with different weights can perceptually seem equivalent. This problem has been explored by Turvey and colleagues in the context of freely wielded rod-like objects whose mass, ellipsoid volume, and ellipsoid symmetry have been varied [51].

Density- or material-weight illusion. The mass and volume of an object are obviously related through its density, and so many investigators have proposed that density plays a dominant role in determining perceived heaviness, especially in the size-weight illusion [14], [38], [52]. Density per se influences the perception of weight as demonstrated by subjects' judgments of the mass of objects fabricated from different materials, an illusion first described by Wolfe [53]. In the density or material-weight illusion, objects with the same mass but made from denser materials, such as brass, are judged haptically to weigh less than those made from less dense materials, such as wood [54].

Ellis and Lederman [55] found that haptically sensed material cues were both sufficient and necessary for a material-weight illusion and that the strength of the illusion depended on the mass of the object. In their study involving objects composed of aluminum, wood or styrofoam, when the density of low mass (50-60 g) objects was doubled, magnitude estimates of weight increased by 23 percent when only haptic cues were available. For higher masses (350 g), there was no effect of material on perceived heaviness. Visual cues regarding the material were sufficient to generate only moderate material-weight illusions, with weight estimates increasing by 12 percent under visual-only conditions. The difference between the high and low mass conditions was found to be due to the higher grip forces used to support the heavier masses, which presumably reduced or eliminated many of the cutaneous sensory cues about the material surface. When the grip forces used to support the low mass objects were increased, no reliable material-weight illusions occurred [55]. However, Buckingham et al. [52] reported that a material-weight illusion did occur with heavier objects (700 g) of varying materials (polystyrene, wood, and aluminum). In their experiment material cues were only available through the visual modality as participants grasped the same manipulandum to lift each object. They proposed that differences in the manner of lifting the objects in the experiments may have contributed to the absence of an illusory effect at higher masses reported by Ellis and Lederman [55]. In addition, Buckingham et al. [52] found that even after the grip and load forces applied to the object reflected its actual mass and not the expected weight, the perceived heaviness of the object continued to be influenced by its material composition. These results concur with the findings on the size-weight illusion, which also showed a dissociation between the sensorimotor and perceptual systems involved in weight perception.

Surface texture-weight illusions. In addition to the effects of material composition on judgments of weight, the texture of the surface grasped by the fingers has been shown to influence the perceived heaviness of an object. Flanagan et al. [56] and Rinkenauer et al. [57] found that an object lifted with a precision grip was perceived to be lighter when the contact surface was rough (sandpaper) than when it was smooth (polyamide or satin). However, further analyses of this effect indicated that the surface texture-weight illusion could not be attributed directly to texture because it did not occur when subjects grasped an object using a horizontal precision grip. In this situation, with the thumb beneath the object and the index finger on top, the changes in grip force with surface texture are minimal because there is almost no shear force causing the object to slide from the grasp [56]. The effect of texture on the perceived heaviness of objects therefore appears to be a function of the grip forces required to support the object. These vary as a function of the weight of the object and the friction between the hand and object surfaces. For a constant weight between 90 and 150 g the grasp forces increase by approximately 30 and 44 percent, respectively, when the surface changes from rough to smooth; however, the change in perceived heaviness or in the difference threshold is only about 5-10 percent [56], [57]. In this illusion, the observer fails to distinguish between the increased normal forces required to grip a slippery object and the frictional forces used to counteract the load.

Temperature-weight illusion. Another material property of objects shown to influence perceived heaviness is temperature. The effects were first reported by Weber [58] who observed that cold objects placed on the forehead felt heavier than warm objects, a phenomenon that became known as the temperature-weight illusion [59]. More recent studies have confirmed these findings and shown that cold objects (kept in ice water) are perceived as considerably heavier than objects of the same weight at neutral temperatures. Warm objects (45° C) are also perceived as heavier than neutral objects, but the effect is much smaller [59], [60]. For cold stimuli, the enhancement in perceived heaviness is large, with estimates increasing by up to 400 percent under some experimental conditions. These effects have been demonstrated on the forehead, hand, arm, abdomen, thigh, and back, and so may be assumed to represent a fundamental property of mechanical-thermal processing [61]. For warm stimuli, the effects are much weaker and pressure sensations are enhanced in some body areas (e.g., forearm), but not others (e.g., forehead).

In all of these studies of temperature-weight illusions, weight has been perceived tactually by placing the object on the skin. This procedure differs from most of the experiments on the size-weight and material-weight illusions in which the object has been actively supported in the hand. In addition, the objects in the thermal-weight illusion studies are typically light (21, 45, and 105 g) and extend over quite a large surface area (1,260 mm^2), resulting in extremely small contact pressures of 0.16-0.82 kPa. To place these values in perspective, when the pad of the thumb makes contact with an object at 1 N the contact pressure is typically around 7.2 kPa [62]. It is not known whether changing the temperature of objects that are actively supported influences their perceived heaviness. Recent results from a force perception experiment suggest that when both tactile and proprioceptive cues are available about the forces generated by muscles, thermal cues from the contact surface do not influence the perceived magnitude of forces generated [62]. This latter finding suggests that the temperature-weight illusion may well be a tactile, as opposed to haptic, phenomenon.

The effect of object temperature on the tactile perception of weight does not appear to be an additive process of two concurrent sensations, and is probably the result of changes in the activity of peripheral receptors. Many slowly adapting (SA) mechanoreceptive afferent fibers in the skin that respond vigorously during sustained deformation are also excited by sudden cooling of the skin [63], which would account for the thermal intensification effects reported. During active lifting, these receptors probably play a more minor role in force perception, as other sources of sensory information provide more veridical cues regarding the forces generated [62].

In summary, weight illusions clearly demonstrate that the geometric and material properties of an object can have a profound effect on its perceived heaviness. As the volume, shape, material composition, contact surface, or temperature of an object varies, so too does the perception of its mass. Variations in these properties can result in significant distortions in perceived heaviness and occur even when the sensorimotor system has adapted to the mismatch between the expected and actual weight of an object. It is clear that haptically derived cues are both necessary and sufficient for these illusions to occur and that the strength of these illusions is greatest when haptic cues about an object's properties are available. It is therefore possible to create new stimuli in a virtual environment whose mass would be perceived to be changing by varying these features of the stimulus.

2.2 Illusions of Geometry

2.2.1 Size Illusions

A sizeable amount of research has been devoted to haptic illusions of perceived size, and more particularly, of linear extent. Linear extent is haptically under- or overestimated systematically depending on the stimulus context within which the estimated extent is presented.

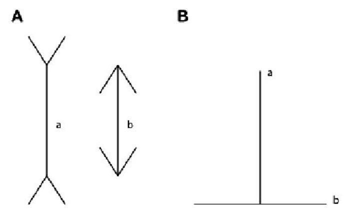

Fig. 2. Typical stimuli used to test haptic versions of (A) The Müller-Lyer illusion and (B) the (misnamed) Horizontal-Vertical Illusion. In both illusions, length a is perceived to be longer than length b.

Müller-Lyer illusion. Much like the visual Müller-Lyer illusion, the haptic perception of line length is modified by the presence of end delimiters (e.g., [4], [64] [65], [66], [67], [68], [69], [70], [71]). For example, in Fig. 2A lines bounded by arrowheads are haptically perceived as shorter than equivalent lengths bounded by fins. The effects of a variety of parameters have been experimentally manipulated with respect to subject characteristics (degree of visual experience, age), stimulus features (figural elements, overall display size, and orientation), psychophysical method (method of adjustment, method of constant stimuli, etc.), and type of instructions (global versus local attention). The illusion magnitude has typically ranged from ~13-26 percent. Strong robustness is usually observed with respect to mean performance; unfortunately, the number of individual subjects showing haptic susceptibility to this illusion has rarely been reported.

That the visual and haptic length illusions in sighted individuals are similar, if not equivalent, in magnitude raises several possibilities regarding the functional and/or neural processes involved: 1) the same underlying processes may be used independently by vision and haptics; 2) as visual spatial processing is more precise, observers may base their haptic judgments on visual images cognitively derived from the initial haptic inputs (e.g., [72]); and/or c) haptic judgments may be based on amodal processing by brain area(s) that receive multisensory input from both haptics and vision. Lacey et al. [73] have considered a number of methodological, behavioral and neural approaches for evaluating these three possibilities.

The presence of a strong Müller-Lyer haptic illusion in congenitally blind subjects [65], [66], [74], [75] is highly informative because it indicates that although visual imagery may be sufficient for the Müller-Lyer illusion, it is not necessary. Thus, the congenitally blind must be capable of adopting nonvisual spatial strategies for processing Müller-Lyer type displays that produce haptic perceptual distortions similar to those experienced by blindfolded, sighted observers. Compensating for such constant errors in visual and haptic spatial processing by blind observers is an important consideration in designing real and virtual tangible graphic displays for training navigation and mobility skills, and for use in a variety of academic disciplines. For example, Gillian and Schmidt [76] have noted that road junctions that form Müller-Lyer configurations occur in tangible navigational maps for the blind, causing perceptual distortions. Line intersections also frequently appear in raised-line pictures (e.g., objects), used as sensory aids for educating blind students in a variety of disciplines (e.g., biology, psychology).

