Use of a haptic device by blind and sighted people: perception of virtual textures and objects

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ABSTRACT

This paper describes a series of studies involving a haptic device which can display virtual textures and 3-D objects. The device has potential for simulating real world objects and assisting in the navigation of virtual environments (VEs). Three experiments investigated: (a) whether previous results from experiments using real textures could be replicated using virtual textures; (b) whether participants perceived virtual objects to have the intended size and angle; and (c) whether simulated real objects could be recognised. In all the experiments differences in perception by blind and sighted people were also explored. The results have implications for the future design of VEs in that it cannot be assumed that virtual textures and objects will feel to the user as the designer intends. A set of guidelines for the design of haptic interfaces and VEs are presented.

Keywords: haptic device; virtual environments; perception of virtual textures and objects; blind users; world wide web.

INTRODUCTION

The design of interfaces to virtual environments (VEs) is currently an important and exciting issue for HCI [2]. The present series of studies contribute to research on user's experiences of VEs and the development of guidelines for the design of haptic or 'feelable' VEs. It is important to know how users haptically perceive virtual objects, so that such objects can be incorporated appropriately into large scale VEs. At present, VEs use visual displays, with some use of auditory and very little haptic information. Haptic perception incorporates both kinaesthetic sensing, (i.e. of the position and movement of joints and limbs), and tactile sensing, (i.e. through the skin) [14]. The development of haptic, kinaesthetic and tactile devices offers a new dimension of realism to VEs and these developments offer further potential applications for such multimedia environments [5].

VEs can be used to simulate aspects of the real world which are not physically available to users for a wide variety of reasons. For example, the interiors of buildings can be simulated before they are constructed to assist the design process or ancient buildings can be recreated so they can be experienced again [24]. VEs can also be used to create environments which exist only virtually. For example, the World Wide Web (WWW) is a system through which users need to navigate and where they may get lost and disoriented [3, 10]. However, as VEs become more realistic through the use of multimedia displays which include haptic, visual and auditory information, the WWW could become a VE, making navigation through it more intuitive. For example, one could move between regions by 'walking' through links rather than jumping from page to page [6]. It may also be that these two uses of VEs soon be combined. The WWW may combine a totally virtually environment to navigate through with simulation of real information at the end of certain links. For example, one could walk through a virtual space to virtual shopping malls where one could try out virtual sample items, from flowers to furniture. This simulated aspect of the real world is explored in our last study, which presented haptic simulations of furniture to participants.

The use of both VEs and haptic interfaces for people with disabilities have begun to be explored. VEs have great potential to assist people with disabilities. For example, in rehabilitation, virtual 'safe arenas' can be developed in which skills can be learnt and then transferred to the real environment [22]. A haptic interface has also been developed for use by blind people with applications such as digital music editing, where the speech output usually used by blind people would conflict with the audio output of the music system [16]. A system with a haptic interface for use by visually impaired children is the Phantasticon [20]. It combines a haptic input/output device with a visual display, and can be used for learning mathematics and painting colour pictures. In the Pantobraille [17], haptic technology (the Pantograph) has been combined with Braille technology for blind computer users. With the Pantograph, blind users can access a graphical user interface. It can be used to point and click in order to interact with icons, windows and menus. It can also be used to feel 2- and 3-D objects. The Pantobraille adds to this the ability to feel textures: either text that has been translated into braille, or the textures of low-resolution graphics.

Currently, VEs can be created for the WWW using Virtual Reality Markup Language (VRML), for example those recommended by Goralski [4]. Currently, these mainly contain graphical objects and scenes, which are not accessible to blind users but haptic interfaces could potentially improve this access. Haptic devices such as the one used in the current study also have the potential to assist both sighted and blind users in the navigation of the totally virtual environment of the World Wide Web (WWW). Navigation could be aided by the use of texture to distinguish different areas of WWW pages.

THE DEVICE

The device used in the current studies was the Impulse Engine 3000™ (shown in Figure 1). It was developed by the Immersion Corporation [9] and was used with software written by Andrew Hardwick (see [7] for a comprehensive description). The system can display virtual textures and objects which the user can feel using a probe. The probe is the length and diameter of a thick pen and has 3 degrees of freedom of motion, i.e. it can move in 3 spatial dimensions: forwards and backwards, up and down, and left and right. The system provides feedback to the user by monitoring the position of their hand and altering the force accordingly [6]. The force is created by three motors which exert resistance against the probe. This gives the user the impression that a texture or object is present.

