

# HAPTIC PERCEPTION IN VIRTUAL REALITY IN SIGHTED AND BLIND INDIVIDUALS

PAUL ROBERT PENN

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# Abstract

The incorporation of the sense of touch into virtual reality is an exciting development. However, research into this topic is in its infancy. This experimental programme investigated both the perception of virtual object attributes by touch and the parameters that influence touch perception in virtual reality with a force feedback device called the PHANTOM™ ([www.sensable.com](http://www.sensable.com)).

The thesis had three main foci. Firstly, it aimed to provide an experimental account of the perception of the attributes of roughness, size and angular extent by touch via the PHANTOM™ device. Secondly, it aimed to contribute to the resolution of a number of other issues important in developing an understanding of the parameters that exert an influence on touch in virtual reality. Finally, it aimed to compare touch in virtual reality between sighted and blind individuals.

This thesis comprises six experiments. Experiment one examined the perception of the roughness of virtual textures with the PHANTOM™ device. The effect of the following factors was addressed: the groove width of the textured stimuli; the endpoint used (stylus or thimble) with the PHANTOM™; the specific device used (PHANTOM™ vs. IE3000) and the visual status (sighted or blind) of the participants. Experiment two extended the findings of experiment one by addressing the impact of an exploration related factor on perceived roughness, that of the contact force an individual applies to a virtual texture. The interaction between this variable and the factors of groove width, endpoint, and visual status was also addressed. Experiment three examined the perception of the size and angular extent of virtual 3-D objects via the PHANTOM™. With respect to the perception of virtual object size, the effect of the following factors was addressed: the size of the object (2.7, 3.6, 4.5 cm); the type of virtual object (cube vs. sphere); the mode in

which the virtual objects were presented; the endpoint used with the PHANTOM™ and the visual status of the participants. With respect to the perception of virtual object angular extent, the effect of the following factors was addressed: the angular extent of the object (18, 41 and 64°); the endpoint used with the PHANTOM™ and the visual status of the participants. Experiment four examined the perception of the size and angular extent of real counterparts to the virtual 3-D objects used in experiment three. Experiment four manipulated the conditions under which participants examined the real objects. Participants were asked to give judgements of object size and angular extent via the deactivated PHANTOM™, a stylus probe, a bare index finger and without any constraints on their exploration. In addition to the above exploration type factor, experiment four examined the impact of the same factors on perceived size and angular extent in the real world as had been examined in virtual reality. Experiments five and six examined the consistency of the perception of linear extent across the 3-D axes in virtual space. Both experiments manipulated the following factors: Line extent (2.7, 3.6 and 4.5cm); line dimension (x, y and z axis); movement type (active vs. passive movement) and visual status. Experiment six additionally manipulated the direction of movement within the 3-D axes.

Perceived roughness was assessed by the method of magnitude estimation. The perceived size and angular extent of the various virtual stimuli and their real counterparts was assessed by the method of magnitude reproduction. This technique was also used to assess perceived extent across the 3-D axes.

Touch perception via the PHANTOM™ was found to be broadly similar for sighted and blind participants. Touch perception in virtual reality was also found to be broadly similar between two different 3-D force feedback devices (the PHANTOM™ and the IE3000). However, the endpoint used with the PHANTOM™ device was found to exert significant, but inconsistent effects

on the perception of virtual object attributes. Touch perception with the PHANTOM™ across the 3-D axes was found to be anisotropic in a similar way to the real world, with the illusion that radial extents were perceived as longer than equivalent tangential extents. The perception of 3-D object size and angular extent was found to be comparable between virtual reality and the real world, particularly under conditions where the participants' exploration of the real objects was constrained to a single point of contact. An intriguing touch illusion, whereby virtual objects explored from the inside were perceived to be larger than the same objects perceived from the outside was found to occur widely in virtual reality, in addition to the real world.

This thesis contributes to knowledge of touch perception in virtual reality. The findings have interesting implications for theories of touch perception, both virtual and real.

## Foreword and Acknowledgements

The main purpose of a thesis is to outline a contribution to knowledge. This endeavour is a two-way street: a person contributes to a body of knowledge, but this process also contributes to the person. Undertaking this Ph.D. has, without question, been the most challenging part of my life to date. I anticipated that it would represent a real intellectual challenge. However, to be honest, I hadn't anticipated the extent of the determination that seeing it through would require. I wonder how many people actually do? There were numerous times when I thought: "is all this really worth it?"

In retrospect it's easy to see why a Ph.D. asks such stern questions about one's determination. The process of research is not easy, not all aspects of it are enjoyable and its end product can be rather different from the one that the researcher might have envisaged. If a researcher abandons their efforts as soon as the true extent of the work that their ideas involve emerges, when they realise that they need to develop their own knowledge base, or when it looks like the experimental results won't say what they wanted them to say, it would be difficult for knowledge to advance at all. Perhaps the most important lesson I've learned about the research process is that it requires determination every bit as much as it requires intellect.

This Ph.D. was sponsored by the Economic and Social Research Council (E.S.R.C) and BT Exact (collaborative studentship no. S00429837015). I am grateful to both organisations for their financial support. For all my efforts, there have also been a number of people, without whose help, the production of this thesis would not have been possible. Unfortunately, my original principle supervisor, Professor Helen Petrie, was unable to continue

in this role during the period in which I wrote this thesis, owing to a move to another university. She was, however, responsible for securing this funded studentship and I thank her for selecting me to undertake this project and for being supportive of my efforts up until her move.

My sincere thanks and gratitude go to Dr. Diana Kornbrot. Having been my second supervisor for most of the studentship, she then took on the role of my primary supervisor after the departure of Professor Petrie. Dr. Kornbrot's enthusiasm, knowledge and insight have helped me immensely throughout the course of this Ph.D. Her contribution to the thesis writing stage deserves particular mention. At the time of her assuming the role of my primary supervisor, I was rather lost and bogged down under the weight of the thesis. Her experience, enthusiasm and patience put me back on the right path.

I would like to thank Professor Richard Young, who took up the role of my second supervisor after Dr. Kornbrot assumed the role of my first supervisor. The fact that he accepted this role and provided invaluable feedback on the thesis in such a short space of time speaks volumes about both his generosity of character and ability as a researcher. I would also like to thank Dr. Richard Wiseman for his assistance in preparing for the viva; his support during that difficult period was greatly appreciated.

I extend my sincere thanks to my industrial supervisors at BT: Mr. Stephen Furner and Dr. Andrew Hardwick. Stephen epitomises my idea of what it means to be a team player, possessing both a sharp mind and an unfailing friendly, supportive and optimistic disposition. Andrew possesses the enviable combination of a remarkably flexible intellect and an inspiring appetite and enthusiasm for knowledge. Both Stephen and Andrew have displayed unfailing commitment to this project and loyalty to me from day one.

An individual's academic and social lives are interdependent. With this in mind, there are a number of people whom I would like to thank for supporting me throughout the course of this Ph.D. I can't list everyone, so I'll restrict myself to mentioning those with whom I have been most closely associated. I'd like to thank my friends and ex-colleagues at the SDRU: Angus Ramsay, Val Johnson, Anne-Marie O'Neil, Dr. Chetz Colwell, Dr. Sarah Morley, Dave Gunn and Carla Harmsworth. I'd also like to thank my long-time friends: Graham Giles, Paul Keeler, Colby Capron, Danny Parrott, Lee Parnell, Bill Poulton and Brian Appleby. Special thanks go to Sarah Champagne-Wilson, for not only always being there for me, but also giving me the opportunity to visit Canada. Finally, I'd like to thank my mum and dad for providing material and moral support, throughout the course of this Ph.D.

As an antidote to the rather serious nature of this Ph.D. thesis and by way of keeping things in perspective, I'd like to end this section with a quote reflecting a philosophy that has always served me well, particularly when the going gets tough or things seem rather uncertain.

"Ladies and Gentlemen, take my advice: pull down your pants and slide on the ice."<sup>1</sup>

Dr. Sidney Freedman (a character from the comedy series M.A.S.H).

