Haptic Virtual Reality for Blind Computer Users

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1. 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. 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. However, they do show that a haptic interface has considerable potential for blind computer users.

1.1 Keywords

Haptic device; virtual environments; perception of virtual textures and objects; blind users; world wide web.

2. INTRODUCTION

The design of interfaces to virtual environments (VEs) is currently an important and exciting issue for the field of Human Computer Interaction [3]. The potential of this technology for people with disabilities has been recognised and is being developed in a variety of different systems [28, 23, 25].

At present, VEs typically 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) [16]. 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 [6].

The series of studies reported in this paper contribute to research on blind users' experiences of VEs and the development of guidelines for the design of haptic or 'feelable' VEs. It is important to know how different users haptically perceive virtual objects, so that such objects can be incorporated appropriately into large scale VEs.

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 [27]. 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 [4, 12]. 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 [7]. 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.

Domain	Example	VR Technology	Reference
Education	Science - simulated laboratory experiments	Head mounted display	Nemire, 1995
Training	Mobility skills - familiarisation with route	Head mounted display	Mowafy & Pollack, 1995
Communication	Gesture recognition - sign to speech translation	Glove input	Kalawsky, 1993
Rehabilitation	Physical therapy - recovery of manual skills	Joystick and / or other interaction devices	Bowman, 1997
Access to Information Technology	Sensory transposition - transfer visual presentation to tactile	Force feedback display	Hardwick et al., 1997

Table 1: Five domains in which VEs can be used by people with disabilities.

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.

Some of the most important applications of VEs for people with disabilities are in education, training, communication, and rehabilitation [20]. A further category is access to information technology, i.e. to both computer-based or electronic information, and graphical user interfaces. The examples described below are grouped into these categories, although there is some overlap (see Table 1).

2.1 VEs in Education

The Virtual Environment Science Laboratory (VESL™) assists students with physical disabilities in learning science. It has a head-mounted display which displays a three-dimensional laboratory with which the student can interact. For example, a student can set up their own experiment using virtual equipment, rather than having a helper to do it. The system also enables students to manipulate objects in a way that may not be possible for them in a real lab, such as operating a stop-watch [19].

2.2 VEs in Training

The 'Train to Travel' system is a prototype designed to train students with cognitive disabilities in traveling independently. It was designed to replace an existing programme of training which involved a teacher accompanying students on real journeys, over a period of weeks or months. The system includes a head-mounted display with head tracking so that the view changes as the student moves their head. The display shows digitised video of the buses, bus stops, and the bus routes between the student's home and the University. The student can become familiar with the landmarks along the journey, and can learn to watch out for them when traveling alone [18].

2.3 VE Technology in Communication

An example of the use of VE technology in communication is the Talking Glove. Although VE technology is used, a virtual environment is not used. The Talking Glove allows non-speaking deaf people to communicate with non-signing hearing people. The deaf person finger-spells words with the hand wearing the glove. The hand formations are converted into synthesised speech and output from a speaker worn as a pendant around the neck. An alphanumeric display is worn on the wrist of the other hand and gives visual feedback to the deaf person [11].

2.4 VEs in Rehabilitation

The Enhanced Sensory Feedback Device (ESFD) is designed for use by stroke patients. It offers muscle re-education to improve the patient's coordination and strength, and cognitive retraining. For the latter it uses simple computer games and a remote-controlled car. It attempts to make rehabilitation a motivating, positive and interesting experience. After a physical therapist has assessed the abilities of the person, such as a stroke patient, the system can show the patient what they are capable of doing so that the patient can practice and improve their abilities [2].

2.5 VEs for Access to IT

Currently, VEs can be created for the WWW using Virtual Reality Markup Language (VRML), for example those recommended by Goralski [5]. 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.

These examples illustrate the wide range of uses of VEs that exist for people with disabilities, and the extent of its potential. The examples also provide a context for the studies described in this paper. Haptic interfaces to VEs are just one of aspect of this range of interfaces, which have particular potential for use by blind people.

3. 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 [10] and was used with software

written by Andrew Hardwick (see [8] 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 [7]. 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.
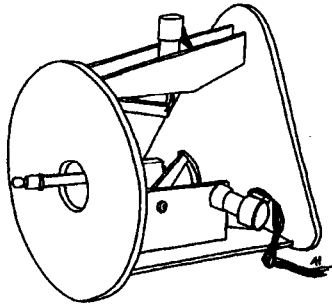

Figure 1: The Impulse Engine 3000™

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.

4. PERCEPTION OF REAL TEXTURE

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 [26]. 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 magnitude of shock etc. via a power function:

$$S = a P^b \text{ (where a and b are constants)}$$

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 [24].
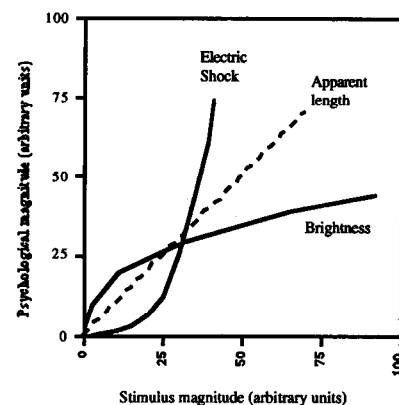

Figure 2: Psychophysical functions for electric shock, apparent length, and brightness. (Graph by Stevens, S.S. reported in [24] p79)

5. PERCEPTION OF REAL OBJECTS

Revesz [21] 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 [16] 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 [22] 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.