Horizontal-vertical illusion. Another familiar visual geometric illusion of extent is the horizontal-vertical illusion (Fig. 2B): a vertical segment is overestimated relative to a horizontal segment of equivalent length. The illusion was originally misnamed because the inverted-T figure actually produces two different visual illusions of extent [77]. One involves underestimating the length of the bisected line relative to that of the bisecting line, regardless of line orientation (bisection illusion*)*. The other involves underestimating the horizontal line relative to the vertical line, and in keeping with its traditional name, horizontal-vertical illusion, is truly influenced by line orientation.

A substantial research literature has further documented tactile and haptic distortions of perceived extent when observers are presented with inverted-T and L-shaped displays (e.g., [4], [65], [75], [78]). Much like vision, the traditional inverted-T figure presented in the horizontal plane produces both a haptic **Bisection illusion** (e.g., [79], [80], [81]) and a haptic **Radial-Tangential illusion**, the latter relating specifically to the direction of hand movements relative to the body (cf line orientation in vision) [5], [82], [83], [84], [85], [86], [87], [88].

Bisection illusion. As noted by Gentaz and Hatwell [89], bisection illusions in vision and touch are similarly affected by several factors. For example, the inverted-T figure produces a larger haptic illusion than the L figure when presented in the horizontal plane [81], [90], lending further support to the idea that the inverted-T figure produces two unrelated haptic illusions of perceived extent. Moreover, when an inverted-T figure is rotated 90 degrees, the direction (not magnitude) of the illusion is similarly reversed for haptics and vision. To the extent that these modalities are equally affected by such factors, the illusions may be visually mediated or explained by common mechanisms. Millar and Al-Attar [80] have proposed that for vision and haptics, the bisection illusion results from the junction point along the bisecting line serving as an anchor that incorrectly biases judgments of movement extent. Guided by this interpretation, they successfully predicted line-division effects that depended on the location of the junction points along the divided line.

Radial-tangential illusion. In contrast, research reveals that the underlying mechanisms for the orientation-dependent illusion of extent in vision and touch are modality-specific. In an early study [87], subjects used a stylus to trace along a fixed distance in a given direction (fixed "standard" stimulus). Then they were required to move the stylus the same distance in a direction at right angles to that of the standard (adjustable "comparison" stimulus). In one condition, the arm movements were "radial" to the trunk, that is, toward and away from the body. In another condition, the arm movements were at right angles to the former, that is, "tangential" to a circle around the trunk. Subjects overestimated radial relative to tangential extents. Unfortunately, arm-movement direction was confounded with stimulus orientation (vertical versus horizontal); in that the radial extents were always vertical, and the tangential ones always horizontal. To eliminate this confound, Davidon and Cheng [84] (see also [83]) presented pairs of extents that were parallel versus perpendicular to the subject's medial plane, each pair consisting of a fixed standard stimulus and an adjustable comparison stimulus; however, this time both were presented at the subject's side, as well as directly in front (as in [87]). The results unambiguously confirmed that unlike vision, regardless of direction of extent (i.e., horizontal versus vertical) radial movements involving the extended arm were consistently overestimated relative to tangential movements (Radial-Tangential Illusion*)*. Moreover, the angular separation between standard and comparison had no effect on the magnitude of the radial-tangential effect [83], in contrast to the visual horizontal-vertical illusion, which is maximal when the angular separation is 90 degrees.

Another notable contrast between the two modalities is that unlike vision, the pure orientation-dependent illusion with an L figure does not occur when it is presented haptically in the frontoparallel (cf horizontal) plane (e.g., [83], [90], [91] [92]). In the frontoparallel plane both arm movements are tangential; hence, one would not anticipate any illusion. More generally, the illusion fails to occur whenever the arm movements are executed in the same direction (e.g., both radial or both tangential in the horizontal plane). Moreover, the illusion actually reverses when the standard L figure is presented to the side, presumably because the vertical and horizontal lines now require tangential and radial arm movements, respectively. Collectively, these results provide strong support for a robust haptic illusion based on arm-movement direction (cf visual line orientation), in which arm movements are referred to a polar body frame of reference, as suggested by Davidon and Cheng [84], as opposed to an oval frame of reference created by the visual field with the horizontal axis being wider than the vertical axis (e.g., [77]).

The reported magnitude of the radial-tangential illusion has ranged from $\sim$10 to 30 percent (e.g., [5], [82], [85]). Unfortunately, no details pertaining to the percentage of subjects showing the illusion are available. Several explanations have been offered.

Cheng [83] suggested the illusion may be explained by an anisotropy in the workspace defined by fully extended arm movements in the horizontal plane. Analogous to an anisotropy of the visual field [77], radial and tangential arm movements define a haptic workspace that is wider horizontally than vertically. Thus, an extent explored radially would constitute a larger proportion of the radial workspace than when explored tangentially.

Wong [88] based his explanation on differences in the dynamics produced by radial and tangential arm movements. Radial movements require more effort and are slower and of longer duration than tangential movements of the same extent (see also [80], [82], [86]). He proposed that the radial-tangential illusion may be attributed to the larger moments of inertia for radial, as compared to tangential, arm movements [93]. The validity of this explanation has been challenged by Marchetti and Lederman [94] and by McFarland and Soechting [86]. These two studies created several complementary conditions in which the moments of inertia were manipulated; however, the results did not support the perceptual predictions derived from Wong's moments-of-inertia hypothesis. Evidence for the radial-tangential illusion raises the interesting possibility that the structure of haptic space may be inherently anisotropic.

Armstrong and Marks [82] have argued against this position, suggesting rather that such distortions in haptically perceived extent are attributable to associated temporal differences in radial and tangential exploratory movements (but see [86]).

The influence of manual exploration on the haptic perception of 2D patterns, 3D objects, and their properties has been well documented (e.g., [72], [95], [96], [97]). Here, we have also emphasized the robust effect of arm-movement direction relative to the body on the radial-tangential illusion. However, research studies described thus far have required extended whole-arm movements in conjunction with relatively large stimulus extents. An important qualification is that when exploring smaller extents (2.5-10.2 cm) with the hand-finger system, the radial-tangential effect is weakened or does not occur, particularly with the smaller extents [98]. It would appear that the haptic system is differentially susceptible to illusions of extent depending on the degree to which the whole arm is involved in manual exploration.

Armstrong and Marks [82] have further suggested that the relation between duration and/or speed of arm movements and haptically perceived extent in the radial-tangential illusion may be a special case of a more general space-time interaction in touch. In support of this suggestion, Wapner et al. [99] showed that when the arm was passively moved, a given extent was perceived to be relatively shorter (longer) as speed was increased (decreased). Hollins and Goble [100] have shown that haptically perceived extent increases as the speed of arm movement slows and the duration increases. Haptically perceived extent of the euclidean distance between the end points of curvilinear pathways explored by hand further highlights the importance of space-time interactions for the haptic system [97], [101], a topic that we will consider further in conjunction with passive stimulation of the stationary body in Section 3.1.1.

Studies with total congenitally blind observers have generally confirmed susceptibility to the inverted-T version of the so-called horizontal-vertical illusion [65], [66], [74], [75]. In addition, Heller et al. [66] found no influence of visual status (blindfolded sighted, early blind, late blind) on illusion susceptibility. Such a finding calls into question the validity of theories that invoke any influence of visual experience on haptic processing, such as visual imagery. Although visual experience may be sufficient, it is not necessary for the haptic experience of this so-called "optical" illusion.

Like the Müller-Lyer illusion, bisection and radial-tangential illusions may occur in a variety of application domains involving vision and/or haptics (e.g., graphics displays). The magnitude of the haptic bisection illusion has been more than halved when subjects are instructed to use two hands and to refer their judgments of extent to multiple external spatial references available and to body-centered spatial cues such as the body midline [80]. That the bisection illusion occurs similarly in vision and haptics suggests that emphasizing external spatial referents and body-based cues may prove effective in reducing potential distortions of extent in visual and/or haptic graphics displays. Accordingly, Millar and Al-Attar [102] applied their earlier approach concerning spatial referent cues to raised-line maps. Blindfolded subjects were required to haptically judge extent within a map context, where inverted-T and Müller-Lyer-type configurations formed road junctions. Notably, the associated haptic illusions of extent were both eliminated.

