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Human Haptic Perception and the Design of Haptic-Enhanced Virtual Environments

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Summary. This chapter presents an overview of interesting scientific findings related to human haptic perception and discuss the usability of these scientific findings for the design and development of virtual environments including haptic rendering. The first section of the chapter deals with pure haptic perception whereas the second and third sections are devoted to the integration of kinesthetic information with other sensory inputs like vision and audition.

4.1 Introduction

More and more research and corporate resources are being invested into the development of virtual environments (VE). The challenge of virtual reality technology is to provide users with sensory stimulations that are as ”realistic” as possible, i.e., for a given situation, producing a sensory flow giving rise to the same percept than the one experienced in ”real” life. Most of the VEs built to date contain visual and spatialized sound displays of high fidelity, whereas haptic display technology that allows for manual interactions with these environments clearly lags behind. Yet, being able to touch, feel and manipulate objects, in addition to seeing and hearing them, is essential for realizing the full promise of VEs. Indeed, haptic perception provides a sense of immersion in an environment that is otherwise not possible. In addition, one of the most important potential applications of virtual reality displays is the development of training and simulation systems, especially in the domains where real practice presents risks for the involved persons. With that respect, haptic displays have a critical role to play since the main part of our interactions with the environment involves tactual and manipulative skills. For instance, haptic-based virtual reality display can be very useful in providing ”safe” surgery or medical exploration training to both human and veterinary novice surgeons [1, 2, 3, 4], where any mistake can have life-threatening consequences. Unfortunately, to date, even the most advanced technological approach cannot build a haptic device that generates a one-to-one

A. Bicchi et al.(Eds.): The Sense of Touch and Its Rendering, STAR 45, pp. 61–106, 2008.
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copy of the real world. Indeed, some physical constraints (of mechanical, temporal and frequency nature) currently prevent haptic devices from providing users with a fully satisfying realistic simulation. However, the unified perception of body/environment relationships is a "construction" of the brain resulting from the integration of the different sensory inputs (as well as other "intrinsic" factors like cognition -experience of a situation, expected sensory inputs context-related- or attention) rather than a one-to-one correspondence with the physical reality. In other words, to make an observer/user experience a given percept, virtual reality technology does not necessary have to generate a sensory flow that corresponds strictly to the physical stimulation leading to this percept in the "real" world, but "only" a sensory flow that elicits this percept. For instance, monitors cannot display real movements of objects but they are able to create an illusion of movement by successively displaying single pictures faster than human visual perception can resolve them. This example illustrates how taking into account the specificities of human perception and exploiting its limits can allow to by-pass technical limitations. Psychophysical experimentation, which is aimed at determining rules associating stimulus properties (e.g. the amount of information available, the nature of this information, the noise associated to the informative signal(s)) to individual's perception, therefore constitutes an issue that cannot be ignored when one wants to develop virtual reality displays.

The purpose of the present contribution is to provide an overview of interesting scientific findings related to human haptic perception and discuss the usability of these scientific findings for the design and development of VEs including haptic rendering. The document deals with pure haptic perception as well as with the integration of haptic sensory signals with other sensory signals like visual and auditory signals. On the other hand, the aspects relative to sensory bandwidths/resolutions of the cutaneous and kinesthetic system are not tackled here (see the contribution of Fritchi et al.).

In the first section, we address the question of how the haptic sensory system derives different properties of the environment and, especially, which part of the sensory input mainly defines these environmental properties within the haptic system. Sensory characteristics often directly specify "optimal" bandwidths and resolutions for haptic devices. Therefore, knowing which cues are important (and which are not) to perceive a given environmental property may simplify the display of the corresponding property and limitations in the capacities of the more general processes may further reduce requirements of the displays. In the second and third sections, we focus on the combination of haptic signals with visual and auditory sensory inputs. Indeed, another promising perspective to try to bypass some technical limitations is to appropriately associate haptic signals with other sensory signals when designing haptic-based displays. Vision seems to be the most apposite sensory input to associate with haptics, since vision and haptics provide a "redundant" direct access to several properties of the surrounding environment (e.g. shape, texture, size, orientation or location of an object). Moreover, our explorative and manipulative interactions with the environment generally occur under visual control. These arguments favor a systematic investigation of visuo-haptic combination in a virtual-reality-oriented perspective. Audition also constitutes a good candidate to be associated with haptics when designing haptic-based virtual-reality displays. In particular, our interactions with physical objects often stimulate our auditory system. Audition can therefore provide information about some "haptically-accessible" environmental properties like for instance the texture of objects. The second section is more specifically devoted to the environmental properties that can be redundantly assessed by the haptic and visual/auditory sensory systems, whereas the third section deals with the influence of visual and auditory cues on environmental properties that are theoretically only accessible to the haptic system.

All along the document, we used the word "illusion" to describe situations in which the percept experienced by the observer/user doesn't correspond to the physical reality (i.e., to the real physical characteristics of the stimulus giving rise to the percept).

4.2 Haptic Perception of Environmental Properties

Our haptic world is rather made-up of objects, surfaces and their properties than of sensory inputs. Of course some of these environmental properties are directly coded by the sensory system and sometimes even just by a small subset of single receptors - like in the case of temperature or small discontinuities on a surface [5], but the perception of many of environmental properties is based on the integration of different sensory sources. These integration mechanisms bear further possibilities for the development of haptic technology, as they may allow for the substitution of one type of sensory input by another type.

In this section, we will analyze the haptic system from the viewpoint of perceived environmental properties. We will start with the perception of the space reached by our hands 4.2.1 and continue with the perception of objects in this space. Material properties of objects and surfaces like roughness, softness or weight are dealt with in 4.2.2, geometrical properties like shape and size in 4.2.3 and the integration of different properties into haptic object recognition in 4.2.4. Finally, the sub-section 4.2.5 deals with the haptic perception of movement.

4.2.1 Manipulatory Haptic Space

With manipulatory haptic space we refer to the perception of the space reached by our hands. The most important thing to say about manipulatory haptic space is that it is pronounced non-veridical and that there is no coherent theory on this fact. Various studies demonstrate various distortions in space perception.

For example, space perception is anisotropic: people, even congenitally blind ones, regularly overestimate the length of touched vertical lines as compared to horizontal ones [6, 7] and they regularly overestimate the length of radial movements (to and from the body) by about 10 percents over tangential ones [8]. Just to give another example, felt orientation of a line in space strongly depends on its - especially tangential - position with respect to the body and trying to orient bars in parallel just by means of touch can result in deviations up to 40, especially if done bimanually [9, 10, 11]. Thereby, oblique oriented bars are less accurately reproduced as compared to those oriented in line with some body axis [12, 13]. Many further distortions - already known from vision - have been reported like the tactual Mueller-Lyer-illusion [14]. Attempts to describe these different distortions by some kind of nonveridical, but inherently consistent haptic metric did not prove successful. For example, a metric derived from distortions in perceived angles at different positions in space did not fit with one derived from perceived length [15].

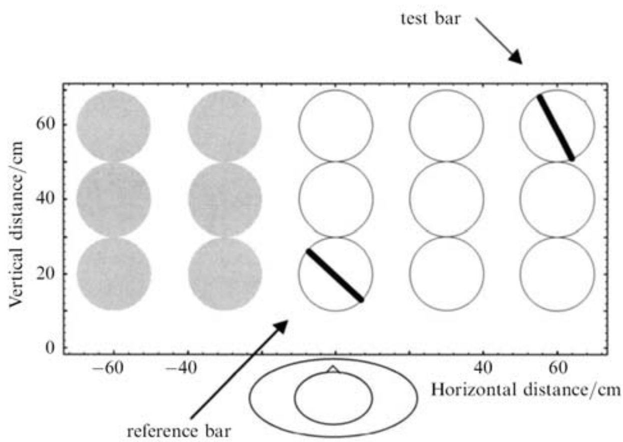

Fig. 4.1. Adapted from Kappers and Koenderink 1999. Subjects seated blindfolded behind the table in such a way that their navel was positioned at coordinates (0, 0). They were instructed to rotate the test bar in such a way that it felt as being parallel to the reference bar. They could neither use their left hand nor touch the edges of the table. No feedback was given.

However, there are numerous studies relating these spatial distortions to different factors within the movements. For example, body and arm position play a role for the size of the horizontal-vertical and radial-tangential illusions [8, 16]. Thereby, the latter was accounted for by different movement velocities in radial and tangential direction: It vanished when people were obliged to assimilate the velocities of their movements in the two different directions [17]. This corresponds to the observation that movement velocity strongly affects estimates of the length of a line up to a factor of 3 (reported for velocities between 0.5 to 50 cm/s [18]). Furthermore, oblique effects (in the vertical plane parallel to the observer) seem to relate to gravitational forces [12] - at least partly [13].

There are other strong illusions directly related to movement patterns: If people move along a curved line and, then, estimate the shortest distance between start and end point, the longer the movement path, the more the distance is overestimated (up to a factor of 2). This is true even if one hand remains on the

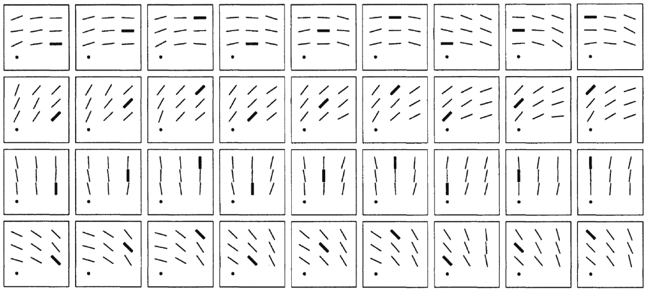

Fig. 4.2. Adapted from Kappers and Koenderink 1999. In each of the squares, the small dot indicates the position of the subject and the thick line represents the reference bar. In each row, the orientation of the reference bar is kept constant but the position varies. The thin lines give the orientation of the test bars averaged over the different settings. If subjects responded veridically, all thin lines within a square would be parallel to the thick line. As one can see in the figure, this is not the case and quite large deviations occur. Going from left to right within a square, the orientations of the lines change mostly clockwise. The lines within a square are often parallel to each other when compared vertically.

starting point [19, 20]. Further, if people move one arm against a constant force, the other arm can estimate its position appropriately, but if the force varies during the movement people make systematic mistakes [21, 22, 23]. This holds also true for actively induced force changes, e.g., when matching the indentation depth of two springs with different compliances [24].

Altogether, the number of illusions in the perception of manipulatory haptic space is large and may, especially, depend upon the way the kinesthetic system derives position and movement of limbs from the muscle receptors. As noted above, this relationship up to now is not well understood. Thus, the illusions are rather interesting for basic research. However, general rules ready for application in haptic displays design are not that easily derived. Consequently, the following suggestions remain highly speculative and subject to further investigation.