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<sup>1</sup> Quote taken from the episode: Goodbye, Farewell and Amen (9-B04) February 28, 1983 Written by Alan Alda, Burt Metcalfe, John Rappaport, Thad Mumford, Dan Wilcox, David Pollock, Elias Davis, and Karen Hall. Information obtained from: <http://www.faqs.org/faqs/tv/mash/guide/>

## **Dedication**

For my mum, Vera Penn, with all my love.



# Preface

I declare that, unless explicitly stated to the contrary, the following work is my own. This thesis has not been submitted for any other qualification at another university or institution.

This thesis is 74,680 words long (excluding references and appendices). It is, therefore, with the prescribed limits for a Ph.D. thesis in Arts, Social Sciences or Education.

Paul Penn.

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# Glossary

Cutaneous sense: “Provides awareness of stimulation of the outer surface of the body through receptors within the skin and associated nervous system.” (Loomis and Lederman, 1986, p31-2).

Force feedback: “The simulation of weight or resistance in a virtual world. Force feedback requires an interface, which produces a force on the body equivalent (or scaled) to that of a real object. It allows a person in cyberspace to feel the weight of virtual objects, or the resistance to motion that they create.” (<http://www.cyberedge.com/4a1.html>)

Haptic Interface: “interface that enables manual interaction with VEs” (Srinivasan, 1995, p161).

Haptic perception: “Perception in which both the cutaneous sense and kinesthesia convey significant information about distal objects and events.” (Loomis and Lederman, 1986, p31-3).

Haptic Virtual reality (HVR): VR that incorporates cutaneous and/or kinaesthetic information being relayed to the user<sup>2</sup>.

Kinaesthesia:<sup>3</sup> “Provides the observer with an awareness of static and dynamic body posture.” (Loomis and Lederman, 1986, p31-2).

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<sup>2</sup> Strictly speaking, the term ‘haptic’ refers to touch in which both cutaneous and kinaesthetic sources of information are available to the individual. However, its use in conjunction with V.R. encapsulates situations in which either or both of cutaneous and kinaesthetic sources of information are available.

<sup>3</sup> The Terms ‘Kinaesthesia’ and ‘kinaesthetic’ are spelt thus in Europe, but often spelt ‘kinesthesia’ and ‘Kinesthetic’ in literature from the U.S. This thesis will use the European spelling, except when quoting authors that have opted to use the U.S. spelling



Kinaesthetic perception: "Perception mediated exclusively, or nearly so, by variations in Kinesthetic stimulation." (Loomis and Lederman, 1986, p31-2).

Posture: "The attitude of the body. Posture is maintained by low-grade, continuous contraction of muscles, which counteract the pull of gravity on body parts". (Definition available on-line at <http://www.neuroskills.com/index.html?main=tbi/hdi/gld.shtml>).

Proprioceptive system: "The proprioceptive system is made up of specialized sensory nerve endings that monitor internal changes in the body brought about by movement and muscular activity. Proprioceptors located in muscles and tendons transmit information that is used to coordinate muscular activity" (Definition available on-line at: [http://sda.jsc.nasa.gov/scripts/cf/gloss.cfm?term=proprioceptive\\_system](http://sda.jsc.nasa.gov/scripts/cf/gloss.cfm?term=proprioceptive_system)).

Tactile feedback: "Sensation applied to the skin, typically in response to contact or other actions in a virtual world. Tactile Feedback can be used to produce a symbol, like Braille, or simply a sensation that indicates some condition." (<http://www.cyberedge.com/4a1.html>)

Tactile perception: "Perception mediated solely by variations in cutaneous stimulation." (Loomis and Lederman, 1986, p31-2).

Tactual perception: "Refers inclusively to all perception mediated by cutaneous sensibility and/or kinesthesia." (Loomis and Lederman, 1986, p31-2).

Virtual Environment (VE): "a computer-generated space that is immersive and interactive." (Definition available on-line at: <http://www.hitl.washington.edu/publications/r-98-22/glossary.html>)

Virtual Reality (VR): “Technology that allows the user to perceive and experience sensory contact with a non-physical world” (Van Erp, 2000, p8).

# 1. Chapter one: Introduction and literature review

This thesis presents a program of research into touch perception in virtual reality (VR) in both sighted and blind individuals with the PHANTOM™ force feedback device.

This chapter comprises both an introduction to the reported research and a review of the literature relevant to the experimental work. Section 1.1 outlines the rationale and aims of the research. Sections 1.2, through 1.7 review the existing real world based literature on: the characteristics of touch; the perception of texture; the perception of extent; angular extent and the isotropy of perceived extent in 3-D space respectively. Section 1.8 summarises the most relevant literature on touch perception in blind individuals in the real world.

Coverage of real world based literature is provided for three important reasons. It provides the context in which the characteristics of touch and perception via touch in VR can be delineated. It also serves to indicate important aspects of touch perception in the real world in need of addressing in VR. It also serves to inform the methodology of the reported experiments.

Section 1.9 underlines the need to study touch perception in VR. It goes on to describe the technology that makes touching in VR possible and highlights the differences between touch in the real world and touch in VR. Section 1.10 reviews the available relevant research on touch perception in VR and outlines the rationale for the specific subject matter chosen for study. Section 1.11 provides a plan of the remainder of the thesis. Finally, section 1.12 summarises the main foci of research.

## 1.1 Rationale and aims of the reported research

Until recently, VR, which has been defined as, “technology that allows the user to perceive and experience sensory contact with a non-physical world” (Van Erp, 2000, p8), has only presented the user with visual and auditory information. The user has not been able to touch the contents of a ‘virtual environment’ (VE), which the author defines as: an interactive computer synthesized environment created by VR technology. The same was true of interaction with Graphical user Interfaces (GUIs) such as Windows; visual and auditory information are present, but the user is only physically touching the hardware (i.e. the mouse and keyboard) used to interact with the Windows environment. The user could not touch any element of the environment itself.

Laypeople probably ascribe considerably less value to the sense of touch than vision or hearing. However, consider how much of life is predicated around some form of physical interaction with the environment, which is only possible via touch, and its importance soon becomes apparent. Our most intimate interactions with the environment and each other occur via touch. It is often called upon to supplement what we see and/or hear, provides information about object properties that are inaccessible to the other senses (e.g. temperature). It also provides information about the spatial layout of nearby objects when vision is unavailable.

Therefore, it is fair to say that the absence of the capacity to use touch in interacting with a VE compromises its realism and usefulness. As Srinivasan (1995) puts it, “Real environments or VEs in which one is deprived of the sense of touch and the feel of objects seem impoverished, seriously

handicap human interaction capabilities and, at worst, can be disorientating".  
(p162)

Biggs and Srinivassan (2001) point out that incorporating the sense of touch into VR is vital for simulating tasks in which touch is of intrinsic value, such as surgical procedures. More generally, Biggs and Srinivassan note that incorporating touch into VR results in more natural and realistic interactions with VEs. Consider the example of an individual engaged in the simple task of picking up and moving an object from one location to another without any information from the sense of touch. The individual would have only visual and auditory information with which to complete the task. They would not be able to feel the contact between their hand and the object, the weight of the object or any contact that the object makes with the surface on which it is to be placed. Intuitively, one would imagine that the lack of this information would have a detrimental effect on the ease with which the individual could perform the task. Indeed, there is research that indicates that incorporating touch into a VE results in significant improvements in the accuracy and time required to perform simple manual tasks, such as the manipulation of virtual objects (Engel, Goossens and Haakma, 1994; Noma, Miyasato, & Kishino, 1996, cited from Biggs and Srinivassan, 2001). There is also evidence to suggest that VR incorporating touch is perceived as being more realistic than VR devoid of touch (Hoffman, 1998).

The briefest consideration of some of the VR applications incorporating touch that have already been developed provides perhaps the best glimpse of the potential of adding touch to VR

### **1.1.1 Current applications of touch in VR**

In recent years, VR incorporating the sense of touch has found a number of applications, some of which are summarised below.