To the extent that displays are haptically explored using a joystick or a pen-like device as part of a haptic interface, radial movements may generally be overestimated relative to tangential movements about the shoulder [83]. As previously discussed, movements involving a fully extended arm (cf finger, hand, or wrist) in combination with relatively large extents are particularly prone to the haptic radial-tangential illusion. It may be possible to minimize such distortions of extent by taking into consideration both the scale of the display and the types of exploratory arm movements permitted. When appropriate, small-scale, grounded haptic workspaces that avoid fully extended arm movements may help render veridical experiences. Other possible approaches include maintaining constant arm-movement speed and/or creating software to nullify constant errors produced by the radial-tangential illusion. Presumably, as this illusion is independent of visual processing, methods such as these could be used to reduce or eliminate the magnitude of this illusion in either haptic or bimodal displays.

To complete this section, we briefly note that several other well-known optical geometric illusions of 1D and 2D size, namely, the **Ponzo** and **Filled Space** (also known as the **Oppel-Kundt** or **Helmholtz) Illusions**, and the **Delboeuf Illusion**, respectively, have received relatively limited attention from touch scientists. At best, evidence to date suggests that they are not robust and/or that they are weak. Further careful study is recommended before any firm conclusions may be drawn.

2.2.2 Shape Illusions

In 1956, Edgington [103] informally described an intriguing illusion of curvature in which a blindfolded observer manually explored the curvature of a surface held vertically by the experimenter between them. The observer haptically explored the surface in one direction while the experimenter surreptiously moved it toward and away from the observer at the same rate. A physically flat surface was reported as curving convexly or concavely away, depending on the observer's finger motions and the inward/outward motion of the surface itself. Scientific confirmation of the existence and magnitude of this intriguing illusion and the stimulus conditions under which the illusion occurs are necessary. Sanders and Kappers [104] have scientifically confirmed the converse phenomenon in which physically curved lines feel straight. Such illusions may prove useful in enhancing haptic perception of 3D curvature in virtual environments.

Elongated rotating disk illusion. If one holds a disk (e.g., coin) between thumb and forefinger and rotates it end over end using the fingers of the other hand, one usually experiences the diameter of the disk in the rotating hand as elongated, relative to that experienced by the holding hand [105] (Fig. 3). The Elongated Rotating Disk Illusion is highly robust, as evidenced by the fact that of a total of 97 subjects, only one failed to experience it. Moreover, over a 30-second interval the magnitude of the illusion grew, first rapidly and then more slowly until it was as much as $\sim$60 percent.

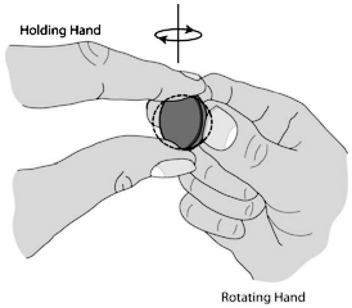

Fig. 3. The Elongated Rotating Disk Illusion. The dashed lines represent the haptically misperceived elongation of the disk in the rotating hand.

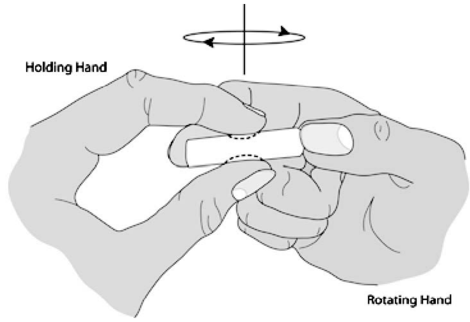

Fig. 4. The Rotating Hourglass Illusion. The dashed lines represent the haptically misperceived narrowing of rod diameter under the fingers of the holding hand.

The size of the disk also influenced illusion susceptibility, with the magnitude increasing as the actual diameter increased. Cormack [105] proposed two alternate explanations that involved differential adaptation to pressure either in the holding hand or in the rotating hand. Subsequently, Watanabe [106] used a set of custom-designed objects to reveal contributions to this illusion from both hands.

Rotating hourglass illusion. A blindfolded observer statically grasps a short rod between thumb and forefinger while the other hand rotates it end to end around the contact site for the holding hand (Fig. 4). The rod diameter at the contact points is perceived to narrow relative to the diameter along the rest of the rod, accounting for the illusion's name [107]. The rotating hourglass illusion is also large and highly robust, with the perceived rod diameter decreasing about 52 percent over a 38 s testing interval.

During this period, the illusion magnitude first increases rapidly, then more slowly. To account for this shape illusion, Jones et al. [107] proposed the following explanation. The sense of pressure resulting from tissue deformation disappears when the rate of that deformation falls below some threshold level [108]. The amount of tissue deformation at the center of the rod rotation is very small and constant, relative to that at points increasingly further from the center. Hence, pressure adaptation is more likely to be partial (even total) at the center of rotation, and increasingly lower (if at all) as a result of the more intermittent stimulation of the skin at points progressively further from the center of rotation. As the greater rate of tissue movement is more likely to be detected further from the center, the probability is higher that the sense of pressure remains. This pressure differential created along the skin by the moving rod may contribute to experiencing the hourglass illusion. That the skin has longer to recover before the next rod rotation in the periphery may further emphasize the pressure differential. Jones et al. [107] suggested that the elongated rotating disk illusion [105] may also be caused by adapting to a pressure differential, this time between the turning and holding hands. By subsequently adapting their apparatus to create a 1-hand version of Cormack's [105] original rotating-disk conditions, they successfully confirmed the presence of the elongated rotating disk illusion of similar magnitude.

Moore et al. [109] further evaluated the efficacy of the differential-adaptation hypothesis by successfully predicting two new related tactile shape illusions that were created by producing differential pressure patterns on the skin during rotation. We will focus mainly on the first of these, which is known as the Ridge Illusion.

Ridge illusion. Subjects lightly grasped a disk between their thumb and forefinger as it rotated horizontally between the two digits at 600 rpm. The surface of this disk contained a circle of conically-shaped "dimples" or holes that sequentially passed between thumb and forefinger as the disk rotated between the two digits. Ninety percent of the subjects reported that the rough dimpled sections felt like ridges (cf holes), resulting in the disk's apparent thickness more than doubling. The areas of the skin that were stimulated by intermittent pressure (higher rate of skin deformation) were perceived to be higher than adjacent areas that received constant stimulation (lower rate of skin deformation, if any). The differential-adaptation hypothesis successfully predicted a higher sense of pressure over the intermittent pressure areas (indents), and thus, the percept of a protruding ridge.

Computer paper illusion. It is possible that the differential-adaptation hypothesis can further explain a variant of the Ridge Illusion known as the Computer Paper Illusion, a haptic illusion that was briefly noted in a preliminary report by Wolfe [110]. Those of us past a certain age will recall an early form of computer paper with intermittent holes present at regular intervals down both sides of each computer sheet, which collectively formed a single stack (0.64 cm high) of connected sheets. The holes served to hold the paper in place as the stack of paper was advanced by pairs of rotating pins at the sides. Wolfe reported that when observers ran their fingers back and forth along a row of such holes, rather than feeling the actual holes, they felt a series of bumps or protuberances.

To conclude this section, we briefly note that the differential-adaptation hypothesis also successfully predicted the existence of a second new illusion, the **Bump Illusion** [109], which is closely related to the Ridge illusion above. The **Fishbone Illusion** [111], which has only appeared in preliminary reports to date, may also be related.

Haptic curvature aftereffect. Other examples of haptic shape illusions that pertain to real objects have parallels in vision, namely curvature aftereffects and contour effects. The haptic curvature aftereffect is a robust phenomenon that has received a fair amount of attention [112], [113], [114], [115]: a flat surface feels curved (convex/concave) after haptic exploration of a curved shape (concave/convex, respectively) that can last as long as $\sim$60 s [112] or as short as $\sim$10 s [113], [114], [115]. Paralleling the traditional explanation of perceptual aftereffects, it is possible that

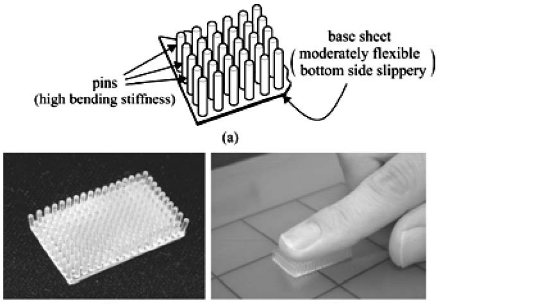

Fig. 5. The tactile contact lens. (a) Basic structure. (b) Photograph of a prototype. (c) Photograph of the prototype being used on a target surface. The pins convert local inclination of the object surface into tangential displacement of the skin surface. Reprinted from Kikuuwe et al. [118] with permission of the ACM.

the response rate of receptors selectively sensitive to the curvature of the adapting stimulus may be somewhat reduced following adaptation. When a neutral test curvature is then presented, those receptors will respond less actively than the receptor subclasses that are selectively sensitive to other points along the curvature continuum. If haptic perception reflects the weighted average of responses across all curvature receptor subclasses, then haptic perception of the neutral test curvature will be biased away from that of the adapting stimulus.