One general rule may be derived from the fact that in everyday-life, when we touch and look around in space, we are not aware of all these distortions. Visual distortions in the same direction can explain this fact just to a very small part [25]. Primarily, it may mean that with vision available we do not care much about coarse haptic relationships and, consequently, it may be of minor importance to get these exactly right in the haptic part of virtual reality. Moreover, specific distortions may suggest specific probably useful applications or directions of research. For example, virtual realities that visually stretch empty space in haptically overestimated directions may be able to increase virtual haptical workspace somewhat - unnoticed by the user. Or, the fact that space perception by the two different hands is especially inconsistent promises simplification in the synchronization of bimanual interfaces.

Finally, space distortions stemming from varying forces have been shown to have a promising counterpart in shape perception, which we will discuss in 4.2.3.

4.2.2 Material Properties

The perception of objects (and surfaces) in haptic space can be split into the perception of their different haptic properties like material and geometry. Material properties are probably the object properties that are the most specifically related to haptics as compared to the other senses. Material properties entail surface properties as well as an object's weight. Surface properties have been further differentiated into perceptual categories like roughness, softness, stickiness and apparent temperature [26]. People tend to discriminate between different real surface materials primarily with the help of the surfaces' roughness and softness followed in some persons by their stickiness [27]. This may mean that the percept resulting from a surface is well described in terms of these two or three dimensions. Likewise the display of haptic material in virtual environments probably may limit, but in each case should concentrate on these two or three dimensions. We will discuss in detail the main psychophysical findings on the former two dimensions; concerning the latter there is relatively little research. Instead, we added a section on temperature which has been quite intensively studied. A final section is on the perception of weight, for which a number of interesting illusions have been reported.

Roughness

Perceived roughness mainly seems to relate to the interspacings between protuberant small elements arising on a relatively homogoneous surface [28, 29]. Two different mechanisms seem to code roughness: With microscale interspacings between elements (<0.1 mm) primarily vibrations resulting from the relative movement of the finger on the surface seem to give rise to the perception of different roughnesses [27, 30, 31]. Neurally, microscale roughness coding involves fast adapting cutaneous receptors with peaks for vibration frequencies of 250 Hz (FA 2) [31]. With larger interspacings up to about 3-8mm coding seems to get predominantly spatial [27]: In experimental textures that take the form of grooves with rectangular profiles, felt roughness strongly increases with the width of the grooves and hardly depends on parameters related to vibration like speed of movement or spatial frequency of the grating [28, 29, 32]. The assumption that the amount of skin deformation is the crucial cue in coding of macroscale roughness, thereby, seems to explain a number of findings including further dependencies of roughness on contact force and groove depth [33, 34] as well as the observation that perceived roughness does not depend on whether the observer moves relative to the surface or keeps his finger pad stationary (passive touch) [27]. Thereby, the perceived roughness seems to rely upon an integrative code across different locations (intensity coding) rather than on the precise spatial pattern of skin deformation [35]. Neurally, macroscale roughness coding, relates to activity differences between adjacent slow adapting cutaneous receptors (SA 1) [36, 37].

Given two codes for roughness at different scales, high-fidelity displays of roughness might implement two mechanisms as well. Microscale roughness requires easier-to-implement vibrations and macroscale roughness heavily relies on spatial cutaneous deformation. This holds albeit people can estimate macroscale roughness without spatially distributed fingertip information, i.e. by the vibrations felt, e.g., through a probe [38]. Obviously, the roughness perceptions through a probe and by the bare finger pad largely differ in richness. There may be intermediate scales (about 300 microns) where vibratory coding seems to have an influence besides spatial and may be able to substitute spatial coding [30].

However, at larger scales some kind of spatial code is likely to be necessary for a rich percept of roughness. Nonetheless, given that this spatial code is an intensity code the variation of single factors within the force patterns or limited combinations of few factors may suffice to obtain the full scale of felt roughnesses. Experimental results suggest that the most effective factors for perceived roughness may be groove width between protuberant elements - in direction of movement as well as perpendicular to it [36] - and contact force. In addition, enhanced shear forces seem to lower perceived roughness [39, 40]. However, optimal implementations will require further investigation into this field.

Softness/Stiffness

Softness is the psychological correlate of the compliance of a surface. Compliant objects can be further classified into those with rigid surfaces (e.g. a piano key) and those with deformable surfaces (e.g. a rubber). Research on softness is sparse. An important study with surfaces having compliances in the range of 5.6 to 0.46 N/mm suggests that softness perception strongly relies upon cutaneous input [41]. In this study, kinesthetic input alone did not allow at all to discriminate between the presented surfaces. Further, if the surface was deformable, kinesthetic input did not add anything to cutaneous input alone (just noticeable differences in both cases $<$12 percents). Softness discrimination in this case probably relies upon the spatial pressure distribution within the skin contact region. In contrast, when the surface was rigid, both kinesthetic and cutaneous inputs seem to be required, but performance lags far behind that for deformable surfaces (JND about 23 percents [42]).

Interestingly, in a situation similar to that with rigid surfaces - tapping deformable surfaces with a tool - discrimination performance approximated that for bare fingers on the deformable surface [43]. This probably reflects the ability to optimize the amount of useful kinesthetic and cutaneous input in relatively unconstrained situations.

However, like for roughness a rich impression of felt softness in haptic displays is likely to require skin deformation spatially distributed across the finger pad. As softness is a haptic property that is like roughness relatively quickly available [35], one may assume that softness also relies upon some integrative code. First evidence for this hypothesis is given by findings relating softness perception especially to the rate at which the contact area spreads with increasing finger pressure [44].

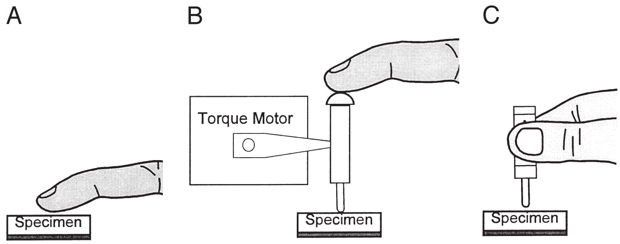

Fig. 4.3. Adapted from Lamotte 2000. The subjects had to discriminate the softness of rubber objects of differing compliance Different modes of contact were used when ranking the softness of the objects. A: subjects ranked softness by actively tapping or pressing each specimen with the distal pad of the middle finger. B: a stylus with a tip diameter of 3 mm was mounted to a torque motor, and a sphere of 10 mm in diameter was mounted to the upper end of the stylus. The stylus exerted an upward and a downward force when tapped and pressed against the specimen, respectively. C: the unconstrained stylus was held in a precision grip and was either tapped or pressed against the specimen. For a given type of active palpation (tapping or pressing), differences in softness were as discernable by the use of a stylus as they were by direct contact with the finger-pad.

The display of a really hard surface is another so far unresolved problem in haptic device technology. The stiffness required to simulate a rigid wall has been estimated to be about 25 N/mm [45]. However, a study which examined tapping on virtual surfaces - displayed by a kinesthetic device - suggests that felt hardness in the higher range (3.45 to 1.72 N/mm) rather depends on the dynamic initial rate of force change in the surface contact than on the static relationship between position and reaction force [46]. Thus, it may be that a fast onset of the forces in a haptic display may help to overcome the necessity to display very high forces.

Temperature

Temperature is often treated as a modality on its own, as it is related to specific receptors for warmth and cold separated from the mechanoreceptors [47, 48]. Normally, objects around the skin temperature (about 33 degrees depending on skin site, person and some further factors) are categorized as indifferent, higher temperatures lead to the description "warm" and lower ones to "cold". Thereby, perception mostly ignores and adapts to slow changes in skin temperature ($<$ 0.01 degrees/s for a stimulator of 14.44 cm^2 contact area at the forearm [49]). Adaptation stops at about skin temperatures below 31 degrees and above 36 degrees where the perceptions of "cold" and "warmth" persist [48]. However, with fast temperature changes ($>$0.1 degrees/s in the above experiment) yet small differences will elicit the reports "cold" and "warm", respectively [49]. The difference thresholds here depend on the skin site stimulated as well as on the exposed area with near perfect spatial summation [50]. For the fingers the thresholds were given for young adults as about 0.1 degrees C difference [51].

Temperature stimuli are well-known to be badly localized, especially warming stimuli within a single dermatome [52]. Similarly, earlier work demonstrated that the temperature felt in one finger pad is heavily modulated by the temperature provided to one or more adjacent finger pads. Thereby, warmth is more easily transferred than cold and the transfer requires a touch component [53, 54, 55].

In virtual haptics these spatial illusions may allow to separate the skin regions of display of temperature and of touch components. For example, it might be possible to attach the respective displays to different phalanges of the same finger. Moreover, given thresholds, slowness of the temperature senses and their adaptation within a range of 31 degrees to 36 degrees may further simplify the built-up of a corresponding device.

Weight

Weight is an object property which, physically spoken, is a function of gravitational force, an object's density and its volume. Interestingly, perceived weight can be further affected by surface material and shape.

The first report of a corresponding weight illusion stems from Weber [56]. He observed that objects wielded between the fingers feel heavier than those resting on the skin. Also long known is the so-called size-weight illusion [57, 58]. Usually, smaller objects feel heavier than bigger ones of the same physical weight. This may relate to some unfulfilled expectancies of weight and/or a mismatch between the objects weight and the applied lifting forces [59]. Amazeen and Turvey [60] systematically reviewed and investigated the influences of size and shape of an object on its perceived weight during wielding it. They came up with a model in that perceived weight is a function of the resistance to rotational forces imposed by the limbs. Perceived weight, then, is directly related to the product of power functions of the eigenvalues of the inertia tensor. This is a 3 x 3 matrix whose elements represent resistance to rotational acceleration about the 3D-axis system around the center of object rotation. The model explains and predicts how perceived weight is affected by shape and may be useful for technical purposes.

Another class of weight illusions relates to surface material. Also rather early Wolfe [61] reported that equal-weight objects with a "dense" surface (e.g., brass) feel lighter than those with a less "dense" surface (e.g., wood). It was suggested that surface material and perceived weight relate via slipperiness and grip force [62, 63, 64]. In order to lift an object with a slippy surface more grip force is required than to lift a sticky object and forceful grips also relate to heavier objects. Hence, slippy objects may feel heavier than sticky ones. Moreover, the influences of surface material on perceived heaviness seem to vanish when the objects are required to be gripped very tightly. It was suggested that - at least in part - the surface-weight illusion is directly related to slip sensations and that the illusion vanishes during forceful grips as the corresponding receptors may be saturated [65]. Finally, there seem to be further more complex interactions between grasping and perceived weight indicated by influences of grip width, number of fingers involved and contact area [66]. Technologically, weight illusions may be useful to display weights that exceed the force range of a specific haptic device (e.g., the PHANToM). Particularly, slip may be an easy-to-implement cue to perceived weight or even induce the illusion that an object can not be lifted due to heaviness. However, an optimal application, of course, awaits for some more investigation. In addition, the model of Amazeen and Turvey [60] may be a good starting point for a perceptually correct representation of object properties during wielding.