- The use of touch in VR as an accessibility tool for blind computer users

The fact that interaction with computers is largely restricted to the visual and auditory sensory modalities is of particular significance to blind computer users. The operating system and applications of a computer are predicated around the user being able to see, hence the term Graphical User Interface (G.U.I). The use of auditory feedback and the computer's keyboard makes navigation around such environments possible for blind users, but the presence of touch might prove very beneficial in this context, as blind individuals use touch to compensate for the lack of vision in navigating around the real world.

Preliminary work into incorporating touch into a Windows environment has already been conducted by Sjostrom (2000). This work involved the development of a number of navigation aids utilizing touch to improve the accessibility of a windows environment for blind PC users. For example, Sjostrom proposed a 'magnet' effect to draw blind users towards windows icons.

Wies, Gardner, O'Modhrain, Hasser and Bulatov (2000) note that: "Physics, chemistry, engineering and mathematics curricular are full of abstract principles and physical concepts, many of which are inherently dynamic in nature" (p108). Lecturers might use pictures, graphs or visual media to facilitate students' comprehension of such information, which presents accessibility problems for blind students. Using the concept of electric fields as an example, Wies et al (2000) report some preliminary work into using touch in VR to allow blind students to explore simulations of complex physics phenomena and examine the data gained from their interaction with the phenomena. Research conducted by Yu, Ramloll and Brewster (2000) specifically addressed using touch in VR to make digital graphs more

accessible to blind PC users by creating touchable representations of line graphs and using cues, such as friction, to allow users to distinguish between different sets of data depicted in a graph. Similarly, VanScoy, Kawai, Darrah and Rash (2000) report preliminary research involving the use of VR incorporating touch to make depictions of mathematical functions accessible to blind students. O'Modhrain and Gillespie (1995) report some work into using touch in VR to make the process of sound editing via a PC more accessible to blind individuals.

There has also been some interest in using VR incorporating touch to help in the mobility of blind individuals. Semwal (2001) outlines the MoVE project, which proposes the development of a VR system in which blind individuals could use touch to explore a virtual map of an unfamiliar location and commit the desired route to memory before trying to negotiate it in the real world.

- The use of touch in VR in medical training applications

Training individuals for the medical profession, where mistakes can be dangerous, can be problematical. Training an individual in a VE, provides a scenario under which the training can be orientated precisely by the tutor and students can rehearse aspects of a medical procedure without serious repercussions should they make a mistake.

There have been a number of applications of touch to VR in the context of medical training. The development of a system that simulates the feel of soft tissue, the effects of making incisions in soft tissue and bleeding associated with such incisions has been reported by Srinivasan, Basdogan and Ho (1999) The Immersion Corporation ([www.immersion.com](http://www.immersion.com)) have developed training simulations involving touch for: vascular access, (the CathSim<sup>4</sup>);

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<sup>4</sup> More details about the CathSim can be found at:  
<http://www.immersion.com/products/medical/vascular.shtml>

endoscopy procedures, (the AccuTouch<sup>5</sup> simulator) and Laparoscopic procedures (the Laparoscopic Impulse Engine<sup>6</sup>).

VR incorporating the sense of touch is being used in simulators designed to train the palpation skills required for diagnosis of tumours (Dinsmore, Langrana, Burdea and Ladeji 1997; Burdea, Patounakis, Popescu and Weiss 1999). Higgins et al (1995, cited from Burdea 1999) reports a simulation for the treatment of arteriosclerosis and Weit et al (1997) have developed an endoscopic sinus surgery simulator.

Researchers are also beginning to examine the potential of VR simulations incorporating the sense of touch in the field of rehabilitation. For example, Burdea, Deshpande, Popescu, Langrana, Gomez, Dipaolo and Kanter (1997) report the development of a system devised to precisely diagnose and rehabilitate hand injuries. Hodges, Anderson, Burdea Hoffman and Rothbaum (2001) report a similar system for the diagnosis and rehabilitation of ankle injuries.

- The use of touch in VR as an educational tool

Srinivasan and Basdogan (1997) point out that VR incorporating the sense of touch can be used to facilitate sighted students' comprehension of complicated scientific phenomena. For example, Batter and Brooks (1991) reported an experiment involving simulations of electrostatic fields. Physics students learning about these fields from VR simulations involving touch outperformed students who received the same VR simulation without the touch information. Wies, Gardner, O'Modhrain, Hasser and Bulatov (2000)

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<sup>5</sup> More details about the AccuTouch can be found at:

<http://www.immersion.com/products/medical/endoscopy.shtml>

<sup>6</sup> More details about the Laparoscopic Impulse Engine can be found at:

<http://www.immersion.com/products/custom/laproimpulse.shtml>



have noted that their work, relating to using touch in VR simulations to facilitate blind students comprehension of scientific data, could also be of benefit to sighted students.

Research is also beginning to address educational applications of VR incorporating touch outside the context of the classroom. For example, researchers at the University of Southern California have incorporated touch into virtual simulations of artifacts from the University's art gallery. Visitors can admire the real exhibits before interacting with the virtual simulations. By touching the virtual simulations of the exhibits, the visitors can appreciate how the exhibits feel without exposing the real exhibits to the risk of damage (McLaughlin, Sukhatme, Shahabi, Hespanha, Ortega and Medioni, 2000).

- The use of touch in VR in entertainment

Touch is also being incorporated into the video game market to enhance an individual's games-playing experience. The Immersion Corporation ([www.immersion.com](http://www.immersion.com)) licenses out its 'TouchSense'<sup>7</sup> technology to developers of games and videogame controllers which, for example, allow the user to feel the recoil of a weapon on a game that involves shooting, or the impact of another vehicle in a driving game (considerably scaled down of course)!

- The use of touch in VR as a creative tool

There has also been some interest in the application of touch to artistic software, thus providing a more veridical experience for artists who work with computers. Sensable technologies ([www.sensable.com](http://www.sensable.com)) have developed an

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<sup>7</sup> more details can be obtained at: <http://www.immersion.com/products/ce/gaminginfo.shtml> (checked in Feb. 2002)

application known as 'Freeform'<sup>8</sup>. This application simulates the feel of modelling in clay and allows trained (or would-be) sculptors, with no background in computing technology, to produce designs in virtual clay.

- The use of touch in VR in communication and collaboration in VEs involving more than one user

The advent of VR that incorporates the sense of touch, together with the growing popularity of the Internet, raises the possibility that two or more users from remote locations could interact using touch over the phone line. Research is underway at BT, ([www.bt.co.uk](http://www.bt.co.uk)) to address the technical problems associated with sending touch information across the web (Hardwick, Furner and Rush, 1997). Research by Sallnas (2000) has investigated using touch to facilitate collaborative interaction with objects in a VE. Research is also beginning to address ways in which to use touch to facilitate communication between users in a VE by, for example, the use of gesture information (Oakley, Brewster and Gray, 2000).

Even at this early stage, the ability to use the sense of touch in VR is an exciting prospect for both blind and sighted computer users. However, if the potential of incorporating the sense of touch into VR is to be fully exploited, a great deal of thought needs to be applied to the way in which it is implemented. The implementation of touch into VR should be informed by research that addresses touch perception in VR.

### **1.1.2 The Teletouch project**

The program of research reported in this thesis represents part of a collaborative project between the Sensory Disabilities Research Unit<sup>9</sup> based

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<sup>8</sup> More information about Freeform can be obtained at:  
(<http://www.sensable.com/freeform/freeform.html>) (Checked in Feb. 2002)

<sup>9</sup> The Sensory Disabilities Research Unit disbanded in September 2001.

at the University of Hertfordshire and BT Exact Technologies. The collaboration began in 1997, with Chetz Colwell conducting research into the perception of virtual texture and virtual object size and angular extent with the IE3000 haptic device (Colwell, Petrie, Kornbrot, Hardwick and Furner, 1998a; Colwell, Petrie, Kornbrot, Hardwick and Furner, 1998b). Upon joining the project at the end of 1998, the author sought to continue to address the fundamentals of haptic perception in VR with the PHANTOM™ haptic device.