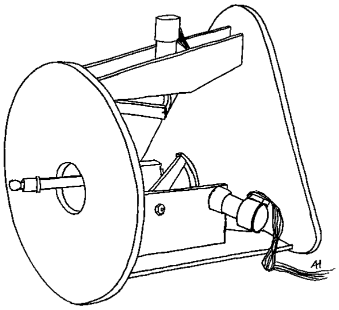

Figure 1: The Impulse Engine 3000™

Three types of virtual stimuli were used in the current studies: textured surfaces; simple 3-dimensional objects such as cubes and spheres; and complex 3-D objects such as an arm-chair and a kitchen chair. The cubes and spheres could be felt from both the inside and the outside of the object. When exploring the inside of an object, it is as if the user is inside the object and they cannot feel the outside of the object. An example from the real world might be exploring the outside of a closed box but not being able to explore inside it and then getting inside the box, closing it, and exploring the inside of it. However, as the Impulse Engine 3000 motors are capable of withstanding only 8 Newtons (approximately 2 lbf) of force from the user, if the user pushes too hard they can have the sensation of pushing through the surface of an object.

PERCEPTION OF REAL AND VIRTUAL TEXTURES

The study of the psychophysics of real textures started with the classic work of Stevens who applied his magnitude estimation technique to the perception of roughness [23]. In a magnitude estimation study, participants are asked to experience a range of stimuli with different physical characteristics (for roughness Stevens used pieces of sandpaper with varying grit size which participants rubbed their fingers across; in other studies Stevens varied the brightness of light, the magnitude of electric shocks, the length of lines and many other physical dimensions of the sensory world). Initially, participants are given a standard stimulus to which they assign for themselves an easily remembered number (e.g. 10). If they think a particular test stimulus is twice as intense (e.g. in brightness, strength of shock, apparent length or roughness of texture), they give it a magnitude estimation (ME) of twice as much (i.e. 20) and if they think it is half as intense they give it an ME of half as much (i.e. 5). Stevens found that the relationship between the sensation of the magnitude of a physical characteristic (S) is related to the magnitude of a physical property (P - which might be brightness, magnitude of shock etc.) via a power function:

$$S = a P^{b}$$

(where a and b are constants)

The magnitude of the exponent (b) in this equation is important, because when it is greater than one ($b > 1$) it means that the intensity of the sensation grows more rapidly than the intensity of the physical stimuli (see curve for electric shock in Figure 2), whereas when the exponent is less than one ($b < 1$) the reverse is true (see curve for brightness in Figure 2). The value of the constant ‘a’ merely reflects the particular number which the participant used for the standard stimulus [21].

Lederman [11, 12, 13] extended the perception of real textures and was able to systematically vary the physical dimensions of the surfaces used, which had not been technologically possible for Stevens. In particular, she varied the width and amplitude of grooves made in aluminum plates in order to investigate the perception of roughness in relation to these two physical characteristics. She found that increased groove width increased perceived roughness with an exponent of 0.25.

Minsky [15] has conducted the only other known investigation of the psychophysics of virtual textures, using a virtual environment known as Sandpaper, operated via a joystick. Using virtual textures which simulated the groove parameters of the real textures used by Lederman, Minsky found that a psychophysical power law held between the perception of the virtual textures and their simulated properties although this was mediated by the force produced by the device rather than the spatial period of the simulated textures. She hypothesized that this was due to the fact that the textures were sensed via a joystick rather than by rubbing a finger over the surface, as participants had in previous studies.

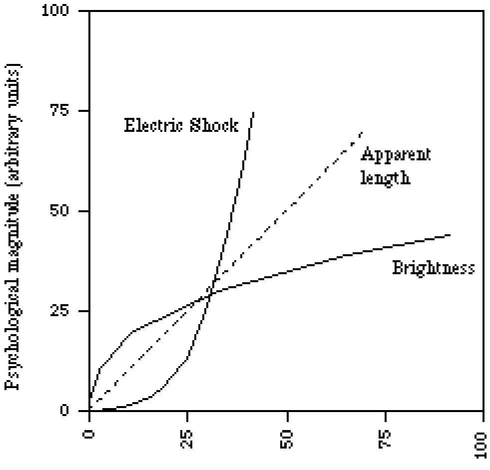

Figure 2: The psychophysical functions for electric shock, apparent length, and brightness.