4.2.3 Geometry of Objects

Geometrical properties of objects have been divided into size and shape [26]. However, for haptics this separation taken from vision may be misleading. For example, proportional relations in rectangles of different size - an aspect of pure shape - seem to be neither spontaneously nor directly perceived in haptics [67]. More importantly, haptic perception of geometrical properties occurs at a wide range of scales from microns to about meters. Consequently, perception of shape is likely to include different mechanisms varying with size. For example, the shape of objects with a size of about 1 cm may be sensed via deformations of the skin at a single finger pad ([38] for the orientation of short bars), whereas shapes of larger scale may require an integration of cutaneous and kinesthetic input over time and different body sites, e.g. different fingers.

Research just starts to understand the corresponding mechanisms. But it suggests that at an intermediate scale cutaneous and kinesthetic input is integrated for shape perception: For example, 2D-objects at the centimeter scale are better recognized when actively touched (i.e, with kinesthetic information) as when passively pressed into the palm [68, 69, 70]. Recent work examined the perception of angles around 90 with arms of 8 cm length [71]. Discrimination thresholds were 4 when cutaneous and kinesthetic input was available and about 8 with one type of input only. Most work has been done on the perception of curvatures. Curvature is numerically defined by the inverse of the radius of a corresponding cylinder. Passive touch with a single finger (cutaneous input only) can detect curvature starting with 5 m-1 and discriminate between high convex curvatures of 287 m-1 and 319 m-1. Absolute thresholds for detecting curvature by active touch or with multiple fingers, i.e. with the help of additional kinesthetic information over time or space, respectively, lies below 2 m-1 [72, 73]. Detection thresholds in active touch for curvatures of 154 m-1 and 286 m-1 were given as 13 and 18 percents, respectively [74]. The better results with active touch, also here, point to the integration of kinesthetic and cutaneous cues [75]. For, haptic devices these findings rather generally suggest that a rich and, especially, detailed illusion of haptic shape will require both kinesthetic and tactile display. Neurally, the cutaneous component in shape perception may be - like roughness and softness - primarily coded with the help of SA1 receptors. For high curvatures, they are known to preserve an isomorphic representation of the pressure gradient on the skin [5, 76, 77].

Sophisticated research on the mechanisms underlying curvature detection suggested that orientation differences between the most outlying parts of the surface were crucial for the decision whether a surface is curved or not, both in active and in multi-finger touch. For example, orientation differences systematically relate to the length of a curve segment and the longer the curve the lower was the absolute detection threshold for curvature [72, 78]. That orientation differences are a very effective cue in haptics also derives from discrimination studies on Gaussian stimuli varying in amplitude and length [79]. In how far this efficiency extends from shape detection to shape discrimination is an open question. However, this cue may be worth some investigation, as its implementation into haptic displays seems to be fairly realistic.

Further interesting influences on the perception of curvature in active touch have been reported. Another curve touched beforehand [80] as well as the manner in which a curved surface is touched affect the resulting percept [81, 82]. For example, a radial stroke is accompanied by better detection of a curve as compared to a tangential stroke [83]. In addition curvature discrimination is better when done unilaterally successively as compared to bilaterally simultaneously [75]. For virtual haptics the latter effect, again (cf. 2.1), promises simplification in the synchronization of bimanual interfaces.

Similar to the findings for haptic space, varying forces evoked some further interesting illusions in perception of shape. For example, virtual curvature - displayed by a kinesthetic haptic device - has been overestimated when high as compared to low frictional forces were simulated [84]. Moreover, perceived orientation of a plain surface can be systematically changed just by varying resistant or assistant forces tangential to the movement on the surface [85]. Most interestingly, the display of the appropriate patterns of tangential forces on a plain surface can evoke a stable illusion of a small bump or a hole [86].

These results demonstrate that the kinesthetic system derives 3D geometry of objects at least partly by force cues in the movement. The results match with force illusions on position perception in haptic space (see 2.1). Haptic display may benefit from these observations, in that they may allow for the haptic perception of a third dimension in relatively cheap two-dimensional devices or for extending a third dimension over the physical workspace in a three-dimensional device. We investigated these effects and found that perceived shape results from a weighted averaging of the contributions of force and position cues [87, 88]. This means that the perception evoked by certain force cues on a plain surface can be clearly predicted and, thus, be technologically applied.

Finally, there was an important study looking for the perception of haptic detail within a virtual reality displayed by a kinesthetic device. Perception capabilities increased with increasing maximum force-output, but the increase reached a limit with maximum forces of about 3-4N [89].

4.2.4 Integration of Properties into Haptic Object Recognition

The human capability to recognize objects just based on haptic information is astonishing. In a seminal study people were able to name 100 well-known hand-sized

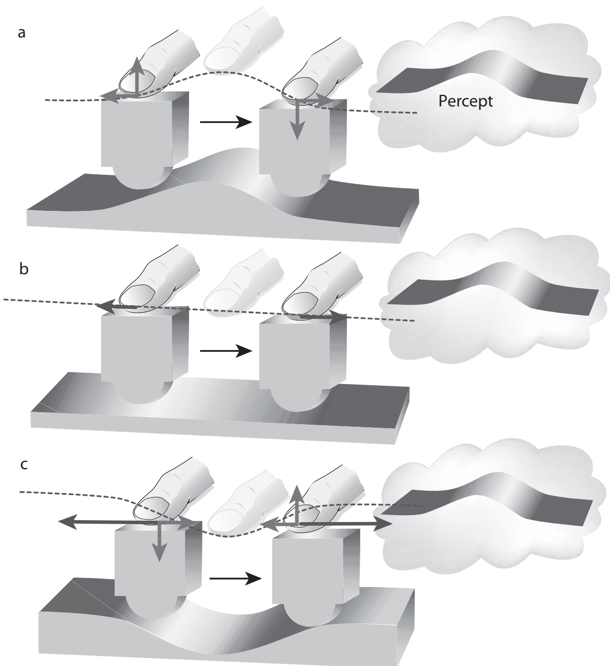

Fig. 4.4. Adapted from Flanagan and Lederman 2001 in a comment on the work of Robles-De-La- Torre and Hayward 2001 about how force and geometric cues contribute to the perception of shape by touching. In the original study, the subjects were instructed to use a fingertip to slide an object over a surface (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 the arrows (fingerpad). 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 (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.

real-life objects within 5 seconds each to 94 percents correct; mostly they just required 2-3 seconds [90]. An interesting question is how people derive and integrate the different haptic properties of objects like shape and material to obtain this efficiency.

A series of experiments extracted a set of so-called exploratory procedures, i.e., relatively stereotyped movements used to extract certain object properties [20]. According to that and further studies there are corresponding relations

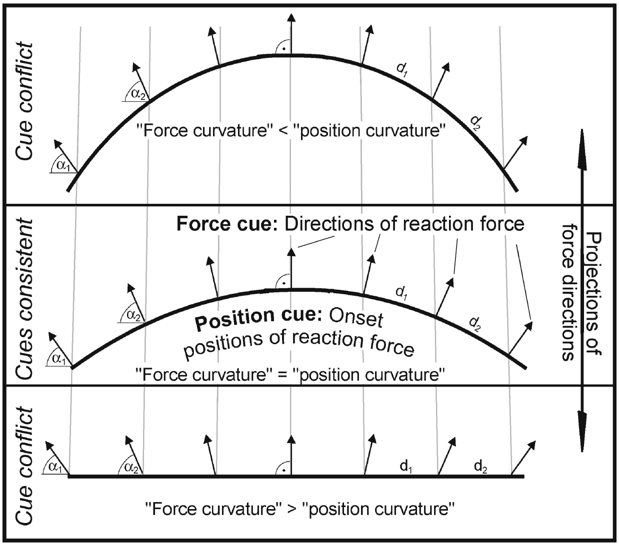

Fig. 4.5. Adapted from Drewing et al. (under revision). For each trial, the participants had to decide which of two successively presented arches (one complete stroke across each arch, i.e., forth-back-forth) felt more convex. The virtual arches could provide the observer with consistent or discrepant position and force cues (see the figure). In shapes with cue conflict, the force directions (?) of one shape were projected on the geometry of another shape, so that the path distances (d) between different force directions were preserved. The results indicate that both force and position cues contribute to the perceived curvature.

between lateral motion across a surface and textural properties, static contact and temperature, hand enclosure around an object and coarse shape, pressured contact and compliance, unsupported holding and weight and, finally, following the contours of an object shape and details. Additional relationships may exist between wielding a hand-held object and its weight, length and orientation [91, 92]. There are good arguments as well as empirical evidence that such exploratory procedures optimize the sensory input required for computation of the related property [20, 93]. And there is good evidence that such exploratory procedures are spontaneously used if the respective haptic property is in question [20, 94, 95].

If people are asked whether a given object is a certain one ("Is this object a cooked noodle?"), they, usually first grasp and lift the object and than show the exploratory procedure related to the haptic property which they formerly indicated to be diagnostic for the decision [96]. The same is true if they are asked for sorting objects by that property. However, if vision comes into play, haptics is just used for judgements concerning material properties like weight and roughness [97].

The latter finding points to the importance of material in haptic object recognition. Indeed prevented from surface material properties and local details (by wearing a thick heavy glove) and using just a single finger haptic recognition performance for every-day life objects drops down to 75 percents correct [98]. Other studies demonstrate that surface material is the most immediately derived property of a surface, followed by the existence of surface discontinuities (bumps) and, finally, by the detailed spatial composition of a pattern - as required to perceive, e.g., the orientation of a bar embossed on a surface. This was related to the fact that textures can be distinguished by some integrative spatial code, whereas spatial composition requires a distributed code preserving the spatial pattern [35]. Other work agrees that details in spatial patterns are relatively difficult to extract [96, 99].

On a higher scale similar principles of property availability seem to hold: If people sort unfamiliar objects by similarity of their haptic shape, in early processing local shape details are most important. Yet with longer processing time global shape gets equal in salience [100]. Thereby, haptic object recognition especially seems to rely upon the features at the back side of an object [101]. These studies may be of strategic importance in the development of haptic devices. Taken together, they suggest priority of material over shape properties in the haptic world, which easily translate into priorities for the development of haptic displays. Further, people's difficulties to extract details in spatial patterns suggest that these are of minor importance for the perceived richness of haptic display as compared to, e.g., textures and the same might hold for the comparison between local and global shape.

4.2.5 Perception of Movement on the Skin

Up to now we discussed haptic properties in a somehow static manner. However, our interaction with the environment is dynamic and movement plays an important role in haptics and haptically guided action. Imagine lifting a raw egg: In order not to break it you will grip it with just as much force as sufficient to prevent it from slipping through your fingers. Neurophysiological evidence [102] has clearly shown that cutaneous receptors (FA1), which signal when slip is about to occur, contribute in vital ways to the skill with which people are able to manipulate objects using precision grips (besides previous experience with the objects). Moreover, the perception of movement on the skin is not just of major importance for dealing with fragile objects, but also an always present side effect of every active exploration of our environment with the fingers.