Haptic simultaneous contrast effect for curvature. When two shapes (e.g., convex standard versus flat comparison) are simultaneously explored with index finger and thumb, respectively, the flat shape contacted by the thumb is perceived as convex [116]. Wintjes and Kappers [116] found that for both 2D and 3D stimuli across a range of curvature contrasts, the overall magnitude of the haptic contrast effect was a substantial 20 percent of the contrasting curvature. The authors proposed that the contrast effect could be attributed to the observers' failure to adjust for their own hand movements.

Contour enhancement illusion. Gordon and Cooper [117] showed that when a thin intermediate paper is manually passed across a surface on which a single undulation appears, observers haptically judge its orientation more accurately than when only the bare fingers are used. However, we note that this contour enhancement illusion is limited to threshold-level undulations (see [19]). In keeping with the explanation proposed for the heightened roughness illusion discussed in Section 2.1.1, the reduced friction forces introduced by using the intermediate paper may serve to enhance the signal:noise ratio, in which the signal is produced by the normal force and the noise by the friction force.

Kikuuwe et al. [118] have since designed and built a clever device known as the "tactile contact lens" that consists of a base sheet and an array of pins arranged on the top side of the sheet (Figs. 5a and 5b). The fingertip makes contact with the pins (Fig. 5c) during active manual exploration. The device can enhance the haptic detection of surface irregularities normally achieved through either the bare finger or a surface of the same thickness as the contact lens, but without pins. Wang and Hayward [7] subsequently analyzed the contact mechanics associated with applying strain tangentially to the fingertip in a progressive wave pattern. They showed that the mechanical response of the fingertip was consistent with the perception of a moving undulating surface.

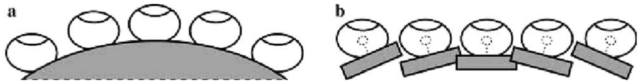

Fig. 6. (a) Traversal of fingerpad over a physical object. (b) A fingerpad deformation trajectory similar to when traversing a real object can be created by rolling a plate on it. This can be accomplished by rotating the plate around a point located at the apex of the bone of the distal phalanx (dashed circle), and by keeping the plate tangent to the virtual shape at the point of virtual contact. From [119] with permission of Springer.

Curved-plate illusion. Dostmohamed and Hayward [119] have explored haptic shape illusions from a different perspective by creating virtual shapes. They designed a device used to vary artificially the trajectory of a region of contact on the fingertip so as to effectively mimic the variation normally created when a person explores a real object with the fingerpad. The servo-controlled device rolls a flat plate on the pad of the finger as the observer explores a virtual surface. Throughout contact, the plate is maintained tangent to the virtual shape at the point of virtual contact, as illustrated in Fig. 6. In this way, the finger's rigid motion is reduced to less than ~1 mm. A number of other cutaneous and kinesthetic cues known to contribute to shape perception are eliminated. The results of a preliminary study confirmed that when integrated over time, the trajectory of the contact region on the fingerpad(s) alone produces an illusory percept of curvature over the relatively low range of curvatures examined in their experiment known as the Curved Plate Illusion. Curvature discrimination via such simplified artificial stimulation was comparable to that produced via direct contact with real objects. In addition, discrimination thresholds were lower for multiple contacts (i.e., 2 versus 1), and fully active touch was significantly better than semi-active touch, where one hand touched passively while the other moved the target object (see also [120]).

More generally, whenever a person haptically explores the contours of a real object, information about its shape is potentially available from its geometry *and/or* the forces (resistive and applied) experienced during exploration. Normally, these two sources covary. Until recently, most researchers have assumed that geometric cues provide the primary source of haptically extracted information about object shape. Hayward and his colleagues have created several tactile/haptic illusions based on the manipulation of force that challenge this critical assumption. For example, Robles de la Torre and Hayward [6] have shown that it is possible to produce robust impressions of virtual 3D bumps and holes by only varying computer-controlled forces delivered to the observer's fingertip via a haptic interface, while holding geometry constant. To more thoroughly explore this phenomenon, the investigators created a number of informative conditions using the haptic interface to generate forces that reflected or opposed those encountered when exploring real or virtual 3D surfaces and shapes (a flat surface, a bump, or a hole).

The physical shapes provided only geometric information (not associated horizontal force), while the virtual shapes presented only horizontal force (not geometric) information. Examples of conditions in which geometry and

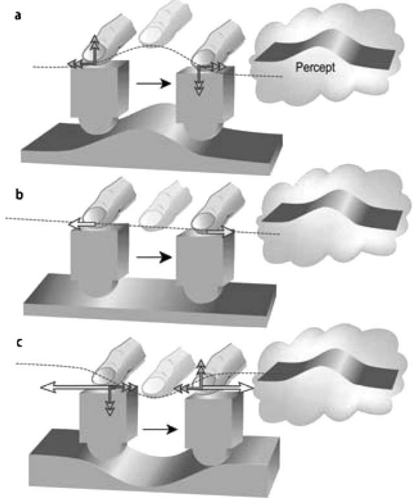

Fig. 7. How force and geometric cues contribute to the perception of shape by touching. Robles-De-La-Torre and Hayward [6] asked people to use a fingertip to slide an object over a surface (which they could not see), and to indicate whether they perceived a bump or a hole. In all cases shown, subjects perceived a bump. (a) The object traverses a real bump, which gives rise to the physical forces shown by double-head arrows. Horizontal forces resist and then assist lateral motion as the object goes over the bump. Vertical forces cause the object and fingertip to rise and fall (dotted line; geometric cues). (b) The object slides across a flat physical surface but horizontal virtual forces (unfilled arrows) consistent with a physical bump are applied to the object through a robotic device. Although the fingertip does not move up and down, subjects perceive a bump. (c) A virtual bump, twice the magnitude of that in b, is combined with a physical hole. The result is a stimulus that has the horizontal force properties of a bump but the vertical geometric properties of a hole. Although the fingertip falls and then rises with the object, subjects still perceive a bump. Revised and reprinted from [121] with permission of Nature.

force cues to shape were uncorrelated are detailed in Fig. 7. Robles de la Torre and Hayward [6] reported no statistical difference between the classification performance required for evaluating physical versus virtual surfaces. Based on the collective results from their study, the authors suggested that haptic shape may actually be influenced by *both* force and geometric cues (based on kinesthetic inputs), these being processed separately and/or weighted separately.

Another example of the value of force in the haptic perception of illusory 2D patterns is provided by Lévesque et al. [122], who explored the possibility of designing a virtual Braille reading display for blind individuals based on laterally deforming the skin.

Aristotle's illusion (Tactile diplopia). One final type of shape illusion that involves distortions in the global representation of an object is known as Aristotle's illusion or tactile diplopia. Under normal conditions when an object is held in the hand it is perceived as a single entity even though separate areas on the fingers signal contact and discrete populations of mechanoreceptors convey information about the object's characteristics. This property of "unity" represents a fundamental aspect of haptic sensory processing [123]. One exception to this phenomenological experience is an illusion first described by Aristotle, who observed that when a small object such as a ball is brought into contact with two adjacent fingers that are crossed, perceptually it appears as if the fingertips are making contact with two, rather than one, object (see Fig. 8).

Fig. 8. The Aristotle Illusion. When a single object such as a pencil or ball is placed between the tips of two crossed fingers, the observer perceives two, as opposed to one, object. Redrawn from [129] with permission of Harcourt Brace.

Aristotle's illusion can also be considered a tactile spatial illusion and so does not fit neatly into the classification system of tactile and haptic illusions adopted in this paper. Because its most predominant feature is tactile diplopia, it has been included with object illusions of geometric shape.

Aristotle's illusion was studied in the early 1900s and was shown to occur at other sites on the body such as the lips, tongue, and ears [124]. More recently Benedetti [125], [126], [127] has conducted a series of experiments in which he has attempted to discern the critical features of the illusion. He showed that tactile information is processed differently depending on how the fingers are crossed (i.e., crossing one finger over another as compared to crossing it underneath). His results revealed that tactile spatial information is processed as if the fingers are uncrossed and that patterns of tactile stimulation are encoded in a body-centered reference system [125]. Although the positions of the fingers are perceived accurately, tactile stimuli delivered to the fingers are misperceived spatially [127]. In a further experiment on the conditions essential for the illusion, Benedetti demonstrated that crossing the fingers was not a necessary condition for the illusion and that it could occur when adjacent fingers were firmly pressed together. When a single spherical object was presented to the fingertips under these conditions, the probability of detecting a single stimulus decreased as a function of skin displacement, such that at a maximum displacement of the fingertip pads a single stimulus was perceived to be double on 96 percent of the trials [126].

This illusion demonstrates that the perceptual experience of tactile stimulation depends on the relative position of the stimulated skin and that proprioceptive inputs that provide information about the position and orientation of a limb do not influence the spatial representation of tactile stimulation. It has been demonstrated that the positions of the fingers are accurately perceived independent of whether they are maintained in the crossed position actively or passively and so there is a dissociation between the localization of tactile stimuli and of parts of the body [127]. Other studies of related phenomena show that the position of a limb can have a profound effect on the perception of tactile stimulation as noted in Aristotle's illusion. For example, Oldfield and Phillips [128] demonstrated that the perception of letters and numbers applied to the skin changed depending upon the orientation of the limb in space.