The general aim of this thesis is to provide an experimental account of the perception of the roughness of texture and the size and angular extent of 3-D objects with the PHANTOM™ device. Using the perception of these attributes, this thesis also aims to address the following issues concerning touch perception in VR. The justification for these issues is outlined in section 1.10, after the exposition of the relevant literature. The purpose of listing them here is merely to make the aims of the thesis explicit from the outset.

- 1) To investigate the impact of the specific endpoint used (i.e. a thimble or stylus) with the PHANTOM™ device on the perception of roughness and 3-D object size and angular extent.
- 2) To investigate the impact of the specific VR device used (PHANTOM™ vs. IE3000) on the perception of roughness and the size and angular extent of 3-D virtual objects.
- 3) To empirically compare touch perception between VR and the real world with respect to the perception of the size and angular extent of 3-D objects.
- 4) To investigate the consistency of touch perception over 3-D space in VR with respect to the perception of extent in the 3-D axes (x,y and z).

- 5) To investigate the impact of aspects of touch perception related to the manner in which users explore objects in HVR. Specifically, the variables of the amount of contact force applied to a virtual texture and whether users control their exploratory movements in the perception of extent.
  
- 6) To compare touch perception in VR between sighted and blind users.

The reported work aims to inform future research on haptic perception in VR. The reported experimentation also has important implications for research on touch perception in the real world.

## **1.2. Touch in the real world**

The following section provides a characterisation of touch in the real world in order to provide the context in which the characteristics of touch in VR can be delineated. It also serves to indicate important aspects of touch perception in the real world of relevance to the study of touch in VR.

Touch in the real world can broadly be characterised with respect to three dimensions. The first dimension relates to the type of sensory information that is available to the individual. The second dimension relates to the dynamics of the interaction between the individual and the object he/she wishes to examine. The third dimension relates to the exploratory procedure used by the individual in examining the object of interest.

### **1.2.1 The types of sensory information involved in touch**

The sense of touch encompasses two different sources of sensory information: cutaneous and kinaesthetic information (Loomis and Lederman, 1986).

Cutaneous information, “Provides awareness of stimulation of the outer surface of the body through receptors within the skin and associated nervous system” (Loomis and Lederman, 1986, p31-2). The term ‘tactile perception’ is used to refer to, “perception mediated solely by variations in cutaneous stimulation” (Loomis and Lederman, 1986, p31-2).

The literature on tactile perception mainly concerns the sensitivity of the skin to pressure and vibration and the ability to localise and discriminate between distinct sensations on the skin. The acuity with which these tasks can be performed varies between different regions of the body, with optimal

sensitivity on the 'Glabrous' (hairless) skin on the lips and fingertips (Sherrick and Craig, 1991).

Measurement of the sensitivity of the skin to pressure is achieved via the application of a small rod or hair to the skin, with differing amounts of force per unit area (Coren, Ward and Ennis 1994). Absolute thresholds for pressure stimuli can be remarkably small (Cholewiak and Collins, 1991). For example, an individual's threshold to pressure varies from around 400mg at the calf, down to as low as 5mg on the face. 5mg of pressure has been, "likened to having a wing of a fly dropping about 3cm onto the skin" (Cholewiak and Collins, 1991, p46).

Measurement of the sensitivity of the skin to vibration is achieved via the application of vibrating stimuli of given amplitude with a varying frequency to the surface of the skin. Once again, the threshold varies between different locations of the body, ranging from a vibration with an amplitude of 20 microns at 200Hz on the buttocks (Cholewiak and Collins, 1991) to 0.2 microns at 250Hz on the palm of the hand (Gescheider, Capraro, Frisina, Hamer and Verrillo, 1978, cited from Cholewiak and Collins, 1991).

The spatial acuity of the skin is often measured by stimulating two distinct points of the skin at diminishing spatial intervals until the individual reports only being able to feel one point. This is called the 'two point limen' (Cholewiak and Collins, 1991). An individual's two point limen differs between 40mm for the calf and 2.5mm for the tip of the index finger (Sherrick and Craig, 1991). The spatial acuity of the skin is also assessed by the error of localization (Cholewiak and Collins, 1991). This method involves the individual's skin being stimulated at one location, then subsequently stimulated at either the same or a different point. The individual is then asked to determine whether he/she was touched on the same or on a different location. The furthest distance at which the individual responds incorrectly,

averaged over a number of trials, is deemed to be the error of localization (Sherrick and Craig, 1991). An individual's error of localization can vary between 2.29mm on the tip of the index finger (Sherrick and Craig, 1991) to 10mm on the front of the legs (Cholewiak and Collins, 1991).

Kinaesthetic information provides the individual with, "both static and dynamic feedback about the position of the body mass as a whole and its individual limbs via receptors located in the muscles and joints" (Loomis and Lederman, 1986, p31-2). "Both movement and postural responses involve tension, compression or twisting forces on the muscles, tendons or joints of limbs. These physical forces are the stimuli for kinaesthesia" (Coren, Ward and Ennis, 1994, p302). The term 'kinaesthetic perception' is used to refer to "perception mediated exclusively, or nearly so, by variations in kinesthetic stimulation" (Loomis and Lederman, 1986, p31-2).

The study of kinaesthesia focuses on the perception of limb movement, the perception of limb position and the perception of limb force (Jones, 2000) Absolute thresholds for limb movement can be very impressive. For example, "humans can detect joint rotations of a fraction of a degree over a time interval of the order of a second" (Srinivassan, 1995, p166). The velocity of the movement affects the movement thresholds: faster movements being easier to detect than slower movements (Jones, 2000). For example, movement thresholds for the distal joints of the fingers decrease from 8° to 1° as velocity increases from 1.25°/s to 10°/s. Between 10°/s and 80°/s remains stable at 1° (Hall and McClosky 1983, cited from Jones, 2000). Thresholds for limb movement also depend on what limb is being moved. Proximal joints have lower thresholds than more distal joints. For example, thresholds for limb movement is "about 2.5° for the finger joints, 2° for the wrist and elbow and about 0.8° for the shoulder" Srinivasan, 1995, p167).

The perception of limb position is usually achieved by asking the participant to align the positions of two corresponding joints on the left and right sides of the body (Jones 2000). Clark, Larwood, Davis and Deffenbacher (1995) found that when attempting to match the position of the interphalangeal joints of the index fingers, errors ranged between  $.75^{\circ}$  to  $6^{\circ}$  over a range of  $100-175^{\circ}$  of finger flexion. Pillard and Bouchon (1968) found that the accuracy with which participants could perform the position-matching task varied according to whether they provided the movement or had it provided by the experimenter. In this experiment, participants were asked to match the position of their outstretched arms. The average error for participants that had the movement provided was  $2^{\circ}$  compared to  $0.6^{\circ}$  when the participants provided the movement.

Research has addressed the question of whether the perception of limb position can be independent of the perception of limb movement that caused the change in limb position. This has been achieved by altering the position of a limb via movements performed at speeds too slow to be perceived: between  $1^{\circ}$  and  $4^{\circ}$  a minute (Jones, 2000). Such research has indicated that individuals can indeed make judgments of position independently of having perceived the movement responsible for the change in limb position (e.g. Clark, Burgess, Chapin and Lipscomb, 1985; Tan, Eberman Srinivasan and Cheng, 1994). Thresholds to a change in limb position resulting from movement of proximal joints is superior to changes in limb position resulting from movements of more distal joints (Clark et al 1985).

With regard to the perception of force, the just noticeable difference (JND) appears to be "5-15% of the reference force value over a wide range of conditions involving substantial variations in force magnitude, muscle system and experimental method" (Srinivasan, 1995, p167). Jones (2000) notes that discrimination deteriorates for forces smaller than  $.5$  N, but that forces as low



as .14 and .2 N can be distinguished. The maximum controllable force that can be exerted by a finger is about 100 N (Srinivasan, 1995).