In principle, two distinguishable kinds of stimulation have been demonstrated to evoke the percept of directed movement across the human skin [103]: lateral stretch of the skin - examined, e.g., with the help of a small probe glued to the skin [104] or a sliding glass plate [105] -, and the spatio-temporally ordered translation of a stimulation across the skin without stretch - realized e.g. by a rolling wheel [106] or an array of pins that are able to indent the skin in normal direction [107, 108]. In most natural situations as well as in most studies on movement perception (e.g. with brushes or probes), stretch and translation cooccur. Neurally, translation seems to correspond mainly to a sequential activation of adjacent fast adapting receptors (FA1, [103]), whereas stretch evokes an initial pattern of response in fast adapting receptors (FA1) and a persisting one in slow adapting ones (SA2), which is sensitive to the direction of movement [31, 105].

Several studies demonstrate that stretch is more easily detected as compared to translation - at least in terms of minimal path traversed: For example, for velocities of 1 cm/s a pure stretch of 0.6 mm on the forearm suffices to detect the direction of motion, whereas a 5 grammes (g) probe (inducing translation plus some stretch) has to traverse 4.4 mm [104]. Moreover the weight of the probe, which relates to the size of its stretch component, strongly influences the threshold - e.g., weights between 1 and 6 g are accompanied by thresholds between 30 to 3 mm on the forearm [109, 110] - thereby, pure translation stimuli do not benefit from force impact [106, 110]. Preventing surrounding skin from the spreading influence of stretch seems to cancel out the advantage of stretch over translation [103] and likewise should be avoided in haptic devices using skin stretch.

Both the detection of stretch and translation are the better the longer the path traversed, the wider the moving stimulus [106, 111] and the more innervated the skin. The latter means that detection is best at the finger pad [112, 113]. For a mean path length the detection rate relates inversely U-shaped to the velocity of the movement - with a left-shifted peak (3 to 10 cm/s for a brush stimulus at the finger pad), for a long path it approximates 100 percents for all velocities examined (e.g. 1 cm at the finger pad for velocities between 0.75 und 250 cm/s) [113]. If a moving stimulus is masked such that just the start and the end of the movement can be sensed, motion detection clearly suffers as compared to a continuous sensation [114, 115].

The percept of apparent motion has been reported for a stimulus consisting of successive multiple indentations at a first location and a successive indentation at a second location on the skin (”continuous rabbit”) [116] and for at least 3 successively activated pins in vibrotactile pin arrays [107, 108]. But also stimuli consisting just of two temporally alternating stimulations at different locations were occasionally observed to result in some apparent motion [117, 118]. However, the pin illusion increases (in terms of detection of directed movement) with the number of pins involved [107, 108]. A similar stimulus even can evoke the percept of smooth continuous motion under certain conditions (velocity from 1.5 to 24 cm/s [103]). Unfortunately, the minimal conditions for the occurrence of smooth continuous motion remained unclear. Stimuli in the two experiments differed in pin distance (2.4 vs 1.2 mm), delays between pin movement onsets (6 to 36 vs. 2.5ms), display site (index finger vs. oral region) and further factors. Technologically minimal conditions may be of major interest. Unfortunately, existing pin arrays with the resolutions described above, usually, are vibratory in nature, which accompanies their use with the finger by a disturbing ’hum’.

Technologically similarly promising, may be another illusion of rather smooth movement, which theoretically relates to the strong cue of stretch combined with translation: A simple comb pressed with a certain force into the skin and excited sequentially by stroking its pins with a probe evokes a strong illusion of motion. This illusion of movement relates to the upcoming shear force displays [119].

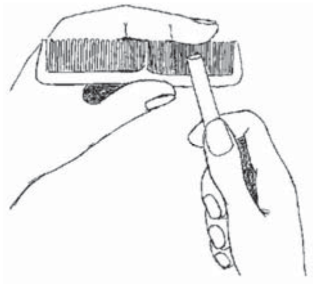

Fig. 4.6. Adapted from Hayward and Cruz-Hernandez 2000. A comb is held so that the line of fine pitched teeth contacts the index tip along its length. At rest, the individual teeth cannot be distinguished apart and create the sensation of a continuous edge. Then, the teeth are gently stroked back and forth at mid length with a stick. The resulting sensation is that of an "embossing" running under the index finger. The motion of each individual tooth is minuscule, of the order of a few micrometers and yet the resulting sensation is very present. (It is also important to notice that the same experiment performed with the coarse pitched side of the comb is not nearly as convincing.) In a second step, the same comb is applied to the skin, but this time such that its teeth indent the skin when bent (achieved by touching the comb on its side and again running the stick). The resulting sensation is remarkably similar if not indistinguishable from the previous case. In both cases, the comb teeth indent the skin, and in both cases skin stretch changes are caused, however in the former case there are changes in the lateral direction only and very small ones in the orthogonal direction.

Existing studies may be taken to suggest a minimum of three pins [107, 108] and a stretch by more than 0.6 mm [104] for a corresponding display. Some more specifications may be estimated, but precise specifications for appropriate spatial, temporal and force parameters are up to further investigation. In line with this, a prototype of shear force device has been developed for investigating the comb illusion more thoroughly including its technical applicability [120].

A further promising movement illusion, which we are currently investigating is the Barber Pole illusion. When a pattern of tangible parallel lines is moved beneath the finger pad, a movement is perceived perpendicular to the direction of lines rather than in the direction of the physical movement of the lines. This illusion has been explained within a more general computational model of tactile flow perception [121] and provides another good starting point for movement display.

4.3 Integration of Haptic Sensory Signals with Visual and Auditory Signals for the Perception of Environmental Properties

The objects that we reach and manipulate are generally located in our field of view. As a consequence, several physical properties of these objects are redundantly coded both haptically and visually. In some cases, our manipulative interactions also generate auditory signals. These signals being specific to the properties of the manipulated object, they can be matched to haptics- or vision-derived representations of this object. One would be very surprised when knocking on what looks like a wooden plank if the haptically felt contact is soft or if the auditory heard noise sounds metallic. The results presented in this section are related to different objects' properties that are redundantly accessible to touch and vision/audition. For each of these physical properties, we provide a review of selected interesting findings together with a brief indication of how it might be used for the construction of novel multimodal workbenches.

4.3.1 Location Perception

Visuo-Haptic Combination

Among others, vision informs us about the location of the objects of the environment. If we consider the visuo-spatial coding in an action-oriented perspective, this information derives from the integration of retinal (position of the object on the retina) and somatosensory (eye orientation in the orbit, head orientation on the trunk) cues. But in absence of visual cues, we can also code the position of a grasped object on the sole basis of haptic cues (via the proprioceptive chain that codes the position and orientation of each body segment with respect to the others). One of the ways that have been employed to try and determine how vision and haptics combine in spatial coding consisted in measuring subjects' perception of their hand's location when related visual and haptic cues are discrepant [122, 123, 124, 125, 126]. Typically, observers viewed one of their hands through a laterally displacing prism and were asked to indicate with the other hand (unseen) where they saw or felt the visible hand to be. The responses in the discrepant condition were compared to proprioceptive and visual control conditions in which the observers received information from only one modality. In all these studies, a strong visual bias of proprioception was observed (in these cases, the visual bias is always larger than 60 percents). In some cases, this visual bias was so important that the responses in the combined cues condition were not significantly different from the ones obtained in the vision alone condition [122, 123, 124]. These results suggest a strong predominance of visual cues over haptic cues in the coding of spatial locations. This dominance of vision over haptics would explain why proprioceptive signals can so easily be recalibrated by visual information either statically [127] or dynamically [128, 129]. However, some recent studies suggest that visual dominance over proprioception only applies for given directions [130, 131]. Indeed, van Beers et al. [130] found that whereas vision clearly dominates for estimation in azimuth, proprioception seems to dominate in depth.

Related results are provided by the study of Gepshtein and Banks [131] showing that touch is better than vision for the estimation of relative distances in depth (vision allowing better accuracy than touch in the fronto-parallel plane). Taken together, these results suggest that during the visuo-haptic integration,

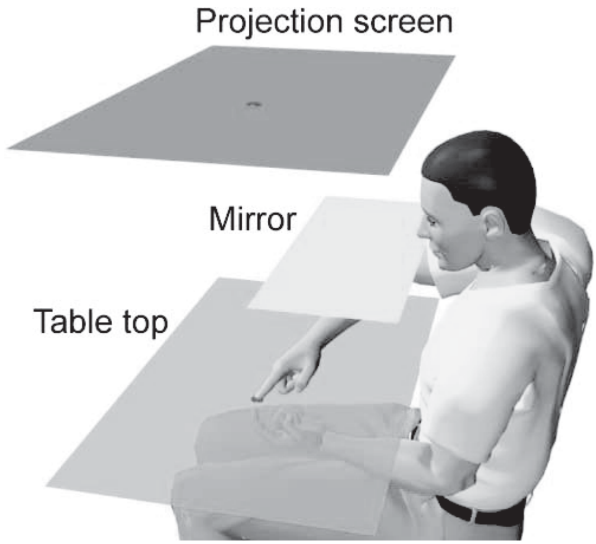

Fig. 4.7. Adapted from van Beers and al. 2002. The subject looked in a mirror, which was positioned midway between a tabletop and a projection screen. They had to use their left hand under the table to point to visual, proprioceptive, or both visual and proprioceptive targets. Proprioceptive targets are defined as the position of the right fingertip, which is placed on a tactile marker on the tabletop. Vision of the table and the right arm was occluded. In the visual target condition, the right hand remained in its starting position, and the visual target was presented. In the combined visual-proprioceptive condition, the visual target was also displayed, but now the subject also had to put the right finger on the corresponding tactile marker. Full visual feedback was provided about the right finger position, shown by the cursor spot (i.e., the image of the projection screen was seen in its place and a red circle was presented to localize fingertip position), during the movement from the starting position to the target. In all conditions, subjects pointed with their unseen left hand touching the underside of the table. No feedback was given. During adaptation, the relationship between actual hand position and red circle position was perturbed by displacing the circle either in azimuth (leftward) or in depth (forward). The results show that the visual-proprioceptive integration varies with direction. The estimates rely more on vision in the azimuth direction, and more on proprioception in the depth direction.

the weight allocated to each cue can vary in a situation-dependent manner according to the relative reliabilities of the cues. The increase in haptics' spatial potency along the antero-posterior axis would then be related to the least reliability of visual cues in depth (due to intrinsic limitation of visual depth perception). Actually, according to the results of Gepshtein and Banks [131], this is exactly what seems to happen, human observers' estimates when vision and touch are combined being very similar to the estimates an "ideal observer" would produce if weighting each informational stream in an orientation-dependent manner (statistically optimal combination of visual and haptic cues as a function of relative cue reliability).

In conclusion, one can say that adding vision to the sense of touch for estimating the location of an object contributes to reduce the variance in the perceptual estimate. Therefore, adding visual information to haptic displays in virtual environments should be beneficial to the reliability of position-related information and allow more salient perceptual estimates.