3 Illusions of Haptic Space

In Section 2, we addressed illusions that involve the tactile and/or haptic perception of external objects and their material and geometric properties. In Section 3, we consider illusions of haptic space, which involve the tactile and haptic perception of the spatial attributes of objects and events located in bodily (Section 3.1) and external space (Section 3.2).

3.1 Illusions of Body Space

We begin by describing a class of tactile, thermal, and haptic illusions that relate to the spatial representation of the body and so involve a somatotopic body map. A number of these illusions involve distortions in the spatial processing of stimuli applied to the skin such as the perceived distance between stimuli or the location of tactile or thermal stimulation. The illusions generally result from interactions between the temporal and spatial properties of stimuli and demonstrate the dependence of distance perception on the temporal parameters of stimulation and on the site where the body is stimulated.

3.1.1 Tactile Illusions on the Skin

Distance: Tau and kappa effects. It has been known since the early 20th century that if the temporal interval between stimuli presented to the skin is very small, the stimuli are perceived to be closer together spatially than they really are. For example, if three tactile stimuli are delivered successively to the skin with the distance between the first two stimuli being twice that between the second and third, but the time interval between the second and third stimulus being double that between the first and second, the perceived distance between the stimuli is dramatically affected. The distance between the second and third stimuli will be judged to be nearly twice as large as that between the first and second stimulus, that is, its magnitude is overestimated by 400 percent. This illusion, illustrated in Fig. 9A, is referred to as the tau effect and for three tactile stimuli is optimal when the ratio of the two time intervals is no greater than 4 to 1 [130], [131]. The tau effect has been demonstrated for distances ranging from 30 to 85 mm on the forearm and for interstimulus intervals (ISI) from about 200 to over 500 ms [130]. (In a complementary phenomenon known as the kappa effect, the judgment of temporal intervals changes with variations in the spatial separation of tactile stimuli [132], [133]; however, this effect has not been consistently reported in the tactile modality [134], [135]).

The tau effect is a space-time illusion that involves stimulating the skin sequentially at two or more discrete points. A related phenomenon that again demonstrates the dependence of distance perception on the temporal parameters of stimulation occurs when a continuous tactile stimulus is applied to the skin and people are asked to judge the distance traversed [136], [137]. Under these conditions, the velocity with which the stimulus moves across the skin influences the perceived extent of the movement, with a given distance being perceived as

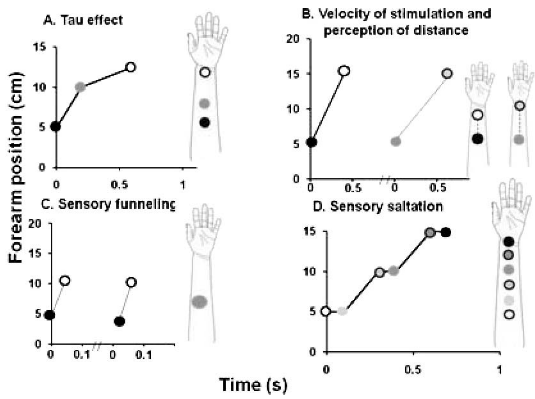

Fig. 9. (A)-(D) Four tactile illusions on the skin. The temporal and spatial properties of the actual stimulus sequences are indicated by the plotted points and the illusory perceived sequences are shown on the forearm. Figure adapted and redrawn from Goldreich [8].

shorter (maximally by about 50 percent) when the stimulus moves at a faster (2,500 mm/s) as compared to a slower (10 mm/s) velocity (see Fig. 9B). Langford et al. [136] also noted that at lower velocities of movement, the perceived trajectory of a straight line traced across the skin is often curved and winding. However, the relation between velocity and perceived distance is not linear; there is a range of velocities (50-200 mm/s) over which estimates of perceived distance are barely affected by the velocity of the tactile stimulus [137]. This range is within that used by subjects when they voluntarily scan textured surfaces and corresponds to the range of velocities at which both the directional sensitivity of somatosensory neurons and human performance at detecting the direction of moving tactile stimuli is optimal [138].

Distance: Weber's illusion. The perception of distance on the skin is not only influenced by the temporal intervals of stimulation but also by the site on the body that is stimulated and the orientation of the stimuli. The distance between two points of stimulation is perceived to be greater on areas of the body with higher spatial acuity (the hand or tongue) as compared to those with lower acuity (the thigh or arm), an effect known as Weber's illusion [139], [140], [141], [142]. The illusion is robust occurring on about 80 percent of the trials when the same distance is presented on the index finger and the forearm or the face and the back. The illusion is, however, much smaller than would be predicted from variations in tactile acuity [143].

Distance: Effect of stimulus orientation. An additional factor that can influence perceived distance is the orientation of the tactile stimulus. On the arm and the thigh, transverse distances are perceived to be greater (by about 70 percent on the arm, 24 percent on the thigh) than longitudinal distances of the same length [142]. However, the tactile perception of distance approaches veridicality (defined visually) in the transverse orientation on the arm, whereas longitudinal stimuli on the arm are consistently underestimated (compression of distance) in magnitude. In contrast to these results, the orientation of the tactile stimulus has no effect on perceived distance on the palm and stomach [142]. This difference between body sites may reflect asymmetrical receptive fields and the contribution of anatomical landmarks such as joints to the perception of distance [140]. The mechanisms involved in these tactile spatial distortions have been presumed to arise centrally because spatial compression occurs at distances at which stimuli are individually perceptible. Tactile illusions of distance can have a profound effect on the representation of external space on the body, due to the influence of the temporal parameters of stimulation on perceived distance. If veridical cues about distance are to be presented in a tactile display, it is essential that the temporal features of the stimuli remain constant.

Movement: Tactile apparent motion (or phi or beta movement). Over the years there have been many studies of the illusion of movement that occurs when a number of discrete mechanical or electrotactile stimuli are presented sequentially on the skin [144], [145], [146], [147], [148], [149]. Observers typically report that the series of taps feels like a single stimulus moving across the skin, an illusion known as tactile apparent motion or the phi phenomenon or beta movement. The interstimulus onset interval (ISOI) that is perceived to be optimal for tactile apparent movement varies directly with the duration of the stimulus for stimuli varying in duration from 25 to 400 ms [149]. For 100-ms stimuli with an ISOI of 70 ms, participants report an "impressive and continuous sense of movement" on 90 percent of the trials [150].

The optimal ISOI for a given stimulus duration decreases significantly as the number of sequentially activated stimulators increases, from approximately 320 ms with three stimulators to 20 ms with 12 stimulators [147]. The apparent movement of a stimulus can occur across the body (e.g., when a stimulus is delivered to each arm) with the relation between interstimulus onset interval and stimulus duration being preserved; however, the movement is qualitatively less robust than the movement reported when stimulation is restricted to a single site such as the thigh or the arm [148].

The illusion of apparent movement induced by sequential activation of a series of mechanical stimulators has been employed in several tactile displays developed to provide directional cues for navigation [151], [152]. As the findings described above indicate, there are optimal ranges of various stimulus parameters such as the duration and ISOI for inducing sensations of movement that need to be considered carefully in designing tactile communication systems.

Errors of localization: Sensory funneling illusion. A number of tactile and thermal illusions involve the mislocalization of stimuli applied to the skin with the result that stimuli are perceived to occur at sites that received no stimulation, or stimuli presented at several discrete sites are perceived to be progressively moving across the skin surface.

When brief stimuli are presented simultaneously at several closely spaced points on the skin they are often perceived as a single focal sensation at the center of the stimulus pattern rather than as a phasic sensation at a number of sites [153], [154], [155]. It is as if the tactile inputs are "funneled" to a central location at which the stimulus is perceived as being more intense than at the individual sites of stimulation. This sensory funneling illusion is highly robust. Gardner and Spencer [154] reported that when participants were asked to localize stimulation on the forearm when three stimulators (spaced 30 mm apart) were activated, they described a single sensation that was localized within a 20-mm band of the middle stimulator on 80 percent of the trials. When only two stimuli are simultaneously presented in close proximity, a phantom sensation is evoked at a location midway between them as shown in Fig. 9C. It is also possible to move the perceived location of this stimulus by adjusting the relative intensities of the two stimuli [155]. Optical imaging studies of the tactile funneling phenomenon have revealed that during simultaneous stimulation of two fingertips there is a single focal cortical activation site in the primary somatosensory cortex between the representations of the two stimulated digits [153]. This suggests that the topographic representation in primary somatosensory cortex reflects the perceived rather than the actual location of peripheral stimulation.