PERCEPTION OF REAL AND VIRTUAL OBJECTS

Revesz [18] suggested that haptic recognition of objects is not immediate, as it is with vision, but that the perception of parts of an object is followed by a cognitive process through which the whole is constructed. Loomis and Lederman [14] provide a comprehensive review of the experimental work of the haptic perception of the attributes of real objects by sighted people. For example, Appelle, Gravetter & Davidson [1] investigated whether sighted subjects reported that different sized rectangular forms had the same or different proportions. They concluded that proportion is not perceived by the haptic sense either directly or spontaneously, as it seems to be with vision. Rolland, Gibson & Ariely [19] investigated the visual perception of the size and depth of both real and virtual objects by sighted participants. This research involved viewing objects with a see-through Head Mounted Display (HMD) (which combines real and virtual scenes). The results suggested that virtual objects were perceived to be further away from the observer than real objects.

No studies could be found which investigated the perception of texture and objects (either real or virtual) by blind people. Given the potential of VEs for presenting information to both sighted and blind people, it was decided to undertake a series of studies investigating the perception of both texture and objects in a VE by both these groups.

CURRENT STUDIES ON PERCEPTION OF VIRTUAL TEXTURES AND OBJECTS

Twenty-two participants took part in all three studies, 9 were blind and 13 were sighted. Six of the sighted participants were female and all the other participants were male. The sighted participants were all university students, from different disciplines. The blind participants were all employed in computer-related jobs or on a computer science course except one, who was a retired audio engineer. Six of the 9 blind participants were either born without sight or lost their sight by the age of 30 months. The other 3 lost their sight between 8 and 26 years of age. The participants ranged in ages from 18 to 65; the average age being 32.

Study 1: Roughness of Virtual Textures

The first study involved virtual textures with varying groove widths, the dimensions of which were as close as possible to those used by Lederman [11, 12, 13], the difference being that those textures involved grooves with a rectangular waveform whereas the textures used in the current study involved sinusoidal shaped grooves. The widths of the grooves varied from 0.375mm to 1.5mm in steps of 0.125mm and had a fixed amplitude of 0.0625mm (shown in Figure 3). There were no visual representations of the virtual textures. A magnitude estimation technique [21] was used to assess the roughness of ten textures with six trials per participant.

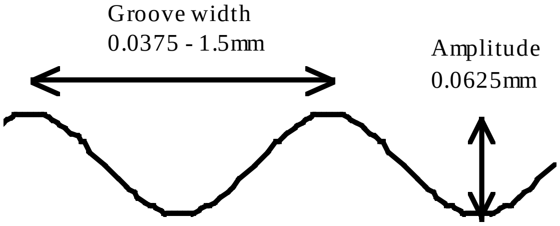

Figure 3: Dimensions of sinusoidal grooves used in Experiment 1.

The data from the first experiment were analysed by calculating the power function for each participant and using regression analyses to determine how much of the variation in the sensation of the textures could be accounted for by the variations in the groove width. Regression analyses were conducted for each participant individually and on the massed data which allowed a comparison of the performance of blind and sighted people.

Overall, there was a highly significant relationship between the perception of virtual texture and its simulated physical characteristics (F 1,216 = 12.09, $p < 0.001$). All nine blind participants also individually showed a significant relationship between perception of virtual texture and its simulated physical characteristics. For three of these participants the exponent was positive, meaning that they perceived the narrower grooves to be rougher than the wider grooves. This was in contrast to the other six participants for whom the exponent was negative, meaning that they perceived the wider grooves to be rougher than the narrower grooves. Only five of the thirteen sighted participants showed a significant relationship between perception of virtual texture and its simulated physical characteristics. For all the sighted participants the exponent was negative. The magnitude of the exponents ranged from 0.51 to 0.84, making them higher than those obtained by Lederman for the closely corresponding real textures. Our results differed from those of Minsky's, in that there was a significant relationship between the simulated spatial characteristics and the psychological sensation, however further analyses will be undertaken to investigate how this relationship is affected by the forces exerted by the device and the user.

The results from the first study showed that more blind people were more discriminating than sighted people in their assessment of the roughness of the textures. Most of the twenty-two participants perceived the wider groove widths to be more rough than the narrower groove widths, although three participants perceived the narrower grooves to be rougher.