The second interesting point to mention in a virtual reality-related perspective concerns the calibration of the visual and haptic scenes. According to the above-mentioned astonishing ability of the sensorimotor system to recalibrate itself (to reduce any "detected" constant offset between the visual and haptic estimates), this calibration does not constitute such a crucial issue. In other words, the two scenarios (visual and haptic) do not have to be strictly and absolutely aligned. This information could facilitate the design of novel visual-haptic workbenches.

Audio-Haptic Combination

When considering the auditory system, speech and music perception are probably the first items one would think of. However, auditory signals also constitute a non-negligible source of information in the spatial domain. For instance, auditory signals can be very useful in informing us about an approaching individual or car in our back hemi-space. Concerning the combination of auditory cues with other sensory cues in spatial tasks, a large part of the literature is devoted to visuo-auditory integration. The used paradigms mainly consisted in simultaneously presenting spatially discrepant visual and auditory stimuli and measuring subjects' performance in localizing either of these stimuli. The most robust and consistent effect observed in these studies is the ventriloquism effect, that is a strong visually-evoked bias in the perceived location of auditory stimuli (see [132] for a review). The investigation of auditory-haptic combination relies on paradigms similar to those used in the visuo-auditory domain, subjects being provided with spatially discrepant auditory and haptic stimuli and asked to localize either of these stimuli [125, 133, 134]. For instance, in the study of Pick et al. [125], blindfolded subjects having a finger from their left hand in contact with a loudspeaker placed above a table (so that they could haptically feel the auditory clicks that were delivered) were instructed to point with their other hand under the table to indicate the perceived location of either (1) their left-hand's finger, or (2) the auditory clicks. The results showed a strong biasing effect of proprioception on the perceived position of the auditory clicks, but a poor effect of auditory stimuli on the haptically-perceived hand position. This "haptic capture" of auditory stimuli in spatial judgments seems rather robust [133, 134].

According to the above-mentioned results, it seems difficult, under "everyday" conditions, to envisage any efficient audition-evoked haptic illusion in the space domain. However, providing congruent auditory and haptic cues concerning objects' positions would probably contribute to reduce the variance of the haptic

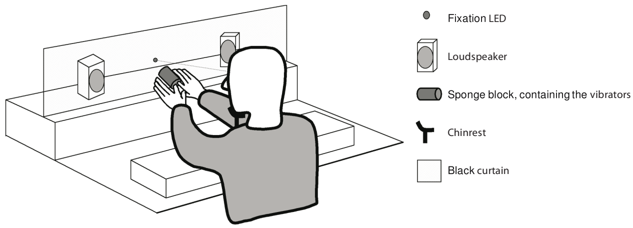

Fig. 4.8. Adapted from Caclin et al. 2002. Participants made left-right discriminations regarding the perceived location of sounds, which were presented either in isolation or together with tactile stimulation to the fingertips. Participants were seated in a dark room and two loudspeaker cones placed 46 cm apart (center to center) were hidden behind a curtain, at ear level. Participants placed their index fingers on two vibrators situated next to each other at the same height as the loudspeaker cones and directly between them. Participants were instructed to fixate on the central LED throughout the experiment and to concentrate on the auditory task while ignoring the vibrations as much as possible during the bimodal blocks. In half of the blocks (corresponding to the bimodal condition), vibrations were delivered to the fingers in synchrony with the sound bursts. In the remainder of the blocks (corresponding to the unimodal condition), no vibrations were presented. The results demonstrate that the apparent location of a sound can be biased toward tactile stimulation (tactile capture of audition) when it is synchronous, but not when it is asynchronous, with the auditory event. In the experiment, directing attention to the tactile modality did not increase the bias of sound localization toward synchronous tactile stimulation.

perceptual estimate (even if to our knowledge, no study going in that direction has been performed to date).

4.3.2 Shape Perception

Shape estimation is a complex task in which our perceptual system has to integrate information over time and space. For the sake of clarity, two-dimensional patterns recognition, three-dimensional shape estimation and curvature estimation are presented separately:

Recognition of Two-Dimensional Patterns

Adding visual information to haptic cues in two-dimensional patterns recognition allows better performances. This has been demonstrated with different tactile stimuli like tangible embossed patterns of Morse and Braille codes [135] or familiar object categories [136]. For tactile recognition of familiar objects, the visual improvement seems related to the synoptic view provided by vision rather than to a better encoding of contours features. Indeed, when the contours of the objects are visually revealed through an aperture during the digital exploration but that any global view of the object is prevented, the recognition performance is not different from the one resulting from the sole tactile exploration [136]. On the other hand, concerning Morse and Braille code recognition, the vision of tactile scanning patterns is sufficient to improve subjects' performance [135]. This visual contribution is so powerful that nave sighted observers are able to identify invisible Braille dots by watching other individuals touch the symbols. For characters recognition, visual cues can also be very useful when the orientation of the presented characters is unusual. Indeed, Heller [137] showed that small amounts of tilt impair touch abilities to recognize Braille characters whereas vision is much less sensitive to these modifications of orientation. Moreover, vision allows much faster responses than touch [137]. These results seem logical if we consider the nature of two-dimensional shape recognition. First, shape is a global structural property and the "synoptic catching" allowed by the visual input constitutes an important advantage over the "fragmentary haptic gathering". This explains that visual-evoked recognition is generally faster than the haptic-evoked one (the gain of information rises to its asymptote much more rapidly within the visual modality than for haptics). Second, most people are relatively unfamiliar with the use of touch for the pickup of two-dimensional shape information. Indeed, the type of two-dimensional information we are most familiar with (e.g. pictures in books, images on TV) cannot be accessed via tactile cues. Besides, it seems than when people have to recognize a two-dimensional picture by touch, they attempt to form a visual image of the object and recognize it by visual mediation [96, 138]. In line with this, Heller [139] observed that recognition performance of late blinds is better than the one of early blinds. Interestingly, such visual dominance could be empirically determined rather than innate, since the relative weight of visual cues in two-dimensional shape recognition increases during the maturation process [140]. This means that our everyday experience "teaches" us that vision is the more reliable and convenient source of information for shape estimation [141]. It is worth mentioning that when the reliability of visual information is reduced [70] or unrealistic [142], the weight allocated to haptic cues is notably increased and can in some cases completely dominate vision. For instance, when clear vision of the edges and contours is prevented, shape estimates are done on the basis of haptic cues [70].

Recognition of Three-Dimensional Shapes

As for two-dimensional patterns, vision seems to constitute a more reliable cue than haptics to recognize three-dimensional patterns. Indeed, shape is more salient and more easily encoded when visual cues are added to haptic information [138]. In the same way, Lakatos and Marks [100] observed that objects presenting different local features but similar overall shape are judged less similar when explored haptically than when vision is available. Interestingly, the role of global features during haptic exploration tends to increase when the exploration time increases [100]. The latter result points out the intrinsic limitation of haptic cues in providing global shape information (at least as compared to vision

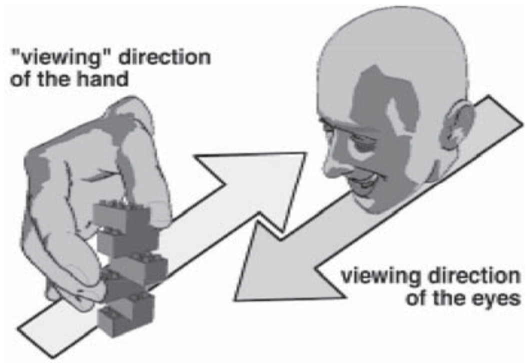

Fig. 4.9. Adapted from Newell et al. 2001. Participants were required to learn four target objects in a sequential order, either visually or haptically using both hands. No explicit instructions on how to learn the objects were given, and the subjects were free to move their hands around the objects during haptic exploration and their head during visual exploration; thus, all surfaces of the objects could be perceived whichever modality was used for exploration. During the subsequent test session (which immediately followed the learning session), four new objects were added to the set of the four learned objects. Participants were instructed to decide if each object presented was from the learning set or a distractor object. Recognition was tested either in the same modality as learning or in the other modality. The results suggest that information integrated across the fingers is analogous to seeing an object from behind.

that allows quite immediate shape estimation). As for two-dimensional patterns, the dominance of visual information over haptics is probably related to the nature of the shape recognition process, favoring global rather than fragmentary information gathering.

Another important point to mention in the perspective of associating visual and haptic cues for three-dimensional shape recognition is the viewpoint dependence phenomenon. The way geometrical properties of objects are stored in visual memory seems to be "orientation-specific", this specificity being related to the most typical or the learned orientation of each object [143, 144, 145]. Visual recognition performance is better when an object is presented in the same orientation than the stored representation of this object. Recently, Newell and colleagues evidenced that this viewpoint dependency phenomenon also applies to haptic recognition [101]. But whereas the preferential viewpoint is the front surface for vision, for haptics, it is rather the back surface (for hand-sized objects). As a consequence, optimal visuo-haptic recognition performance occurs when the front view from the presented visual object matches the back view of the same object in the haptic modality.

In another experiment, the same group of researchers showed that to recognize 3D objects, haptic learning is relatively poor as compared to visual learning [146]. The best recognition performance was observed when both vision and haptic were available during the learning phase, showing that the combination of different visual and haptic information in memory results in more robust object recognition than a representation based on information from one sensory modality alone.

Curvature Estimation

When the curvature of a surface is assessed using both visual and haptic cues, the resulting percept is strongly biased by the visual input [147, 148, 149]. For instance, Gibson [148] showed that when an individual moves his hand along a straight surface while looking through a wedge prism that causes the surface to appear curved, the surface is felt as curved. The same "biased" feeling can be induced even when the viewed hand is not the observer's hand but another person's hand moving in synchrony with it [149]. Despite some incongruence, subjects reported to experience the hand as being their own (they somehow had the feeling that they lost control over its movement).

In conclusion, it seems that the visual system is better suited than the haptic system for shape perception. This might be because shape recognition implies information integration over the spatial distribution of the object. Indeed, whereas the visual system receives this information in "parallel" (that is at once), haptic information gathering is "serial". As a consequence, the haptic system has to integrate spatial information over time, which makes it less reliable. It seems thus that for shape estimates, jointly provide subjects with visual and haptic displays would be really beneficial to VR setups. First, because as mentioned above, the association of visual and haptic signals improves the accuracy of the observer. Second, because the important dominance of vision over haptics in this domain should allow to more easily and flexibly side-step any technical limitation to the presentation of realistic haptic displays. The latter issue constitutes an exciting perspective for future research.