Errors of localization: Sensory saltation illusion. The most well-known spatial illusion involving mislocalization on the skin is sensory saltation. In this illusion a series of short pulses delivered successively at three different loci on the skin is perceived as a stimulus that is progressively moving across the skin "as if a tiny rabbit were hopping" in a smooth progression from the first stimulator to the third (p. 178, [156]). Saltation is distinguished from the phi phenomenon, which is primarily an illusion of movement rather than displacement. For sensory saltation, the optimal number of taps is 3-6 (Fig. 9D). The illusion can occur with as few as 2 and as many as 16 taps, although it is considerably diminished under the latter conditions [156]. The temporal separation between the stimuli also influences the strength of the illusion with intervals between 20 and 250 ms being optimal. As the interval between the presentation of stimuli is reduced, the taps are perceived as being much closer spatially until at an interval of about 20 ms there is no spatial separation at all [157]. At interstimulus intervals of 300 ms or more, the taps are localized accurately [134].

It is possible to create saltatory movement in two or more directions on the skin by appropriate temporal and spatial activation of the stimulators. Although the original demonstration of the illusion involved three contactors spaced along the forearm, many of the subsequent studies involved a "reduced rabbit" paradigm. This consisted of presenting three stimuli at two locations [134], [158], [159]. In this latter experimental paradigm the task is to report whether a tactile stimulus was felt at a location midway between the other two points of stimulation [160]. The saltation illusion is robust; that is, it has usually been observed on 80-90 percent of trials. This value is equivalent to the percentage of responses reported when a tactile stimulus is actually presented at each location [158], [160]. The strength of the illusion has been evaluated by comparing the percentage of trials in which a tactile stimulus is reported at a specific location during illusory and real stimulation [160] or by determining whether participants can reliably discriminate between real and illusory stimuli. Under optimal stimulation conditions, participants cannot distinguish between real and illusory locations (81 percent versus 82 percent "present" responses) [160]. When they must decide whether two stimuli presented sequentially are the same (i.e., both real or illusory) or different (one real, the other illusory), they are better in the former situation (82 percent correct); however, even with different stimuli they identify them as the same on 63 percent of the trials [161]. This suggests that percepts elicited by real and illusory stimulation are phenomenologically quite similar.

One spatial factor that determines whether sensory saltation occurs is the area of skin over which the tactile stimulation is delivered. This region, known as the saltatory area, varies in different regions of the body from 2.28 cm^2 on the volar surface of the index finger to 145.7 cm^2 on the forearm. In general, there is a negative correlation between the size of the saltatory area and the density of sensory innervation, which is in turn directly related to the cortical receptive field size [162]. This suggests that saltation is constrained by the anatomical organization of the somatosensory system. Consistent with this hypothesis was the finding that saltation did not occur when contactors were placed across the body midline, unless there was tactile stimulation at the midline [134]. It has been shown, however, that the perceived location of the saltatory stimulus does not have to be on the body and can "hop out of the body" onto an external object such as a stick laid across the tips of the index fingers [163]. This latter finding suggests that the representation of external objects in the environment, and in particular tools held in the hand, can be incorporated into the body schema in the brain, which would be of considerable advantage in computing the dynamics of hand-held objects during tool use.

Various explanations have been considered to account for the phenomenon of sensory saltation, most of which have focused on central rather than peripheral neural mechanisms. It was established early on that the illusion was not due to the traveling waves that are transmitted along the skin and underlying tissues during each pulse because the illusion occurs when electrocutaneous rather than mechanical stimuli are used. In addition, there is little difference between the two modes of stimulation in terms of timing and parametric range within which the optimal effect occurs [156]. Moreover, the temporal features of saltatory phenomena in vision and audition are very similar to those reported for the somatosensory system, which again points to a central basis for the illusion. Brain imaging studies have revealed that the activation of the contralateral primary somatosensory cortex is comparable during illusory and veridical stimulation of the forearm, indicating that illusory percepts can affect primary somatosensory cortex in a manner equivalent to physical stimulation [158]. This indicates that the illusion does not reflect higher level cognitive processing and that the mislocalization of peripheral stimulation is reflected in the activity of neurons in primary somatosensory cortex.

The phenomenon of sensory saltation can be used to optimize the design of tactile displays and the implementation of tactile communication systems. By appropriate selection of the spatial and temporal sequence of motor activation, it is possible to create a display with a perceptually higher spatial resolution than the number of actuators would indicate [164]. In addition, the saliency of a tactile signal that makes use of sensory saltation may indeed prove to be greater due to the perception that the signal is dynamic rather than static. In the context of tactile displays used as communication systems for navigation or orientation [165], it is possible to create directional signals on the skin (such as tactile vectors) from discrete inputs with the selection of appropriate time intervals. Cholewiak and Collins [161] have demonstrated that saltatory stimuli can adequately duplicate sensations generated with higher density tactile arrays and so increase the perceived resolution of a display.

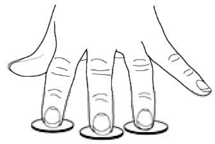

Fig. 10. Thermal referral. From Jones and Lederman [170], reprinted with permission of Oxford University Press.

Thermal spatiotemporal illusions. There are very few reports of spatiotemporal illusions that involve the thermal system. This may reflect the limited perceptual experiences associated with cooling and warming the skin and the pervasive nature of spatial summation in the thermal senses, which limits the ability of people to specify precisely the site of stimulation [166]. There is one anecdotal report of the apparent movement of a thermal stimulus between the forearms when they were sequentially stimulated at a delay of 250 ms, which is similar to the "phi" phenomenon reported for vibratory stimuli [167], and two reports of thermal sensory saltation [134], [168]. Trojan et al. [168] used a CO_2 laser to deliver three infrared laser pulses (at 15.3 and 25.4° C above baseline skin temperature) on the forearm and subjects indicated the perceived position of the middle stimulus with a 3D tracking system. They found that the perceived position of the middle stimulus was displaced in the direction of the third stimulus by an average of 51 mm, and that the displacement increased linearly as the delay between the middle and the third stimulus decreased, consistent with the results from tactile studies. The CO_2 laser stimuli used to heat the skin activated both warm and nociceptive fibers and so it is not possible to exclude the contribution of the nociceptive system to thermal saltation.

Thermal referral. The ability to localize thermal stimulation in the absence of tactile cues is often very poor. Although simultaneous tactile cues can help localize thermal stimulation, the interaction between thermal and mechanical inputs can lead to constant errors in localizing thermal sensations when adjacent regions of the skin are differentially stimulated. Green [169] described a thermal illusion involving the hand in which the thermal sensations arising from the middle finger changed as a function of the sensations experienced at the two adjacent fingers. When the index and ring fingers were placed on cold (or warm) thermal stimulators and the middle finger was placed on a thermally neutral stimulator, cold (or warmth) was felt on all three fingers as shown in Fig. 10.

The perceived magnitude of these thermal sensations was the same as that experienced in the control condition in which the temperature of the thermal stimulator under the middle finger was varied and the outer two stimulators remained thermally neutral. Green [169] also showed that thermal stimulation from adjacent fingers can enhance the perceived warmth or cold of a surface touched by the middle finger. The referral of thermal sensations required equivalent tactile experiences on the fingers, in that it did not occur when the middle finger was held above the stimulator. The illusion was also not evident when the middle finger of the contralateral hand touched the center stimulator. Further experimentation on the spatial limits of this illusion revealed that referral remained strong even when the stimulators were spaced along the length of the forearm; however, it diminished as the distance between stimulators increased. Green [171] also noted that warmth referred more readily to a site of tactile stimulation than cold. Tactile inputs therefore appear to guide thermal localization. In the context of thermal displays, these results indicate that thermal inputs delivered to a number of adjacent sites will not be processed independently and that the perceived magnitude of any thermal input can be influenced by those delivered concurrently.

Summary of tactile and thermal illusions of body space. Spatiotemporal illusions demonstrate a fundamental principle of tactile perceptual processing, and indeed all sensory processing, namely that when two events occur within certain spatial and temporal bounds, the localization of one event in space or time is influenced by the presence of the other. The implications of these illusions for tactile displays are that physical distances will be perceived differently at different sites on the body and when the temporal parameters of stimulation change. Tactile patterns based on sequentially activating a series of actuators on the skin therefore need to be evaluated at the location where the display will be mounted. As was noted previously, the functional resolution of a display depends on how patterns are presented; short presentation intervals tend to produce spatially attenuated patterns, which may not be efficacious for vibrotactile communication systems developed for use by the visually or hearing impaired.

Spatiotemporal illusions also provide insight into the assumptions that normally guide human perception. Goldreich [8] has proposed a Bayesian observer model that replicates the perceptual length contraction and time dilation associated with a number of the tactile spatiotemporal illusions described above. The observer model incorporated two prior assumptions: first, that stimuli separated by small spatial and temporal intervals originate from a single source of stimulation that has uniform motion and second, that objects in contact with the skin move slowly. The adequacy of such a simple model suggests that human observers may take advantage of prior tactile experience regarding the speed with which objects move across the skin to improve their perception beyond the limits imposed by the spatial and temporal resolution of peripheral sensory signals [8].