Whether the mechanisms of cutaneous and kinaesthetic perception can be completely differentiated on a practical basis is questionable. Very rarely in day-to-day life do situations transpire which involve exclusively cutaneous or kinesthetic perception. Indeed, the deprivation of one source of information can have a deleterious effect on an individual's ability to perform a task involving simple manipulation. For example, Joansson and Westling (1984) demonstrated that participants' ability to pick up an object and maintain sufficient grasping force such that it would not slip was significantly impaired when tactile information was removed via anaesthesia.

The most familiar type of touch occurs when both cutaneous and kinaesthetic information is available. This is referred to as 'haptic' perception or, "perception in which both the cutaneous sense and kinesthesia convey significant information about distal objects and events" (Loomis and Lederman, 1986, p31-3).

### **1.2.2 The dynamics of touching interactions**

The second dimension in characterising touch relates to the dynamics of the interaction between the individual and the stimulus. Gibson (1962) differentiated between 'active' and 'passive' touch. The basis for the distinction lies in whether the individual is instrumental in producing the movements of the hands used in acquiring a stimulus. "Active touch refers to what is ordinarily called touching. This ought to be distinguished from passive touch or being touched" (Gibson, 1962, p 477). The difference between active and passive touch can be illustrated with reference to the example of feeling a textured surface. If an individual were to move one or

more fingers across a texture, this would be deemed active touch.

Conversely, if the texture was to be moved under the individual's stationary finger/s, or the individual was to have their finger/s moved over the texture, this would be deemed passive touch.

Gibson (1962) felt there was a fundamental difference in the nature of touch according to whether the individual controlled the 'pickup' of information. In Gibson's words: "to apply a stimulus to an observer is not the same as for an observer to obtain a stimulus" (1962, p490). Gibson argued that the use of either active or passive touch has implications for the effectiveness of haptic perception. In support of his position, Gibson (1962) offered an experiment in which participants were asked to recognize simple 2-D 'cookie cutter shapes', with a mean diameter of 2.5cm. The shapes were presented in one of three exploration conditions. In one condition, the shapes were pressed onto the participants' palms (static passive condition). In another condition the shapes were rotated back and forth whilst being pressed onto the participants' palm (passive moving condition). In a final condition, the participants were allowed to examine the shapes with their fingers in whatever manner they wished (active condition). The accuracy with which the 2-D shapes were identified was 49%, 72% and 95% for the static passive, passive moving and active conditions respectively. Whilst this experiment did provide some support for Gibson's assertion that active touch was superior to passive touch, Loomis and Lederman (1986) rightly pointed out that it was not clear from this study, whether the superiority of the active touch condition could be attributed to participants being able to control their exploratory movements, the availability of kinaesthetic information per se, or the higher acuity of the fingertips relative to the palms.

Schwartz, Perey, and Azulay (1975) presented the same cookie cutter 2-D shapes used by Gibson (1962) to participants under the active and static passive conditions used in Gibson (1962). However, they added a further

exploration condition whereby the contours of the shapes were passed under the participant's stationary finger (a passive tactile condition). Recognition accuracy scores for the static passive and active conditions were 39% and 94%, which was in agreement with Gibson (1962). However, participants in the additional passive tactile condition accurately identified 93% of the 2-D shapes. Heller and Myers (1983) noted that Schwartz et al (1975) had permitted the participants in the passive touch conditions more time to explore the shapes than the participants in the active touch condition. This was deemed to be a significant confounding influence on the results since Heller (1980) found that restricting the amount of time participants had to examine 2-D shapes had a detrimental effect on subsequent recognition accuracy relative to participants who were allowed as much time to examine the shapes as they wished. This occurred irrespective of whether the stimulus was presented actively or passively on the fingers or the palm.

Heller and Myers (1983) compared the recognition accuracy of participants that either explored 2-D cookie cutter shapes actively with the palm, had the objects placed statically onto their palm, or had the objects placed on their palm and rotated by the experimenter. Their results indicated that accuracy in the active condition was significantly greater than the two passive conditions, which did not differ significantly. This experiment indicated that it was the availability of kinaesthetic information about the contours of the shape provided by the movement of the palm that was responsible for the superiority of active touch. This was because movement of the stimuli provided by the experimenter in the condition in which the hand was stationary did not yield significantly better recognition accuracy scores than the condition in which the shapes were pressed statically onto participants' palms.

Magee and Kennedy (1980) compared participants' ability to identify raised line drawings of familiar objects under two conditions. In one condition,

participants traced the perimeter of the raised line drawing with their fingers (active haptic condition). In the other condition, the experimenter guided the participants' fingers around the perimeter of the drawings (passive haptic condition). The number of correct identifications was significantly higher for participants in the passive condition than for participants in the active condition. A further experiment reported in Magee and Kennedy (1980) compared participants' ability to identify the raised line drawings under two further exploration conditions. In one condition, the participants had the images moved beneath their stationary index finger (tactile sequential condition). In the other condition, participants had their fingers traced over the images, without making contact with the raised lines that defined them (passive kinaesthetic condition). The performance of the participants in the passive kinaesthetic condition was significantly better than the participants in the tactile sequential condition. Furthermore, the performance of the participants in the passive kinaesthetic condition was about the same as the performance of the participants in the former passive haptic condition. Thus, the results of this study supported Heller's assertion that kinaesthetic information was the source of superior identification of 2-D drawings, but also indicated that whether the kinaesthetic information was acquired via active movement or passive movement was not significant.

Symmons and Richardson (1996) and Symmons and Richardson (1999) noted that experiments in which active and passive touch had been compared often differ in variables other than just the active or passive nature of the exploration movement. For example, Heller and Myers (1983) allowed participants to explore the outline of 2-D shapes in the active condition, but pressed the shapes onto the participant's palm in the passive condition. Magee and Kennedy (1980) tried to equate movement between the active and passive conditions, but the participants were not allowed to retrace their movements.

Symmons and Richardson (1996) reported an experiment in which participants were asked to identify capital letters and simple raised line drawings, such as a heart or a star, using a device called the Tactile Display System (TDS). The participants' exploration of the stimulus occurred in either an active condition or a passive condition. The participants in the active condition explored the raised line drawings via their index finger, which had been inserted into the TDS. This device then monitored the active participants' exploration of the raised line drawings and subsequently reproduced those movements to the passive participants. The participants in the passive condition were significantly faster in identifying the objects and letters than the participants in the active condition. Further investigation by Simmons Richardson and Kennedy (1999) sought to determine which components of the participants' passive exploration of the stimuli for their identification. The experimenter manipulated the participants' passive exploration of the same stimuli as had been used previously. Participants could feel the raised lines of which the stimuli was comprised, the shearing forces between the skin and the paper resulting from exploration of the stimuli and the kinaesthetic information resulting from the movement involved in exploring the stimuli, or other permutations of these sources of information. The results indicated, "kinaesthesia was a major factor in guiding identification and that shear and the line were much less effective". (1999, p6). Symmons and Richardson (1999) stated that the superiority of the passive condition could be attributed to the fact that "active participants had to plan and command actions as well as examine information. Passive-guided participants may be advantaged because of a reduced burden" (Symmons and Richardson, 1999, p6).

Lederman and Taylor (1972) proposed that active and passive touch are not dichotomous, but rather two extremes of a continuum. Their point was that touch involves a number of components other than just whether the individual produces the movement involved in the touching process.