4.3.3 Size Perception

A large part of the experiments dealing with the combination of visual and haptic cues in size estimation have been performed using three-dimensional objects that could be directly grasped or manipulated by the subjects. In many cases, subjects had to estimate the size of objects that they could haptically explore and that were simultaneously seen through distorting lenses (or water). Several authors came up with the conclusion that vision strongly dominates haptics in this domain, subjects "feeling what they see" without being really aware of the conflict between visual and tactile cues [150, 151, 152]. Similar results have been observed in line length estimation [153]. The reported visual bias is in some cases important enough to have an effect even when the distortedly seen grasping hand is not the subject's one but a plaster replica [151]. Miller [154] also observed an important visual bias but this was found to rely on the subject's belief that the visual and haptic stimuli are emanating from the same distal object. Some other authors reported average judgments constituting compromises between visually and haptically perceived sizes [155]. Actually, these authors found out that the observed average judgments could be explained by strong inter-subjects differences, certain subjects relying much more on visual cues and some other being rather influenced by the haptic input. More recently, Heller [156] found that important shifts in modality reliance can occur between vision and haptics, and that these shifts depend on a variety of circumstances. It is also worth mentioning that this authors report a reduction of the visual bias when the subjects are provided with a visual feedback of their "manipulating" hand. Finally, using a paradigm in which they systematically manipulated the variance associated with the estimate of visual cues, Ernst and Banks [157] showed that visual and haptic cues are probably integrated in a statistically optimal manner, according to a reliability-based weighting of each sensory input. Such a result provides an explanation for the results mentioned above, suggesting that a combined use of visual and haptic cues optimizes perception performance by taking advantage of cue redundancy (see also [131]). This is what also suggests a study performed by Wu and colleagues [158] in which subjects had to evaluate the length of rectangular slots (paired comparisons), the position of which could vary along the antero-posterior axis. When only visual cues were provided, farther objects were perceived to be shorter (visual bias related to perspective cues). When only haptic cues were provided (haptic exploration of the slots with a stylus), no haptic bias was observed but the haptic resolution was on average poorer than the visual one. When both visual and haptic cues were provided, the visual bias was reduced and the resolution better than in the haptics alone condition, suggesting a fusion of sensory data in an optimal manner.

As shape, size constitutes a global structural property that is more reliably encoded by the visual than the haptic system (see [138] for a review). However, as demonstrated by some findings mentioned above, when combined, vision and touch supplement each other nicely. So, in the perspective of designing visual-haptic workbenches, vision could be used to supplement missing information in the sense of touch (and vice versa), the best performance for size-estimation being achieved when both modalities are available.

4.3.4 Orientation Perception

When individuals estimate the orientation of two-dimensional stimuli using visual and haptic information, they generally rely much more on the visual input [123, 159, 160, 161, 162]. For instance, Singer and colleagues [161] used a paradigm in which subjects were first exposed for a short period to a haptically horizontal and visually tilted bar, and were then asked to rotate the bar till it feels horizontal. In that case, the subjects tend to set the bar at or near the visual horizontal, exhibiting a visual capture of haptic information. Similarly, using prims, Klein [123] observed a strong visual bias of the perceived orientation of the index finger, the amplitude of this bias seeming to vary as a function of age (being stronger for children ranging from 9 to 16 than for a 18 year-old-group).

With respect to this, visual capture effects might be exploited for the construction of an integrated visual-haptic setup, the visual input basically providing the

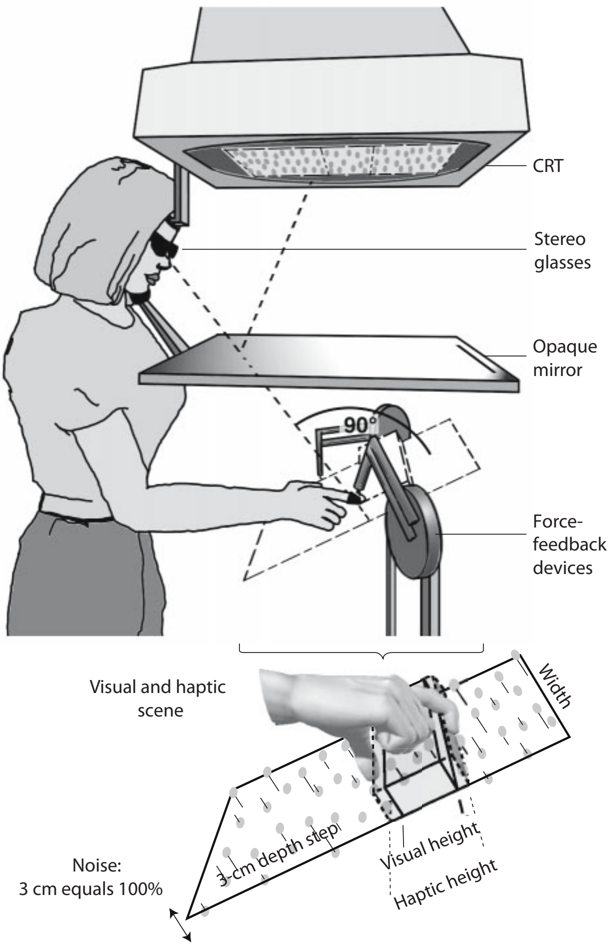

Fig. 4.10. Adapted from Ernst and Banks 2002. Observers looked at and/or felt a raised ridge and judged its height (vertical extent). Observers viewed a reflection of the stereo stimulus, the surfaces of the stimulus being perpendicular to the line of sight. The right hand was beneath the mirror and could not be seen. The haptic stimulus was presented with two PHANToM force-feedback devices, one each for the index finger and thumb. In the haptic-alone experiment, observers indicated which of two sequentially presented ridges was taller from haptic information alone. In the visual-alone experiment, they did the same from visual information alone. In the visual-haptic experiment, observers simultaneously looked at and felt two raised ridges that were presented sequentially. In one presentation, the visually and haptically specified heights were equal; in the other presentation they differed. On each trial, the observer indicated which stimulus seemed taller. The results show that visual dominance occurs when the variance associated with visual estimation is lower than that associated with haptic estimation.

frame-of-reference for the haptic modality. This might be important when the visual and the haptic scene cannot be perfectly aligned, but have to be presented separately due to technical limitations.

4.3.5 Texture Perception

Visuo-Haptic Combination

Texture identification can apparently be performed with comparable matching accuracy and precision using vision, touch, or both touch and vision [163]. These authors report magnitude estimates of roughness that are similar whatever the mode used. However, in this study, subjects were never provided with vision of their hand during texture exploration. Using a task in which individuals had to discriminate the smoothest of three abrasive surfaces, Heller [164] showed that bimodal visual and tactile input prompts better performance than information derived from either modality alone, and this advantage of combining vision and touch was found to relate to the visual control of the haptic exploration. Concerning the respective accuracy of touch and vision in texture estimation, further studies showed that if both modalities allow similar highly accurate discrimination performances for coarse stimuli (abrasive surfaces with a spatial frequency inferior to 1000 grit), touch seems to be superior to vision for finer textures (in between 1200 and 6000 grit) since visual performance is quite poor in this range of textures [165]. It can be noted for information that the haptic performance in fine textures evaluation could result from the exploitation of the vibratory sense. Indeed, the author reports that subjects used different scanning strategies when touching the finest surface, pushing their index fingers against the surfaces in an attempt to discriminate them.

Concerning the relative weighting of visual and haptic cues for texture discrimination, discrepant cues give rise to compromise estimates that is approximately midway between haptics- and vision-based estimates [163]. However, the instructions given to the subjects can produce a strong dominance of either visual or haptic cues [166]. These authors found that instructing subjects to judge the spatial density of the texture stimulus induces a visual bias whereas putting the emphasis on roughness evokes a tactile bias. Another visual bias can be induced by magnifying (a large magnification is required) the view of seen surfaces that are simultaneously touched. Indeed, Heller [167] reports that under these circumstances, very smooth surfaces can be felt as rougher than they are.

The sense of touch seems to be indispensable to the generation of reliable simulation of rough texture. Indeed, as opposed to what can be observed for other physical properties like shape or size, texture perception relies almost equally on touch and vision, with some situations where touch dominates (e.g. roughness evaluation). This ”specificity” of texture assessment is of course linked to the fact that texture is a substance-related attribute that can be ”extracted” locally [138]. The reported ”superiority” of touch over vision for roughness perception likely indicates that touch is better suited (i.e. provides a more reliable estimate) than the visual modality to estimate this physical property. However, a recent

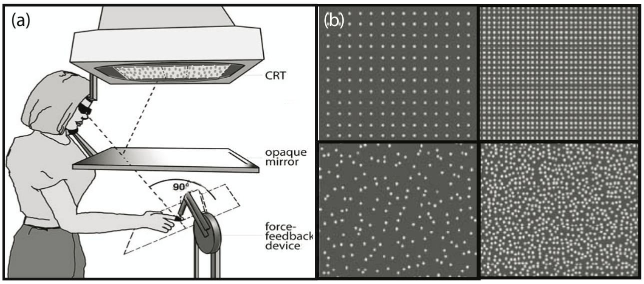

Fig. 4.11. Adapted from Drewing et al. 2004. Participants judged textures according to their roughness and their spatial density under visual, haptic and visual-haptic exploration conditions. The right index finger was connected to the PHANToM. Simultaneously, the participants looked via a mirror at the screen. The mirror aligned the visual and haptic stimuli and prevented the participant from seeing his or her hand (a). The stimuli were raised-dot patterns (b provides examples of sections of textures with lowest and highest density (left and right) and lowest and highest jitter (upper and lower)). Participants were well able to differentiate between the different textures both by using the roughness and the spatial density judgment. When provided with visual-haptic textures, subjects performance increased (for both judgments), indicating sensory combination of visual and haptic texture information. Performance for density and roughness judgments did not differ, indicating that these estimates are highly correlated. This may be due to the fact that the textures were generated in virtual reality using a haptic point-force display (PHANToM).

study performed using a virtual reality workbench reports that textures can be well discriminated both by vision alone and haptics alone, and that providing both sensory inputs improves the discrimination performance [168].

Audio-Haptic Combination

Tactile cues have long been considered as completely dominating auditory cues for texture perception since providing auditory cues to subjects during tactile exploration of textured surface failed to improve [164] or have any influence on texture perception [169]. However, recent studies evidenced that auditory cues can indeed significantly alter tactile texture perception along the dimensions of both roughness and wetness [170, 171]. In these studies, texture evaluations related to the palmar surface of the hands [170, 171] and abrasive surfaces [171]. During tactile exploration of the surfaces, subjects were provided with on-line-recorded auditory cues corresponding to the friction of their hand on the explored surface. These auditory cues could be modified, by amplifying or attenuating the high-frequency components, or just modulating the volume. The results showed that high-frequency amplification increases roughness and dryness perception (high-frequency attenuation inducing the opposite effect). Dryness perception was also evidenced to depend on the sound volume, an increased volume giving rise to a drier perception.

These results are interesting for the design of multimodal virtual-reality display, since they show that auditory cues provided during tactile exploration can alter texture perception. This is notably true for the rendering of dryness that seems difficult to achieve "mechanically". Concerning roughness, an appropriate combination of visual and auditory cues should enable to "improve" the modulation of the tactile percept by "non-tactile" cues.