3.1.2 *Illusions of Body Schema*

Knowledge of the relative positions of different parts of the body in external space is often referred to as the body schema or body image. A number of illusions involve distortions in the body schema with the result that the perceived size, length, and position of a limb are quite discrepant with its physical state. There are many illusions that involve changes in the perception of the body schema

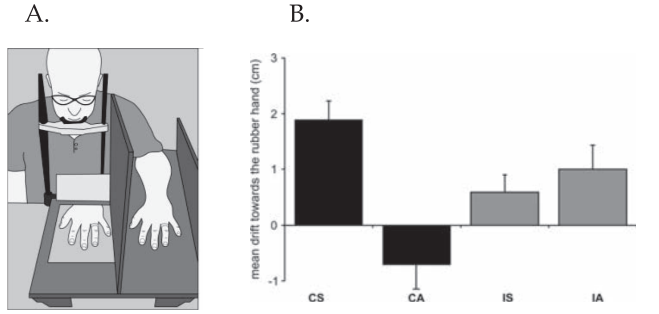

Fig. 11. (A) Experimental setup for the Rubber Hand Illusion. Redrawn with permission of the authors from [181]. (B) Mean proprioceptive drifts averaged over 10 participants. Point zero indicates the felt position of the participant's hand prior to stimulation. A positive drift represents mislocalization toward the rubber hand. CS: congruent rubber hand with synchronous stimulation; CA: congruent rubber hand with asynchronous stimulation; IS: incongruent rubber hand with synchronous stimulation, IA: incongruent rubber hand with asynchronous stimulation. From [183], with permission of Oxford University Press.

such as the phantom limb illusion [172] and distortions in the size and shape of body parts induced by anesthesia [173], [174]. These phenomena are germane to our understanding of the sensory mechanisms involved in representation of the body (see [175] for a recent review) but are beyond the scope of the present review, which focuses on illusions relevant to the display of tactile and haptic information. The rubber hand and vibration illusions are phenomena that occur in normal healthy individuals and involve distortions in the representation of the body. The rubber hand illusion has been used to explore the malleability of the body image and the degree of realism in virtual environments [13]. In contrast, vibration-induced movement illusions have been exploited to determine how the tactile perception of distance on the skin is referenced to the proprioceptive representation of the body [176] and as a possible source of feedback in controlling prosthetic limbs [177].

Rubber hand illusion. The rubber hand illusion refers to the misperception that involves referring tactile sensations experienced on an unseen hand to a visible artificial hand (a rubber hand), as if the visual input "captures" the tactile stimulation (see Fig. 11A). Botvinick and Cohen [178] were the first to report that following synchronous tactile stimulation of an unseen hand and a visible rubber hand, a significant percentage of subjects (42 percent) indicated that they felt the touch of the brush on the rubber hand and not of the hidden brush stroking on their unseen hand. Subsequent studies have reported that the illusion can be generated in approximately 80 percent of people after as little as 30-60 s of stimulation [13], [179], [180]. This visuo-tactile illusion also affects proprioception with the result that there is a distortion in the sensed position of the unseen hand after tactile stimulation—the perceived position of the unseen hand is now displaced in the direction of the rubber hand as illustrated in Fig 11B (CS condition). Proprioceptive drift as reflected in errors in reaching or pointing to a target location with the unseen hand after stimulation has therefore been used as a quantitative measure of the rubber hand illusion in addition to questionnaire responses [181], [182], [183]. With this metric, the illusion has been reported in approximately 70 percent of participants tested [183]. The perceived position of the real hand does not, however, align with that of the rubber hand; the drift is in the order of 15-30 percent of the full distance between the two [182].

For the illusion to occur, the artificial hand or arm must resemble the normal hand or arm in size and shape, the two hands must be congruent (i.e., both left or right hands), the orientation of the two hands should be aligned and the direction of tactile stimulation should be similar [181], [182], [183]. The strength of the illusion is also related to the distance between the normal and rubber hands and declines considerably when the two are separated by distances greater than 27 cm [180]. It is essential for the illusion that the tactile stimulation delivered to the two sites is synchronous; when the stimulation is asynchronous the number of subjects reporting the illusion decreases dramatically (see condition CA in Fig. 11B) [178], [184].

These findings indicate that "bottom-up" processes in which visual and tactile percepts are integrated provide a necessary but not sufficient condition for the illusion to occur. The illusion depends on a plausible and congruent relation between the visual and tactile inputs. It does not occur when either a neutral object (e.g., a wooden stick) is stroked concurrently with the hand or when the rubber hand is in a different orientation (e.g., rotated 90 degrees) from that of the real hand. However, it can also be elicited when the participant's other hand passively strokes the rubber hand; therefore, visual cues are sufficient but not necessary for the illusion [179]. "Top-down" influences involve integrating the concurrent visual and tactile or proprioceptive and tactile inputs with a preexisting cognitive representation of the body [182].

The rubber hand illusion has provided a template used by many investigators to study the malleability of the body's image. In the context of virtual environments the rubber hand illusion has been replicated, albeit less robustly, with an entirely virtual three-dimensional arm and hand [13], [184]. It has therefore offered an experimental model for studying the relative speed with which the body image can be altered and has implications for how the body may be represented in virtual environments and mixed-reality systems [13]. In addition, the illusion has provided a vehicle for studying the nature of the multisensory processes that integrate visual, tactile, and proprioceptive information [182]. Consistent with the results from a number of behavioral studies, the rubber hand illusion shows that the perceived position of the hand is based on a weighted sum of visual and proprioceptive information. It appears that visual information about the rubber hand is weighted heavily when combined with proprioceptive information from the real hand, provided that the rubber hand is placed in an anatomically plausible posture [185]. Neuroimaging studies suggest that premotor and parietal cortices are involved in the illusion and reveal three contributing neural mechanisms: one that involves multisensory integration from the visual, tactile and proprioceptive modalities; another that is concerned with recalibration of proprioceptive representations of the upper limb; and a third that is engaged in the attribution of limbs to oneself, that is, a feeling of body ownership [179], [183], [186]. The multisensory integration involves cortical systems concerned with processing information in peripersonal space—the sector of space in close proximity to the body, in which objects make contact with the hands or face.

Vibration illusion. The haptic vibration illusion has been extensively studied because of its importance in understanding how afferent signals from receptors in muscles are used to sense limb position and movement [187]. In the initial descriptions of this illusion, Goodwin et al. [188] observed that percutaneous vibration of a muscle tendon at 100 Hz induced illusory movements of the limb about which the vibrated muscle acts. Using blindfolded subjects who were required to track the position of their immobilized, vibrated arm with their unperturbed arm, Goodwin et al. [188] found that vibrating the biceps muscle tendon produced the illusion that the forearm was extending, as if the vibrated muscle were being stretched. Conversely, when the triceps muscle tendon was vibrated the arm was perceived to be flexing. The illusion is primarily one of movement, although an error in the perceived position of the limb of $\sim$5-8 degrees is associated with the movement [188]. It is a relatively robust illusion, occurring in 60-88 percent of participants tested [176], [189], [190]. The illusion is presumed to result from the intense firing rates of muscle spindle receptors induced by vibration, which are interpreted by the central nervous system as indicating that the muscle is being stretched [191], [192]. This illusion does not occur when the joint is vibrated and is not affected by skin anesthesia; hence, it is critically dependent on muscle receptor activity [188], [193]. If a muscle is actively stretched while vibration is applied, subjects can perceive their limbs to be in anatomically impossible positions. For example, during vibration of the wrist flexor muscles, Craske [194] noted that subjects often indicated that the hand seemed to be bent back toward the dorsal surface of the forearm. This suggests that the cortical sensory centers involved in processing proprioceptive information are not constrained by the anatomical limits of joint excursion and extrapolate from the previously calibrated position sense. Such plasticity may be an essential component of the capacity to incorporate tools and other hand-held devices as extensions of human limbs.

3.2 Illusions of External Haptic Space

We now consider illusions pertaining to an object's spatial position and orientation in external haptic space.