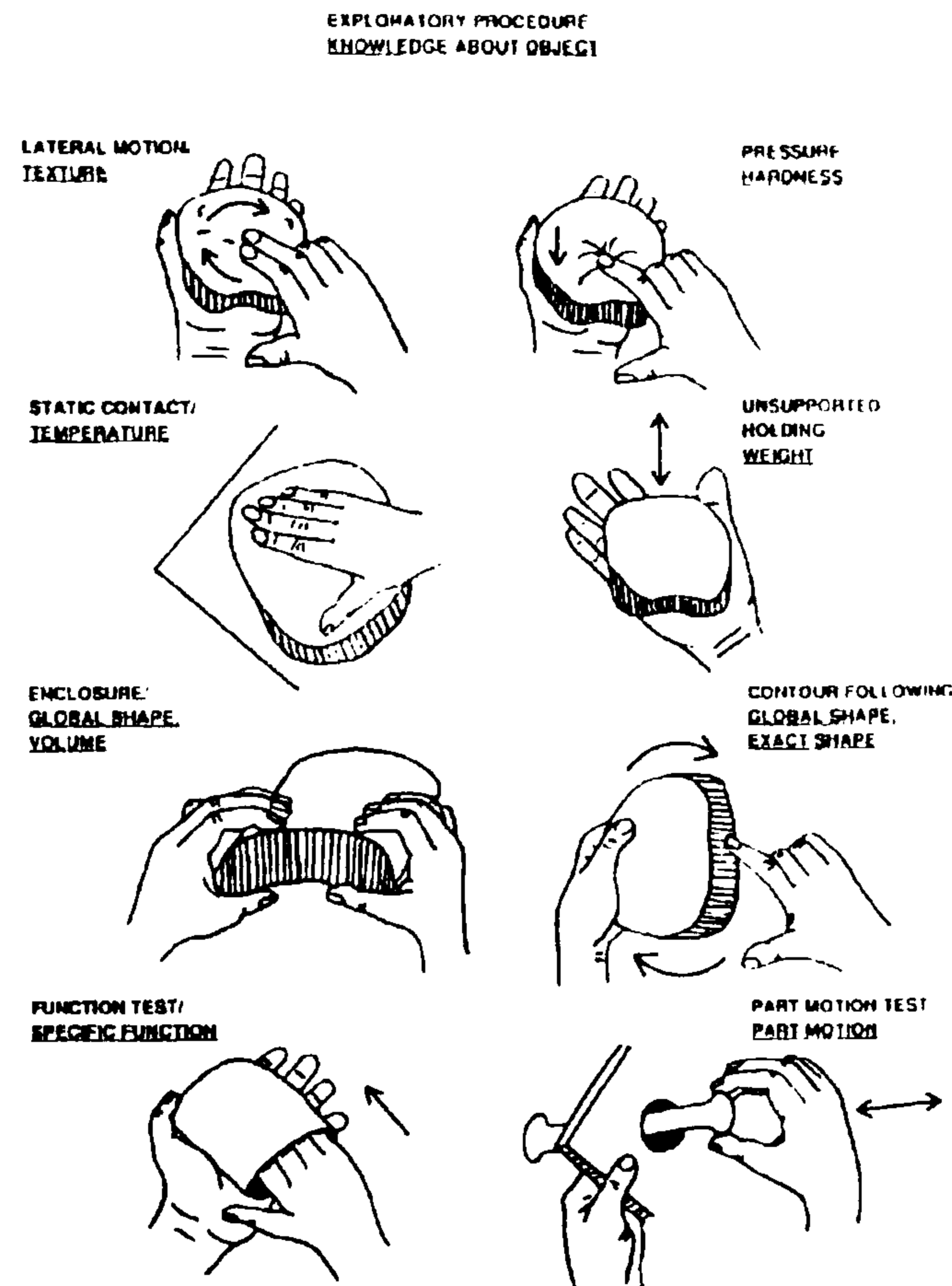
Consider this point with reference to the previously mentioned example of the exploration of a textured surface. In this instance, individuals may or may not have control over the fingers used in interacting with the texture and the amount of contact pressure they apply to the texture, in addition to whether they are producing the movement between their finger/s and the texture. Indeed, the movement itself also entails several components that individuals may or may not exercise control over, such as: whether the texture moves relative to the individual or the individual moves relative to the texture; the velocity at which the movement occurs and the direction of the exploratory movement. Lederman and Taylor (1972) stated that, “the touching process may be considered more or less active, depending on the degree of control the subject has over the various components of the touching process” (1972, p401).

### **1.2.3 Exploratory procedures**

Another dimension of touch is the manner in which individuals use their hands to extract the desired information about the object being touched. The characteristics of haptic exploration have been of interest to researchers for some time. There have been numerous attempts at distinguishing between different types of touching behaviour. For example, Revesz (1950) distinguished between ‘Simultaneous touch’ and ‘Successive touch’. “Simultaneous touch involved inspection of a form and its parts in a single act” (Appelle, 1991, p171) ‘Successive touch “occurred whenever an object or its parts were touched in separate acts distributed over time” (Appelle, 1991, p170). Similarly, Heller (1983, cited from Appelle 1991) distinguished between ‘synthetic’ and ‘analytic’ touch. Synthetic touch is performed to “obtain an overall gestalt impression of form” (Appelle, 1991, p170). Analytic touch, on the other hand, is performed to “gain an exhaustive impression of the object’s features” Appelle, 1991, p170).

However, prior to the late 80's, researchers had not conducted a detailed examination of the interaction between the object attribute being examined and the exploratory behaviour used to examine it. Lederman and Klatzky (1987) had been struck by how well participants could identify real 3-D common objects using only touch (Klatzky, Lederman and Metzger 1985). "We began to suspect that the explorers hand movements might provide the secret to the success with which touch alone can identify common objects" (Lederman and Klatzky, 1993, p30).

Lederman and Klatzky (1987) began to systematically study what participants did with their hands when asked to evaluate a particular object property. In the first of a series of experiments, Lederman and Klatzky (1987) asked participants to feel a multidimensional object i.e. an object that could be evaluated with respect to a number of it's properties: texture, hardness, temperature, weight, volume and shape. They asked the participants to judge an object on the basis of one of these properties and then, on the basis of that property, select a match from a series of comparison objects. The participants' hand movements were videotaped for subsequent analysis. The results indicated that, "although subjects were usually unaware of what they did with their hands, the movements themselves were both purposive and systematic". (Lederman and Klatzky, 1993, p30) They called these hand movements 'exploratory procedures' (EPs) An EP is, "a stereotyped movement pattern, having certain characteristics that are invariant and others that are highly typical" (Lederman and Klatzky, 1987, p342). The EPs identified by Lederman and Klatzky (1987) are depicted in figure 1.1



**Figure 1.1 Exploratory procedures and their associated object properties as identified by Lederman and Klatzky (1987). Picture taken from Lederman and Klatzky (1993)**

Lederman and Klatzky (1987) reported a further experiment to further delineate the characteristics of the EPs. Participants were asked to perform the same property-matching task as before, but on this occasion the experimenter instructed the participants to use a particular EP with the designated object property. This procedure was repeated so that all the participants examined each object property with every EP. Lederman and Klatzky categorised each EP by its accuracy in matching the object attributes used in the study. An EP was assigned a value 3 if it was necessary to judge an object property; it was assigned a value of 2 if the EP was optimal for judging the property, and a value of 1 if the EP could match the property at above chance level. Finally, an EP was assigned a value of 0 if it could not match the property at above chance level. The ratings ascribed to the EPs for the various object properties are noted in figure 1.2. Lederman and



Klatzky (1987) also noted the breadth of sufficiency of each EP, that is to say the number of properties that each EP could judge above chance level. The average time required to judge the properties with each EP was also noted. This is displayed in Figure 1.3

	Texture	Hardness	Temperature	Weight	Volume	Global shape	Exact shape
Lateral Motion	2	1	1	0	0	0	0
Pressure	1	2	1	0	0	0	0
Static contact	1	0	2	0	1	1	0
Unsupported Holding	0	1	1	2	1	1	0
Enclosure	1	1	1	1	2	2	0
Contour Following	1	1	1	1	1	1	3

**Figure 1.2 The amenability of EPs to property matching judgments. Table taken from Lederman and Klatzky (1993)**

	Duration (s)	Breadth of sufficiency
Lateral Motion	3.46	3
Pressure	2.24	3
Static Contact	0.06	4
Unsupported Holding	2.12	5
Enclosure	1.81	6
Contour Following	11.20	7

**Figure 1.3 The average time taken to perform an EP together with the breadth of each EPs sufficiency. Table taken from Lederman and Klatzky (1993)**

Lederman and Klatzky found that the pairing of an EP to a particular object property was not an accident, "In general, the procedure people used to ascertain an object dimension during free exploration was the optimal one (in terms of providing the greatest accuracy, or when their was a tie, speed)" (Klatzky and Lederman, 1987, p429).