4.3.6 Tactile Contact Perception

Visuo-Haptic Combination

Tactile contact detection is primarily taken care of by cutaneous sensors. However, in many situations, such contacts can also be visually detected. Our everyday life provides the central nervous system with a lot of "opportunities" to learn visuo-tactile associations (e.g. visual information associated to the contact of our right hand on our left forearm when we scratch it). Viewing a "touched" body site improves the reaction time to discriminate the tactile stimulation [172, 173]. This "improving" effect applies even when the body site is only viewed indirectly via a video camera [172]. Interestingly, greater visual improvement is observed for the familiar site of the face (various situations where visual and tactile cues can be associated through a mirror) than for the rarely viewed site of the neck, tending to confirm that the beneficial effect of cue combination is, at least partly, influenced by some learnt associations.

Visual improvement of tactile contact detection has also been demonstrated with patients presenting sensory loss of light pressure, the presence of visual input boosting in some cases subthreshold tactile stimulation into conscious awareness [174, 175]. This improvement phenomenon has been shown to occur even when the "boosting" visual stimulus is not directly presented on the patient's hand but on a rubber hand placed in alignment with it [175]. Reciprocally, competing visual stimuli can interfere with tactile detection [176, 177]. Another good example of the close relationship linking vision to haptic in tactile contact detection is provided by a study of Ramachandran and colleagues [178] with amputees. Indeed, these authors report that in some cases, when amputees are presented with a moving reflection of their intact arm in a mirror (so that the reflection appears where the missing limb would be seen if present), they can experience kinesthetic and proprioceptive sensations in the phantom-limb. In these conditions, when precisely localized touches are delivered on the intact arm, touch sensations can be evoked at exact mirror-symmetrical locations in the phantom-limb. Finally, we can mention the results of Botvinick and Cohen [179] that nicely demonstrated how visual capture of the perceived hand position in space can be accentuated by an appropriate combination of visual and tactile cues. In this study, a rubber hand somewhat misaligned with the real hand was perceived by the subjects as being their own following an adaptation phase during which the unseen real hand was stroked in temporal correlation with seen strokes on the rubber hand.

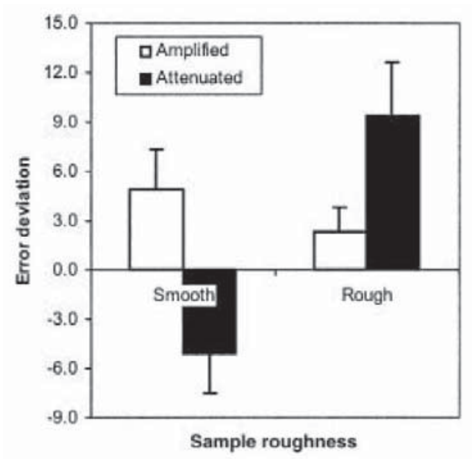

Fig. 4.12. Adapted from Guest et al. 2002. Participants had to repeatedly categorize one of a pair of sandpapers as either the rough or smooth member of the pair. The touching action suggested was to use the first finger of the preferred hand. Participants were specifically instructed to ignore the touch sounds they heard, and to base their judgements exclusively on the feel of the touched surface. The figure displays error deviations (defined as test condition error rate minus normal sound error rate) for both sound manipulations (high-frequency amplified and high-frequency attenuated sound) and both sample roughness levels (rough and smooth). Error bars show 1 SE. These results show that the attenuation of high-frequency sounds alters discriminative performance, consistent with the production of a smoother tactile sensation. On the other hand, high-frequency amplification leads to a trend towards rougher sensations.

These results highlight the powerful effect of the visual input in enhancing (or reducing) "touch sensation". This effect could be widely exploited in the conception of multimodal virtual displays, using for instance congruent visual and haptic stimuli to accentuate the haptic perception, or just at the opposite, incongruent visual and haptic stimuli to "mute" the haptic percept. A future line of research could consist in exploring visual stimuli maximizing such enhancing/reducing effects. In line with this, our recent results showing that vision and touch are integrated in a reliability-dependent manner for the perception of sequences of events [180] suggest that having a protocol measuring the variability of each modality to perform the target task would provide useful guidelines for the management of the rendering resources.

Audio-Haptic Combination

As vision, audition can also have a strong influence on tactile contact perception. We recently ran an experiment in which subjects had to count the number of tactile taps (each sequence randomly varying between 2 and 4 taps) delivered on the index fingertip. Subjects could not see their hand or the device used to

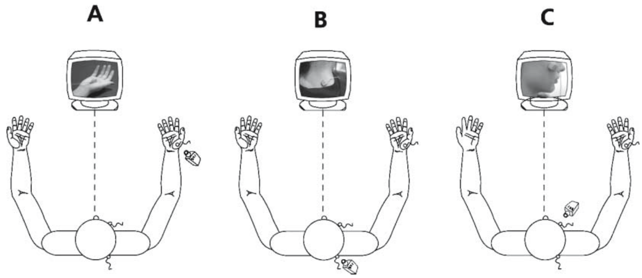

Fig. 4.13. Adapted from Tipper et al. 2001. Subjects undertook a tactile target-detection task. Their primary task was to release a foot pedal when a vibration was detected at the target site, which could be the face or the neck. Simultaneously, a monitor placed at the midline displayed a body site, which could be the hand (A), the neck (B) or the face (C). There were three visual-tactile relationships: (1) neutral; for example, viewing the hand (A) while detecting tactile targets to the face or neck; (2) compatible; for example, viewing the neck (B) while detecting tactile targets to the neck; (3) incompatible; for example, viewing the neck (B) while detecting tactile targets to the face. The results show that vision of a body site, independent of proprioceptive orienting, can influence tactile detection. This conclusion is reinforced by the fact that these crossmodal interactions are produced at body sites that can never be directly viewed. That is, they are sites that have no history of proprioceptive orienting of eyes and head towards them.

deliver the taps. For some trials, a sequence of auditory beeps was presented simultaneously to the tactile stimulation (the temporal window of both tactile and auditory sequences overlapped). The number of beeps of each auditory sequence could be less (-1), the same or more (+1) than the number of presented taps. The perceived number of tactile taps was significantly biased by the presented number of beeps, giving rise to an auditory-evoked tactile illusion [181]. Similar results were found elsewhere with a different design [182]. We can mention here that if audition clearly influences tactile contact perception, the opposite effect seems harder to elicit. Indead, in two other experiments, we tested whether tactile taps can bias the perceived number of auditory beeps. In both experiments, the perceived number of auditory beeps was biased by the simultaneous presentation of tactile taps but the bias was significantly weaker than the one induced by beeps on taps [183, 184]. In one of these experiments, we showed that reducing the reliability of the auditory input decreases the bias of audition on touch and increases the bias of touch on audition [184]. The latter result suggests that for contact perception, audition and touch are integrated in a reliability-dependent manner.

These results are very interesting for the design of multimodal virtual-reality display, since they show that (1) when provided, auditory cues are combined with haptic cues for the perception of tactile contact and that (2) an appropriate use of these auditory cues can give rise to a tactile illusion, that is to "cheat" the tactile sensory system. For instance, this illusion could probably be used to

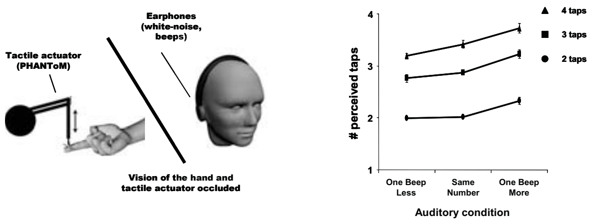

Fig. 4.14. Adapted from Bresciani et al. 2005. The subjects had to count the number of tactile taps delivered to the index fingertip (sequences of 2 to 4 taps) and to ignore simultaneously presented auditory beeps. The number of beeps delivered in the auditory sequence were either the same as, less, or more than the number of taps of the tactile sequence. The figure shows the number of perceived taps as a function of both the actual number of delivered taps and the auditory condition. Presenting less beeps in the auditory sequence than taps in the tactile sequence ('One Beep Less') reduced the perceived number of taps. Similarly, presenting more beeps in the auditory than taps in the tactile sequence ('One Beep More') increased the perceived number of taps. These results show that task-irrelevant auditory stimuli can modulate tactile perception of sequences of taps.

increase the perceived frequency of a tactile stimulation when this stimulation is around the saturation threshold of tactile sensors.

4.4 Visual- and Auditory-Evoked Biases of “Pure” Haptic Perception

In the previous sub-section, we reported some experimental results related to the integration of haptic and visual or auditory cues when two sensory inputs are informative (redundancy) about the same property(ies) of the environment (objects of the environment). In the present sub-section, we will focus on the influence of visual and auditory inputs on the haptic perception of some properties that are intrinsically only accessible to the haptic channel. This issue is of particular interest to understand the principles ruling cue combination, since it highlights how the central nervous system associates directly-informative and non-directly-informative cues when perceptually ”interpreting” incoming sensory signals.

4.4.1 Force Control

Contribution of Visual Cues

The control of force production is intrinsically haptic since it exclusively relies on efferent signals related to the motor command and afferent proprioceptive signals provided by the neuromuscular fuses (cutaneous signals emanating from the point of application of the force are also somewhat informative). However, it has

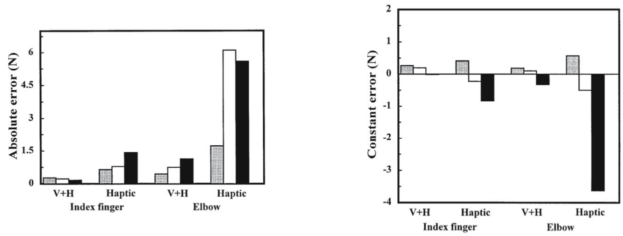

Fig. 4.15. Adapted from Jones 2000. The experiment aimed at estimating the accuracy with which forces can be maintained by the elbow flexor and index finger flexor muscle groups when only haptic feedback is available, and how this compares to force control when visual feedback about the force being produced is also provided. Subjects grasped a rod with their right hands and pulled the rod using the elbow flexor muscles. Four target forces were generated isometrically (4, 10, 20, and 30 N) for 120 s. Each force was maintained at a constant level using only haptic feedback or both haptic and visual feedback. In the haptic condition, subjects initially used the meter to attain the target force and once this was reached the display was turned off and they were instructed to maintain the target force for 120 s. In haptic and visual condition, the digital meter provided continuous visual feedback of the forces produced. The figure shows group mean absolute errors (upper panel) and constant errors (lower panel) in maintaining a force at 2 (gray), 4 (white) or 6 (black) N with the index finger flexors or 10 (gray), 20 (white) or 30 (black) N with the elbow flexors for 120 s using visual and haptic feedback (V+H) or only haptic feedback. The results show that over a relatively long time period, subjects are able to maintain an isometric force at constant amplitude using only haptic cues. When subjects are provided with visual feedback in addition to haptic feedback, the errors naturally decrease and performance under these conditions probably represents optimal force control.

been evidenced that adding visual feedback to the haptic feedback improves the accuracy of the force control [185, 186]. For instance, Jones' experiment consisted in testing subjects' ability to control index finger (range 2-6 N within 1 N) and elbow flexion forces (range 10-30 N within 4.5 N). Even if, using only haptic cues, subjects were able to maintain an isometric force at constant amplitude over a relatively long time period, providing an additional visual feedback resulted in a threefold decrease in the coefficient of variation of the produced force.