3.2.1 Parallelism

Kappers and her colleagues [195] have convincingly demonstrated that people exhibit surprisingly large and consistent deviations when haptically judging two bars as parallel. Kappers and Koenderink [196] initially required blindfolded subjects to unimanually perform three different tasks within the horizontal plane: rotate a test bar to feel parallel to a reference bar, rotate two test bars so that they felt collinear, and point a test bar toward a marker presented in different locations (Fig. 12). The authors observed a gradient of perceived distortions in the left-right (but not vertical) direction as a function of interstimulus separation, with orientation errors increasing up to as much as $\sim$40 degrees in the maximal separation condition. Although the orientation gradient slopes were qualitatively similar across subjects, their magnitude varied substantially. In addition, haptic oblique effects (normal and reversed) were observed, depending on the magnitude of the slope of the orientation gradient, as will be discussed in Section 3.2.2. Collectively, these results clearly indicate that haptic space is noneuclidean within the horizontal

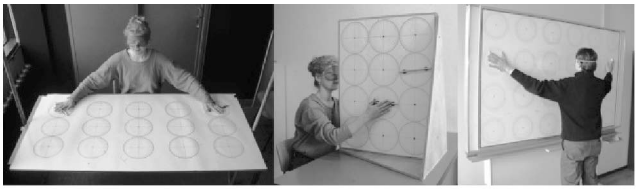

Fig. 12. Parallelism task setup for (a) horizontal, (b) mid-saggital, and (c) fronto-parallel planes. Reprinted from [195] with permission of the Canadian Psychological Association.

plane. Other experiments have generally confirmed and extended these findings. Kappers [197] observed the same orientation gradient of distortion to occur across the entire horizontal plane within reach of fully extended arms and with both unimanual or bimanual exploration (although 2-handed exploration produced 18 percent greater distortion than 1-handed exploration). Orientation gradients and oblique effects were also observed within mid-saggital (in the vertical, but not horizontal, direction) [198] and frontoparallel planes [199] (Fig. 12).

Kappers and her colleagues (e.g., [200], [201]) have interpreted their empirical results in terms of the adoption of an intermediate frame of reference in which allocentric (i.e., referred to external space) and egocentric (i.e., referred to the body, and most likely the hand) frames of reference are differentially weighted in the representation of haptically derived parallelism, depending on the relative importance of these reference frames to each person.

As haptic variants of three other well-known geometric visual illusions—the **Zöllner Illusion** (also related to parallelism) and the **Bourdon** and **Poggendorff Illusions** (both related to collinearity)—have received either limited study and/or produced ambiguous results, they will be discussed no further.

3.2.2 The Oblique Effect

Haptic versions of the oblique effect, in which oblique stimulus orientations are processed *more poorly* than either vertical or horizontal orientations, have frequently been reported [202]. This reliable perceptual effect has been documented using a variety of response measures [196], [201], [202], [203], [204], [205]. Interestingly, Kappers has sometimes found reverse oblique effects in parallelism tasks [200], where oblique orientations are processed *better* than vertical and horizontal orientations. In keeping with their intermediate frame-of-reference hypothesis (Section 3.2.1), they argue that regular oblique effects are more likely to occur when observers strongly favor an allocentric frame of reference; conversely, reverse oblique effects are more likely to occur when an egocentric frame of reference is strongly favored.

4 Themes for Future Consideration

In closing, we briefly highlight a number of important general themes that emerge from the research discussed in our survey of tactile and haptic illusions. These may be used to guide future scientific studies of illusions of touch and their possible applications.

4.1 Modes of Touch

Beginning with the work of Katz [206], Revesz [75], [207], and Gibson [123], touch scientists have asked whether active and passive modes of touch produce the same experiences, qualitatively and/or quantitatively (for a more in-depth discussion, see [208], [209]). With active touch, observers freely explore the concrete world, receiving sensory input from both cutaneous and kinesthetic systems. With passive touch, the observer remains stationary with contact produced by an external agent (e.g., the experimenter); purely passive touch offers only cutaneous information [170]. The mode of touch used to generate and study illusions is an important issue to consider inasmuch as the illusory experiences and the manner in which they operate sometimes differ in direction and/or magnitude (e.g., [210], [211]).

4.2 Spatiotemporal Interactions

The interactions between space and time represent a fundamental property of tactile and haptic sensory processing. The perception of distance on the skin is influenced by the time intervals between stimulus presentation, and similarly the perception of the extent of active hand and arm movements can change as a function of movement velocity. These spatiotemporal interactions must be considered in the design of tactile and haptic displays because physical distances will not be perceived accurately if the temporal conditions of stimulation or movement change. However, there is generally a range of stimulus durations and movement velocities that result in veridical perception. Such durations and velocities should be employed if precise mapping between physical and perceived distance is essential for a particular application, as, for example, in telerobotic surgery.

4.3 Aftereffects

Aftereffects are a common feature of the tactile and haptic modalities, although tactile aftereffects are often less robust than those reported in the visual system. Typically, following some relatively brief ($\leq$1 min) period of passive or active stimulation such as feeling a textured surface move across the skin or actively exploring a curved surface, a stationary stimulus presented to the same area of skin is perceived to move [212], [213] or a flat surface feels curved [115]. These phenomena are generally explained in terms of adaptation of specific classes of peripheral receptors, although the precise neural mechanisms involved are not well understood. In marked contrast to visual aftereffects for which the direction of motion of the aftereffect is generally most salient in the direction opposite to that of the adapting stimulus (i.e., a negative aftereffect), both positive and negative aftereffects are frequently reported after tactile stimulation [213], [214].

4.4 "Action for Perception" and "Perception for Action"

A substantial body of experimental findings pertaining to the somatosensory system has distinguished both functionally and neurally between "action for perception" and "perception for action" [215]. With respect to *"action for perception,"* we have highlighted the critical importance of hand movements for haptic perception in general (for a recent review, see [17]), and for some illusory phenomena more specifically, such as illusions of extent (see Section 2.2.1). In future, it will be important to explore other ways in which manual actions produce robust constant errors in haptic perception. With respect to "*perception for action*," within the context of weight illusions it has been clearly demonstrated that sensory feedback is used to change the dynamics of grasping and lifting when there is a mismatch between the predicted and actual sensory signals. But this feedback fails to impact significantly the perceptual systems involved in estimating weight. In future research, it would be of interest to determine whether haptically perceived cues, and in particular haptic illusions, impact motor performance.

4.5 Intensive versus Spatial Haptic Processing

Lederman and Klatzky [216] have previously drawn an important distinction between the processing of material and geometric object properties. As they empirically confirmed, coarse variations in material properties can be discriminated relatively quickly ($\sim$200 ms) by encoding variation in magnitude along a single dimension, such as the amount of skin deformed when haptically judging coarse surface roughness. They have described such processing as *intensive.* In contrast, geometric properties can potentially involve *intensive* (i.e., magnitude) and/or *spatial* processing, the latter taking more time because it also involves using some spatial reference system (dependent on both task demands and individual preferences). Consider the length of a raised line as an example of a simple geometric property. Short lines applied to the fingertip or palm can be discriminated intensively in terms of the span of skin deformed; larger extents will more likely need to be examined haptically, thus making duration of exploration available as a different intensive code. Alternatively, geometric extent may be evaluated spatially via passive or active touch by referring the inputs (tactile or haptic) to a spatial frame of reference, most likely body-based (hand-, arm-, torso-centered). The intensive-spatial distinction has processing ramifications not only with respect to the relative speed of processing, but also to constant errors that might result from the particular spatial reference system adopted. Such effects on speed and accuracy are relevant when considering the role of touch inputs in guiding motor actions, and in the design of haptic interfaces for performing perceptual and motor tasks in teleoperator and virtual environments.

4.6 Relevance for Tactile/Haptic Displays

The scientific study of illusions is relevant to understanding how to optimize the presentation of information in tactile and haptic displays; moreover, it has also benefited from the development of these devices. Virtual textures, surfaces, and springs have been created that provide insight into how people process tactile, haptic, and multisensory cues. New illusions have been discovered as a consequence of the capacity to present novel stimuli with devices in which the mechanical and temporal profiles of stimulation can be precisely controlled. It is important to remember the essential practices of perceptual research when these phenomena emerge and that the robustness and strength of the illusion should be reported.

4.7 Cross-Modal Illusions and the Experience of Synesthesia

We return here to the fascinating finding that haptic illusions have been experienced in the absence of any physical haptic stimulation. For example, the dynamic visualization of a physical force produces the feel of a virtual spring [11], [27], [30], as discussed in Section 2.1.2. Biocca et al. [27] speculated that such cross-modal illusions represent a form of *synesthesia* that may enhance the user's experience of spatial and sensory presence in an immersive virtual environment. Neuroscientists have investigated the neural mechanisms that support the experience of synesthesia (see, e.g., [217], for a review). In the future, it would be interesting to explore whether the neural basis of synesthesia similarly subserves cross-modal illusions involving touch in virtual environments.

4.8 "What" versus "Where" Pathways

Finally, we note that the differentiation of tactile illusions into two categories, one pertaining to objects and their properties and another to the perception of space mirrors the "what"/"where" distinction hypothesized for the visual system, where there is one processing stream for visual object perception ("what") and another for spatial vision ("where") [218]. Somatosensory scientists have recently begun to vigorously debate the existence of two processing streams in touch that may be functionally and neurally (in)dependent [215]. This significant theme deserves considerably greater exploration with respect to our understanding the nature of tactile/haptic processing in general, and more specifically, of tactile illusions.

Acknowledgments

The authors thank Aneta Abramowicz for her assistance in preparing some of the figures and, with Cheryl Hamilton, the reference section. This work was supported in part by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Canadian Institutes of Health Research to Susan J. Lederman, and from the US National Science Foundation (NSF) to Lynette A. Jones.

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