Study 2: Recognition of Object Size and Angle

The second study involved the exploration of a number of virtual objects. The Impulse Engine 3000 allows virtual objects to be explored from both inside and outside the object, so for some of the virtual objects used, both inside and outside presentation were given to investigate any differences this factor produced. The virtual objects used were: cubes (outside presentation), cubes (inside presentation), spheres (outside presentation), spheres (inside presentation), rotated cubes (outside presentation), sheared cubes (inside presentation). Three sizes of each type of virtual object were presented: cubes with edges ranging from 1.0 cm to 2.5 cm (see Table 1), spheres with diameters ranging from 1.5 cm to 2.5 cm. The amount of rotation of the cubes varied between 30° and 70° and the amount of shear between 18° and 64°. Since this was an initial exploratory study, a full factorial design was not used. Each type of virtual object was presented three times, with a range of different sizes and angles of rotation and shear. A multiple choice matching response method was used. Participants were asked to feel an object and then choose from a set of four objects the one they thought they had felt. Sighted participants were shown scale drawings and blind participants were shown scale tactile 2-D representations.

Since a full factorial design was not employed, a series of analyses of variance were used to analyse different components of the data. Mean perceived sizes/angles for the various objects used are shown in Table 1. No significant difference was found between the perceptions of sighted and blind participants, except that the sighted participants judged the sheared cubes more accurately than the blind participants. Both groups were

Table 1: Mean perceived size/angle of virtual objects with percent over- and underestimation (data from sighted and blind participants combined)

Object Type	**Actual Size/Angle (cm/degrees)**	**Perceived Size/Angle Inside presentation**		**Perceived Size/Angle Outside presentation**	
		Mean and standard deviation (cm/degrees)	**Over/Under estimation (Percent of actual)**	**Mean and standard deviation (cm/degrees)**	**Over/Under estimation (Percent of actual)**
Cube	1.0	1.8 (0.40)	+ 80%	See Note 1.	
	1.5	1.7 (0.30)	+ 13	1.6 (0.50)	+ 7%
	2.0	2.4 (0.20)	+ 20	2.0 (0.50)	0
	2.5	See Note 2.	-	2.4 (0.20)	- 7
Sphere	1.5	2.1 (0.1)	+ 27	1.2 (0.40)	- 20
	2.0	2.3 (0.1)	+15	1.8 (0.50)	- 10
	2.5	2.5 (0.1)	0	2.3 (0.30)	- 8
Rotated cube	30°	-	-	40° (12.0)	+ 33
	50°	-	-	52° (12.0)	+ 4
	70°	-	-	45° (18.0)	- 36
Sheared cube	18°	20° (11.0)	+ 11%	-	-
	41°	37° (11.0)	- 10%	-	-
	64°	59° (9.7)	- 8%	-	-

1. Preliminary investigations showed that a 1 cm edge cube was too difficult for participants to find in the outside presentation, so it was omitted.
2. Preliminary investigations showed that a 2.5 cm edge cube was too big for the virtual space available.

significantly more accurate in their perception of larger objects than of smaller objects. For example, the 1.0 cm edge cube was perceived on average to have a 1.8 cm edge when explored from the inside, an overestimate of 80%, whereas the 2.0 cm cube was perceived on average to have a 2.4 cm edge, an overestimate of only 20%. The size of the objects felt from the inside tended to be overestimated, the mean overestimation across all sizes of cubes and spheres being 25.8%. However, the size of objects felt from the outside tended to be underestimated, with a corresponding mean underestimation of 6.3%. Finally, the angles of the rotated cubes seemed to be difficult to judge, although this may have been due to the lack of a reference point for judging the rotation in the VE.

Study 3: Recognition of Complex Objects

The third study was of a more exploratory nature. The participants were asked to feel one or two of the following virtual objects: a sofa; an armchair; and a kitchen chair. A pilot study found that participants could not determine what the object was by just feeling it. Therefore the participants were told what the shape represented before they felt it. Once the participant knew what shape to 'feel' for, they could usually make sense of it quite quickly. However, this is not true for all complex objects. For example the kitchen chair was extremely difficult to make sense of, even when the user was informed of the shape they were feeling. When asked whether they thought that they would have been able to identify the sofa and armchair without being told what they were, participants said that although they could feel the shape of all the components of the objects, such as the arm-rests and legs, they would not necessarily be able to work out what they represented in combination.