6. CURRENT STUDIES

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.

6.1 Study 1: 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 [13, 14, 15], 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 [24] was used to assess the roughness of ten textures with six trials per participant.
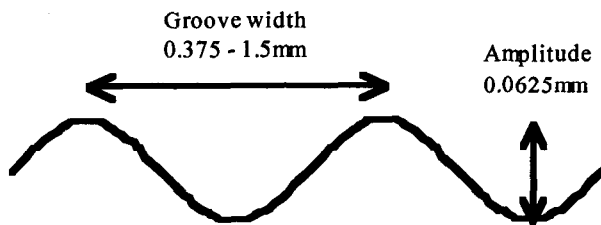
Groove width
0.375 - 1.5mm

Amplitude
0.0625mm

Figure 3: Dimensions of grooves used in Exp. 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 [17], 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.

6.2 Study 2: 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 2), 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 2. 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 significantly more accurate in their perception of larger objects than of smaller objects. For example, the 1.0 cm edge

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	30°	-	-	40° (12.0)	+ 33
cube	50°	-	-	52° (12.0)	+ 4
	70°	-	-	45° (18.0)	- 36
Sheared	18°	20° (11.0)	+ 11%	-	-
cube	41°	37° (11.0)	- 10%	-	-
	64°	59° (9.7)	- 8%	-	-

Table 2: Mean perceived size/angle of virtual objects with percent over- and underestimation (data from sighted and blind participants combined).

Notes: 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.

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.

6.3 Study 3: 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.

7. 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 with only a few minutes practice they could adjust to 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 [9] 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).
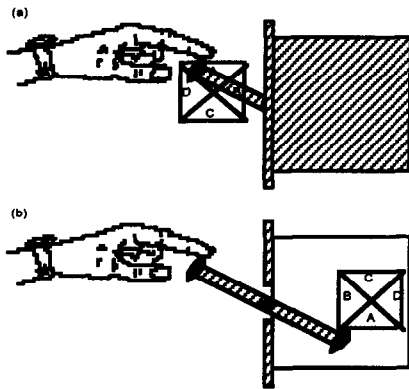

Figure 4: Different mental models of the location of virtual space: a) outside and b) inside.

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 5a). 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 5b).
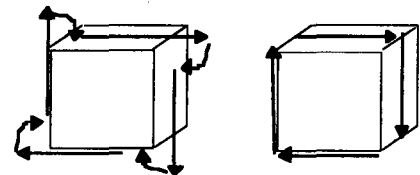

Figure 5: Development of probe control. a) probe slips off the object. b) probe stays in contact with object.

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 6). 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.
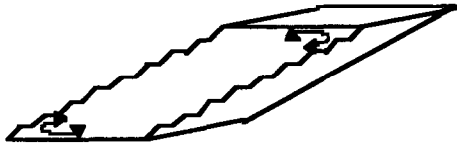

Figure 6: Cross-section of the inside of a sheared cube.

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.

8. CONCLUSIONS

From the three studies described above, we found that some interesting issues have arisen. These should be considered in the design of haptic interfaces and virtual environments, particularly for people with visual disabilities.

Virtual Textures
- It cannot be assumed that physical variations in roughness of virtual textures can be easily detected or discriminated from one another, i.e. virtual textures may not be perceived in the same way as their real counterparts.
- Users may vary in their perception of virtual texture in terms of the size of the differences which they can detect.
- Users may vary in their perception of virtual textures in terms of what feels rougher and what feels smoother.

Virtual Objects
- Users may perceive the sizes of larger virtual objects more accurately than those of smaller virtual objects.
- Users may feel virtual objects to be bigger from the inside and smaller from the outside (the "Tardis" effect[1]).
- 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.

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[1] The Tardis is a time travel machine in the popular British television series, Dr. Who. From the outside it is only the size of a telephone booth, but inside it is multi-roomed. For a VRML simulation of the Tardis, see http://home.t-online.de/home/kiwano/well1.wrl.

Interaction with Interface and VEs
- 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.
- Users may have differing mental models of where the virtual space is located.
- Users' mental models may vary in relation to what part of the device is "touching" a virtual object.
- Users do not appear to be disturbed greatly by being able to push through the surfaces of objects (but care should be taken if the laws of physics are broken in other ways).
- Most users quickly learn strategies on how to explore virtual objects with a particular device, although some may find it useful if these are provided.

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. 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. Such devices have enormous potential for enhancing VEs for both blind and sighted people. Additional investigation of the fundamentals of haptic perception is planned. This will include a comparison of the perception of real and virtual textures and objects. It is hoped that the current experiments will be repeated using alternative haptic devices. Potential applications for haptic devices will be further explored, in particular, tactile maps for blind people.

9. ACKNOWLEDGMENTS

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