Lederman and Klatzky (1990) found that participants tended to use a two-stage sequence of exploratory procedures when identifying common objects,

such as a comb, a can opener or a pair of glasses. Initially participants would tend to use the most broadly sufficient EPs that could provide rough information about most object properties quickly i.e. unsupported holding and enclosure. Participants would then move on to using an EP that was optimal for judging the property most diagnostic of the targeted object class. Further investigation by Klatzky and Lederman (1999) confirmed that the participants use of the unsupported holding and enclosure EPs was sufficient to produce above chance level identification of the stimuli and that the second stage of EPs were executed to increase the accuracy and confidence of the participants decisions.

### **1.3 The haptic perception of object attributes**

The following section provides an overview of the literature on the haptic perception of object attributes in the real world relevant to the reported experimentation. Any object is comprised of a number of attributes, or properties, (the two terms are used interchangeably). Lederman, Summers and Klatzky (1996) make the distinction between an object's 'material properties' e.g. texture, temperature and hardness, and 'geometric' properties e.g. shape and size.

There were a number of criteria underlining the selection of the attributes chosen for study. Firstly, the attribute had to be amenable to presentation in VR with the PHANTOM™. This precludes the use of attributes such as temperature, as no force feedback device, PHANTOM™ included, can relay this information to a user. Secondly, the author felt that in the interests of providing a reasonably broad contribution to the field, it would be interesting to look at the perception of one or more examples from the material and geometric categories of object attributes proposed by Lederman et al (1996).

Some of the object attributes mentioned above are divisible into subclasses. For example, the shape of an object or, 'object form', which refers to an object's spatial layout (Appelle, 1991). As Appelle (1991) points out, object form itself is comprised of a number of attributes: "an isolated contour can be described in regard to its extent and its position (or orientation). Contour interactions.... can be described in regard to contour number (form complexity), angle, relative extent, (proportion)" (Appelle, 1991, p176).

The specific object attributes chosen for study were: the perception of texture, specifically the roughness of texture, and the perception of size (extent) and angular extent. Their selection was influenced both by their importance as constituents of any object per se and also on the available literature regarding how they are perceived haptically, both in the real world and VR. For all of the attributes studied in this thesis, there is some, albeit not always a great deal, of literature concerning the way they are perceived in the real world, which provides context for their study in VR. There is also some work on the perception of the above attributes in VR, some of it forming part of the early stage of the Teletouch project, which used a different device (the IE3000).

Thus, first and foremost, the selection of these attributes was to provide a preliminary account of the perception of these attributes with the PHANTOM™ device. However, their use also permitted the role of the specific device used on haptic perception in VR to be addressed. This parameter of haptic perception in VR is addressed in more detail subsequently, after exposition of the relevant real world based literature and the introduction to haptic VR in section 1.9.

## 1.4 The haptic perception of texture

“Texture refers to most of the physical properties of objects, fluids and substances excluding large scale shape. Texture does not include temperature, but it does include such attributes as surface roughness, hardness, elasticity and viscosity” (Loomis and Lederman 1986, p32-26).

Despite the fact that the haptic perception of texture is an activity familiar to us all, Lederman (1982) notes that little research into texture perception was undertaken until the 1960s and that, in the field of texture perception, the perception of the textural property of roughness has received nearly all of the attention of researchers.

Much of what is known about texture perception has been discovered using methodology derived from the paradigm of psychophysics. Psychophysics is the study of the “relationship of the sensation (psychological effect) to the Physical stimulus” (Snodgrass and Levy-Beger, 1985, p59). Snodgrass and Levy-Beger (1985) provide a good source for work using psychophysical methodology.

Psychophysics is concerned with two primary questions. The first question concerns the perceptual limits of a particular sensory modality for a given stimulus. The second question concerns the relationship between variations in a physical parameter of a stimulus and the sensation that the stimulus produces. Over the years, psychophysicists have attempted to resolve these questions by examining three primary perceptual tasks, those of: stimulus detection; stimulus discrimination and stimulus scaling. The subject of scaling is described in some detail here, as it is methodology used in the studies of texture perception reported in chapter two.

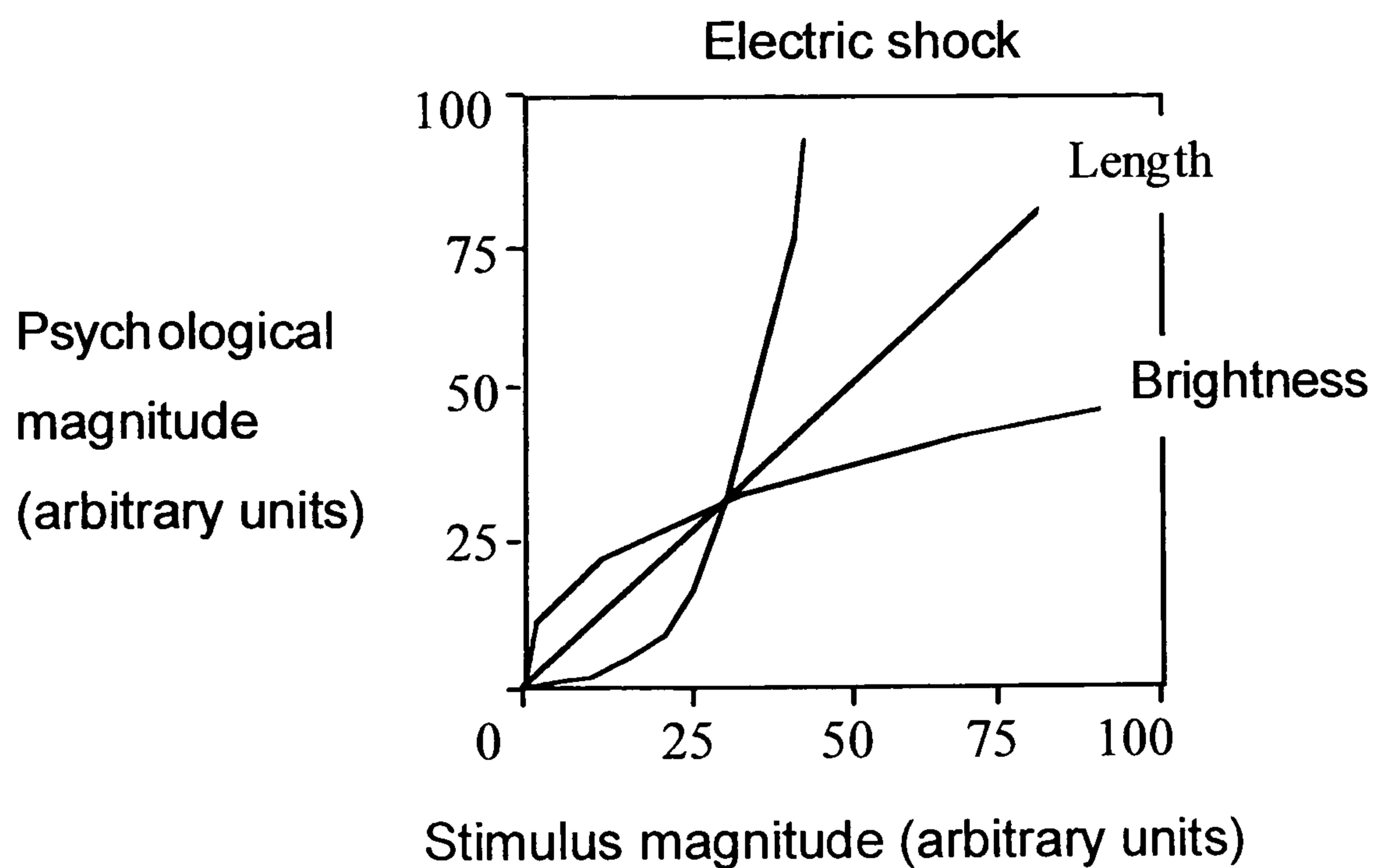
The purpose of scaling in psychophysics is to uncover the psychophysical function, that is: “the relationship between the physical intensity of such simple stimuli as lights tones and temperature and their corresponding psychological intensities” (Snodgrass and Levy-Beger, 1985, p75). In experiments 1 and 2 it is used to obtain the psychophysical function relating perceived roughness to the physical properties of a textured surface.