Such results are very interesting in a VR perspective. If we think for instance of tele-surgery interfaces, providing users with a visual feedback could constitute a good way of improving users' performance in situations where a very fine and accurate control of the produced force is required (vital). Another related way of taking advantage of visual feedback for force control would be training issues. If we stay in the surgery domain, augmenting the visual feedback during training could allow novices to "tune" their sensorimotor system by helping them associating the incoming afferents with the appropriate motor commands to produce. However, such training should be performed with great care in order to avoid visual dependency in situations where the real practice cannot provide the same visual feedback.

Contribution of Auditory Cues

To our knowledge, no study to date investigated the effects of auditory feedback on the control of force production. However, auditory feedback has been shown to facilitate the maintenance of stance in stroke patients [187]. Stroke patients were provided with an auditory feedback generated by the forces actuated by the feet on a force platform. This auditory feedback significantly reduced sagittal torque variance (body sway) when postural control was perturbed applying vibratory stimuli on the calf muscles. This result clearly demonstrates that auditory feedback can be successfully used to "improve" motor control. Thus, as for visual feedback, one could expect a positive influence of auditory feedback on the control of force production.

4.4.2 Softness/Stiffness Perception

Contribution of Visual Cues

As for force control, softness/stiffness evaluation intrinsically relies exclusively on haptic information. This "local" substance-related property can be evaluated by the distance an object such as the finger penetrates a surface when applying a normal force, or by the force required to break through a surface, or even by elasticity (the rate or extent to which a surface recovers its previous position after deforming under force). Of course, everyday life experience "teaches" us some correspondence rules between the sensed produced force and the visually perceived resulting indentation in the explored surface. Wu and colleagues [158] explored the possible benefit of visuo-haptic combination in stiffness evaluation. Subjects had to perform paired comparisons to determine the relative stiffness of virtual compliant buttons. When only haptic cues were provided, rear buttons were felt to be softer than front ones (with a bias of 10 percents). When both visual and haptic cues were provided, the anteroposterior bias disappeared and the resolution of the estimates improved from 10 percents (in haptic alone condition) to 5 percents. These results tend to indicate that associating visual feedback to haptic exploration is profitable to the accuracy of stiffness evaluation and contributes to overcome the biases inherent to haptics alone estimates. However, visual feedback in stiffness estimation should be used carefully since any discrepancy between visual and haptic cues seems to give rise to a strong visual bias [188]. Indeed, the latter authors ran an experiment aimed at determining the contribution of visual feedback to stiffness estimation. For the subjects, the experiment consisted in determining which one of two presented springs was stiffer (paired comparisons). The subjects could press the springs and feel the corresponding displacement and forces through their hands. In addition, the deformation of the springs was displayed graphically on a computer monitor. Subjects could not readily observe the location of their hands. The relationship between the visually presented deformation of each spring and actual deformation was systematically varied between experimental trials. The results demonstrated a clear visual dominance over the kinesthetic sense of hand position. Indeed, the subjects essentially ignored all kinesthetic hand position information regarding spring deformation and based their judgment on the relationship between the visual position information and the indentation force sensed tactually. This basically means that when indentation-related visual cues are available, subjects tend to shift from a haptic-control mode to a visual-control mode.

This visual bias of perceived stiffness would surely be a good way of overcoming some intrinsic limitations of haptic devices. Indeed, when considering force displays, one of the problems encountered is related to the realistic simulation of walls [189]. Appropriately using the "visual capture" of stiffness perception would facilitate the simulation of "perceived" rigidity with smaller "physical" stiffness.

Contribution of Auditory Cues

As visual cues, auditory cues can affect the haptic perception of stiffness. DiFranco and coworkers [190] conducted a study where subjects had to haptically evaluate the stiffness of different virtual surfaces by tapping on these surfaces. While tapping on these surfaces, subjects were provided with various impact sounds corresponding to the sounds that can be heard when tapping on soft and hard surfaces. The results showed that the perceived stiffness of the surfaces was significantly influenced by the nature of the heard impact sound. Indeed, surfaces paired with auditory cues that are typically associated with tapping harder surfaces were perceived as stiffer.

As visual cues, auditory cues can be useful in augmenting the subjective sensation of stiffness in multimodal virtual-reality displays. Because both vision and audition efficiently succeed in altering haptic perception of stiffness, combining adequately these cues should maximize the potency of the effect.

4.4.3 Weight Perception

The weight of an object is rated on the basis of the force necessary to lift it. Thus, heaviness estimation constitutes a pure haptic measurement. However, our daily experience during the ontogenesis provided us with an a priori inference system based on the visual properties of the objects. For instance, we know that the weight of an object is often correlated to its size. In the same way, we learnt that the material the object is made of has a strong influence on its weight. In line with this, some authors investigated the relationships between the visually accessible properties of the objects (likely to induce a priori inferences about a given object's weight) and the haptically perceived weight of these objects. The size (volume) of the objects is for instance a visually accessible property inducing a systematic bias in perceived weight [57, 191, 192], a small object being perceived as heavier than a larger one presenting the same objective weight (and surface appearance). This illusion is called size-weight illusion and is generally attributed to a priori inferences related to objects' size, a large object being expected to be heavier than a small one [57]. The material an object is made of also constitutes a visually accessible property biasing its haptically perceived weight [193, 65]. Indeed, objects made of a dense material are judged to be lighter than objects presenting the same mass and volume but made of a less dense material. This illusion is called material-weight illusion [193]. Finally, De Camp [194] reported an effect of color on the perceived weight of objects (color weight illusion). According to his results, red and black objects tend to be haptically perceived as heavier, whereas yellow and blue objects are generally estimated as lighter. But as opposed to the size- and material-weight illusions, the color-weight illusion seems more difficult to explain in terms of a priori inferences of visual origin since on the sole basis of visual information (without any haptic assessment), black and red colored objects are subjectively estimated as heavy and yellow objects as light [194]. As a consequence, a simple a priori-induced bias would lead to a pattern of haptic estimation opposite to the one observed by De Camp.

The abovementioned illusions should not be neglected when designing multimodal VR interfaces. A good knowledge of these illusions could avoid some accidentally induced misperceptions resulting from the use of misleading scales or from non-controlled choices of objects' surface.

4.4.4 Friction Perception

We recently ran an experiment aimed at determining whether sound can alter friction perception. Two main points motivated this study. The first point relates to the fact that the generation of real-time friction (static and dynamic) in virtual reality rendering poses many well-known computational difficulties. Finding auditory stimuli altering friction perception during tactile exploration would ease the computation, optimize the design of multimodal virtual prototyping software and perhaps allow some form of sensory substitution in some scenarii. The second point concerns the development of a multi-level haptic interface [195]. In this interface, the human fingertip interacts with the haptic device when a contact is made in the virtual environment. During a contact motion, virtual induced friction must be rendered. However the actual fingertip/device's contact friction is different from the virtual one to be rendered. As a consequence, an automatic control-based adaptation of actual fingertip/device and actual friction coefficient to the one experienced in the virtual environment is not trivial and seems difficult to achieve. If auditory cues turned out to influence friction perception, the use of appropriate sound rendering could allow to partially fulfil the quality of friction rendering.

In the experiment, subjects explored surfaces presenting different frictions and had to compare them (in a paired-comparisons design). The auditory feedback provided during surface exploration was manipulated to determine whether the nature of this feedback would contribute to increase or decrease friction perception. Unfortunately, the results we obtained suggest that friction perception is independent from the auditory feedback.

4.5 Conclusions

We collected here a large number of scientific findings relative to human perception and we systematically discussed the relevance and the usability of these findings for the development of VEs including haptic displays. The pool of presented results clearly highlights that the development of haptic-based VEs can benefit from many facets of the current knowledge about human perception.

Concerning the "pure" haptic perception of environmental properties, the standard of knowledge reveals preferences within the world sensed by the human haptic system and, thus, suggests priorities for future directions in technological development. For example, many studies demonstrated that material properties of objects like texture are the most quickly available in haptic perception and, especially relate to this sense as compared to others 4.2.4. Further, the present review demonstrates that most environmental properties specifically related with haptics as well as haptic shape and movement perception strongly benefit from cutaneous input. Thereby, this kind of input, which is related to tactile displays, seems to be necessary to achieve a rich and present haptic virtual reality and cannot be substituted by other input. However, many illusions and principles in human haptic perception suggest possible ways to simplify this and other problems in the development of haptic display technology. These illusions might be of some use to build devices that are more powerful and display a richer haptic world than the ones currently available. There are a few examples that seem directly applicable and for which only the most appropriate parameters of display are still to be determined. This is for instance the case of the comb illusion, which might be used for the display of movement on the skin 4.2.5. Some other haptic principles and illusions look very promising but further investigations are necessary to better define their technological applicability. This may hold for illusions of three-dimensional objects by two-dimensional forces 4.2.3 or distortions in the apparent location of temperature 4.2.2. Finally, there are some ideas which at the current standard of knowledge are speculative, but bear much potential to simplify haptic device. For instance, one might take advantage of the efficiency of the orientation differences for shape perception 4.2.3.

Concerning the integration of haptic signals with other sensory signals, the different results presented here suggest that appropriately adding vision and/or audition to touch displays would be highly profitable to the fidelity of VR simulations. So - obviously - the general rule should be to create a simulation which is as rich as possible and which includes as much information as possible to convincingly recreate the physical environment in VR. However, as mentioned in the introduction, this will not always be "possible". For instance, technical limitations can prevent haptic VR displays to provide rich enough or accurate enough simulations. The literature reviewed above puts forward some "illusions" that are worth to explore in order to optimize the design of multimodal displays. In particular, some of the issues we dealt with seem quite promising (e.g. visually-driven attention to enhance or reduce haptic perception 4.3.6, use of visual or auditory feedbacks to "augment" force control performances 4.4.1, exploit auditory impacts and visual capture of stiffness perception to side-step mechanical limitations to "wallness" simulation 4.4.2). Of course, so far no general rule enables to overcome technical limitations in one modality (touch) by the substitution of another modality (vision or audition). But more psychophysical investigations concerning the combination of haptic cues with visual and auditory cues (e.g. best ways of optimizing cue combination, limits to discrepancy when using illusions) should soon give rise to exploitable solutions.

Acknowledgments

This work is part of the TOUCH-HapSys project financially supported by the 5th Framework IST Programme of the European Union, action line IST-2002-6.1.1, contract number IST-2001-38040. For the content of this paper the authors are solely responsible for, it does not necessarily represent the opinion of the European Community.

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