These complex objects were made of simple component objects butted together. For example, the sitting area, back rest and arm rests of the sofa were all cuboids. A problem with this is that the probe can slip into the very small space between the component parts and the user has to get out of the space before continuing to explore the object.

DISCUSSION

The way in which a user of the Impulse Engine 3000™ can explore virtual objects differs from the way in which real objects are felt in several ways. Firstly, the device currently requires the user to feel textures and objects with the probe. This is not a particularly intuitive way of interacting with objects and several participants said they would rather use their hands because they are more used to feeling their environment in this way. During the studies the participants needed to adjust to feeling objects via an intermediate tool. However, participants did find that this situation. As one participant remarked "I don't regard the probe as a pivot, I regard [it] as an extended hand".

Secondly, as mentioned the motors of the Impulse Engine 3000™ are capable of withstanding only 8 Newtons (approximately 2 lbf) of force from the user. This means that if the user applies more force, they get the impression of being able to push the probe through an object. For example, the user can push through the front surface of a cube and arrive at the rear of the cube. The user therefore has to adjust to this new way of interacting with objects.

Thirdly, in order to feel the inside of a real object an 'entrance' is needed, for example a door into a room. However, to feel inside a virtual object such as a cube, no entrance is required: the user can explore the inside of the object without having to use an entrance. Interestingly, participants were not observed to have any difficulty with this aspect of the virtual world obeying different laws of physics to those of the real world.

Hardwick, Rush, Furner & Seton [8] observed an interesting phenomenon associated with the Impulse Engine 3000, whereby people differ in terms of where they think the virtual space is located in real space. Some people have a mental image of the virtual space being outside the device, so that virtual objects are felt to be near the hand and are touched by the end of the probe that they hold (Figure 4a). In contrast, others imagine the virtual space to be within the device, so that virtual objects are touched by the other end of the probe (Figure 4b).

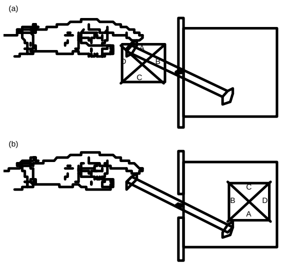

Figure 3: The different mental models of the location of the virtual space: (a) outside and (b) inside the device.

This phenomenon was explored further during the current studies by asking each participant to touch the top of a virtual cube (a method used informally by Andrew Hardwick). When the participant touched what they imagined to be the top of the cube, it could be seen by the investigator (Chetz Colwell) whether they moved their hand up or down. She could judge from this where the participant imagined the object to be, either inside the device, outside the device, or half-way in between (i.e. in the vertical plane of the front of the device, see Figure 1). This judgement was then confirmed with the participant by asking them where in real space they thought the object was located, and to point to this location. The phenomenon seemed to occur regardless of whether the exploration was of the inside or the outside of the object.

Data on this phenomenon were collected from 19 of the participants. 14 (74%) imagined the objects to be located inside the device, 4 (21%) imagined the objects to be outside, and 1 (5%) imagined them to be half-way. Three (33%) of the blind participants imagined the objects to be located outside of the device, compared to only 1 (8%) of the sighted participants. Of the participants who imagined the objects to be outside the device, 3 were blind and 1 was sighted. Therefore, this phenomenon may be more prevalent amongst blind people than sighted people, but is worthy of further investigation.

A further difference between the mental models of the participants was in which part of the probe they believed was touching the objects: some believed that the objects were touched by one end of the probe (either the end they hold or the other end) whereas others believed that as they move along an edge of an object, the length of the probe was touching the object. This difference also seemed to occur regardless of whether the inside or the outside of the object was presented.

Participants also differed in the way they imagined touching the back of an object that was being explored from the outside. Some imagined that they were feeling it with the end of the probe that they were holding. Others imagined that the probe was going through the object and that there was a knob at the other end of the probe that prevented the probe from being drawn through the object.

During Study 2, many participants were observed to get temporarily lost in the virtual space (a phenomenon which could be known as being 'lost in haptic space'). For example, when searching for an object for the first time, participants were observed to have difficulty keeping the probe in contact with the object. As the user moves the probe along, and then to the end of one side of a cube, the probe tends to slip off into empty 'space' (Figure 4a). The user then has to explore this space with the probe in order to get back to the object and find the next side. This can result in the user losing track of where they are in relation to the object because they have no reference points to use as navigational aids. This can make the recognition of the shape of objects quite difficult. Most participants found that after a few minutes' practice they could trace around an object quite easily, staying in contact with its surfaces the whole time (Figure 4b).

In general most of the objects used in Study 2 appeared to be easy to explore but some objects were more difficult than others. For example, the inside of the sheared cube with the larger degree of shear, was particularly difficult to feel. It had two difficulties associated with it (Figure 5). Firstly, the angled sides did not feel smooth; they felt jagged, and as the probe moved along them it made a different noise from that made when moving along a smooth surface. Secondly, it was often difficult to perceive the corners of the object because the probe moves from one side to an adjacent side without the user being aware of the corner. These difficulties did not seem to prevent the participants from building up a mental image of the shape, because the results of Study 2 suggest that they were able to judge the angle of the shear.

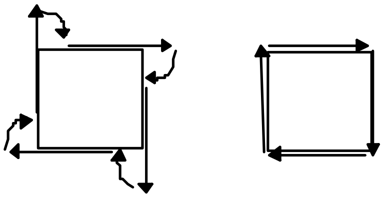
(a) (b)

Figure 4: The user develops control over the probe with experience. (a) at first the probe slips off the object into 'space'. (b) after a few minutes' practice the probe stays in contact with the object.

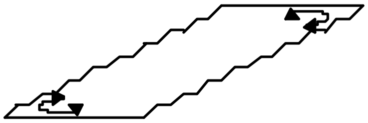

Figure 5: Cross-section of the inside of a sheared cube: the angled sides do not feel smooth and the probe cannot get into corners.

GUIDELINES FOR THE DESIGN OF HAPTIC INTERFACES AND VEs

From these three studies, we have developed a set of preliminary guidelines which can aid in the design of haptic interfaces and VEs.

On virtual textures:
(1) Users need to be able to easily discriminate between different simulated textures; do not assume that physical variations in roughness are easily detected or discriminated from one another.
(2) Users may vary in their perception of texture, both in the size of the differences which they can

detect and in the way they feel textures (e.g. what is rougher, what is smoother).

On virtual objects:
(3) Users perceive the sizes of larger virtual objects more accurately than those of smaller virtual objects.
(4) Users feel virtual objects to be bigger from the inside and smaller from the outside (the "Tardis" effect[1]).

Guidelines (3) and (4) both suggest that if it is important for users to perceive size accurately, virtual objects may need to deviate from their real world dimensions in the virtual world.

(5) Virtual objects need not follow the same laws of physics as real objects, e.g. users can push through the surface of an object. Current technological constraints mean that virtual objects may not be able to simulate all aspects of their real world equivalents. This does not appear to disturb users greatly in terms of pushing through the surfaces of objects, but care should be taken if the laws of physics are broken in other ways.
(6) Users may have difficulty orienting virtual objects in space; if this is important, other cues as to the orientation of the virtual world may be needed (e.g. by providing floors or walls to the space)
(7) Users may need to learn strategies on how to explore virtual objects with a particular device. This is probably not time-consuming, but useful strategies should be provided for users.

On complex objects and their orientation:
(8) Users may not understand complex objects from purely haptic information; multimedia information may be required to give a sense of complex objects and what they mean.
(9) Complex objects that are made up of component objects may have very small spaces between the components into which the haptic pointer may slip. Users may have to remove the pointer from the gap in order to continue to explore the object. They may also be confused by objects by finding unexpected gaps in objects.

On haptic space and its navigation
(10) Users may become 'lost in haptic space'. Provide navigational information support to try to avoid this problem.
(11) Users may have differing mental models of where the virtual space is and what part of the device is "touching" a virtual object. Watch for any consequences of these factors.

CONCLUSIONS

This paper has presented a series of three studies exploring the perception of virtual textures and objects using the Impulse Engine 3000 haptic device. These studies have illustrated both the potential and some of the problems of using current haptic technology to simulate real world objects or to create totally virtual objects. In designing haptic interfaces, designers need to exercise care and not assume that the virtual world will be perceived in exactly the same ways as the real world, particularly given the current limitations of haptic devices which use probes and joysticks. To this end, we have provided a preliminary set of guidelines for the design of haptic interfaces and VEs, based on the results of these studies. Clearly these guidelines will need to be developed as further research is conducted in this area. However, the current devices do provide realistic feeling textures and objects which replicate the psychophysical properties of real textures and can be judged like real objects. These virtual objects and textures have enormous potential for enhancing VEs for both sighted and blind people.

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