Stevens (1957) devised a technique for the scaling of stimuli known as ‘magnitude estimation’. Using the stimulus intensity property of volume and the sensation of loudness as an example, an experiment using the magnitude estimation procedure would work in the following way. The participant would first assign an arbitrary number to the perceived loudness of a baseline (standard) sound. The number the participant ascribes to this sound is referred to as the modulus. The participant would then be presented with a series of sounds, differing in their respective volumes. After being presented with each sound, the participant would be asked to ascribe that sound with a number that reflects how loud they perceived it to be relative to the baseline sound. So, for example, in the above hypothetical example, if the participant assigned the baseline stimulus with a loudness value of 10 and thought the following stimulus to be twice as loud they would assign it a value of 20. Conversely, if they thought it was half as loud they would assign it a value of 5.

Stevens applied the magnitude estimation technique to an array of perceptual continua (e.g. brightness, loudness, heaviness) and found that a power law best described the relationship between the physical stimulus intensity and the intensity of the resulting sensation. Thus, Steven’s Law states the relationship between the perceived magnitude of a physical characteristic (S), is proportional to the actual magnitude of the physical characteristic of the stimuli (P) raised to some power (b) thus:

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

The value 'a' reflects the number the participant ascribed the standard stimulus. The value 'b', is referred to as the exponent. It describes the relationship between the perceived magnitude of the physical stimuli and the actual magnitude of the physical stimuli. An exponent of more than 1 indicates that the perceived intensity of the stimuli will increase more rapidly than the actual intensity of the Stimuli. This is the case with the exponent for electric shock (shown in figure 1.4). The converse of this applies when the exponent is less than 1. This is the case for the exponent for brightness (shown in figure 1.4). An exponent of 1 means that the perceived intensity of the stimulus increases at the same rate as the physical intensity of the stimuli. This is the case for the exponent for apparent length, also shown in figure 1.4). Thus, the exponent for a stimulus is also referred to as the psychophysical function.



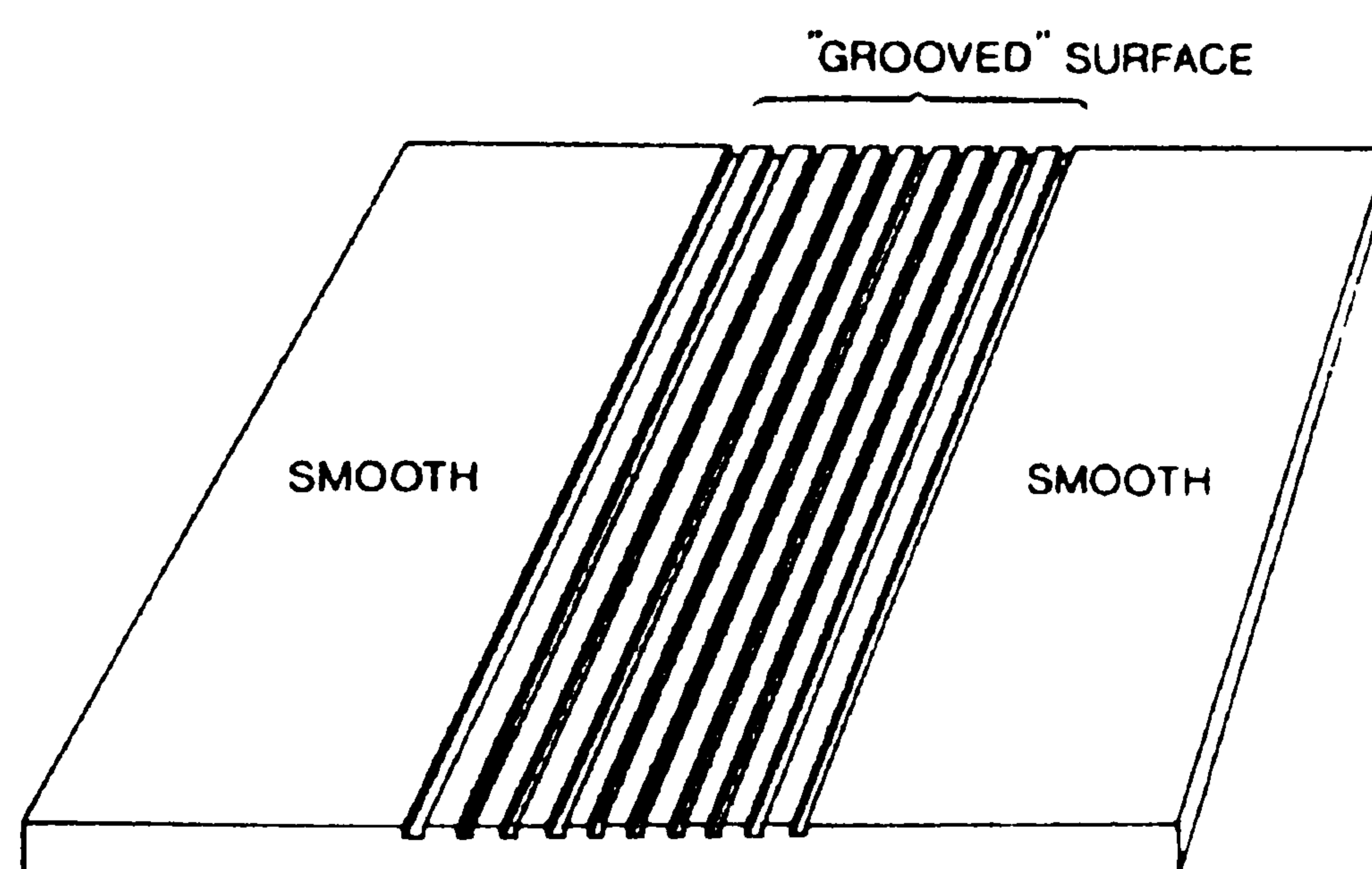
**Figure 1.4 Psychophysical functions for electric shock, apparent length and brightness. Picture taken from Snodgrass and Levy-Beger, 1985, p79**

### 1.4.1 The haptic perception of Roughness

Loomis and Lederman (1986) define roughness as: “undulations or protrusions of a surface that are of a much smaller scale than the fingertip, but large enough to permit tactual discrimination between the surface in question and one that is smooth” (p31-27).

Stevens and Harris (1962) reported an experiment in which they used the magnitude estimation procedure to investigate roughness perception. In this experiment, participants made magnitude estimates of both the roughness and smoothness of sandpapers of different grit values by sweeping their index and middle fingers across the stimuli. Grit value refers to the number of openings per inch in the sieves used to produce the sandpaper. The value corresponds to the diameter of the particles of which a paper is comprised and the spacing between those particles: the higher the grit number the larger the particles and the greater the spacing between them. The results of the experiment showed that perceived roughness increased with decreasing grit values i.e. with larger particles and greater particle spacing. Conversely, perceived smoothness decreased with higher grit values i.e. with smaller particles and narrower particle spacing. The exponents for roughness and smoothness judgments were equal, indicating that roughness and smoothness are reciprocally related. In other words, in identifying one stimulus as rougher than another, one is implicitly saying that remaining stimulus is smoother and vice versa. This may seem slightly obvious, but not all sensations that one may think lie at opposite ends of the same perceptual continuum necessarily do. For example, the exponents for the sensations of warmth and cold differ notably, thus warm and cold refer to two sensory continuums, not opposite extremes of one.

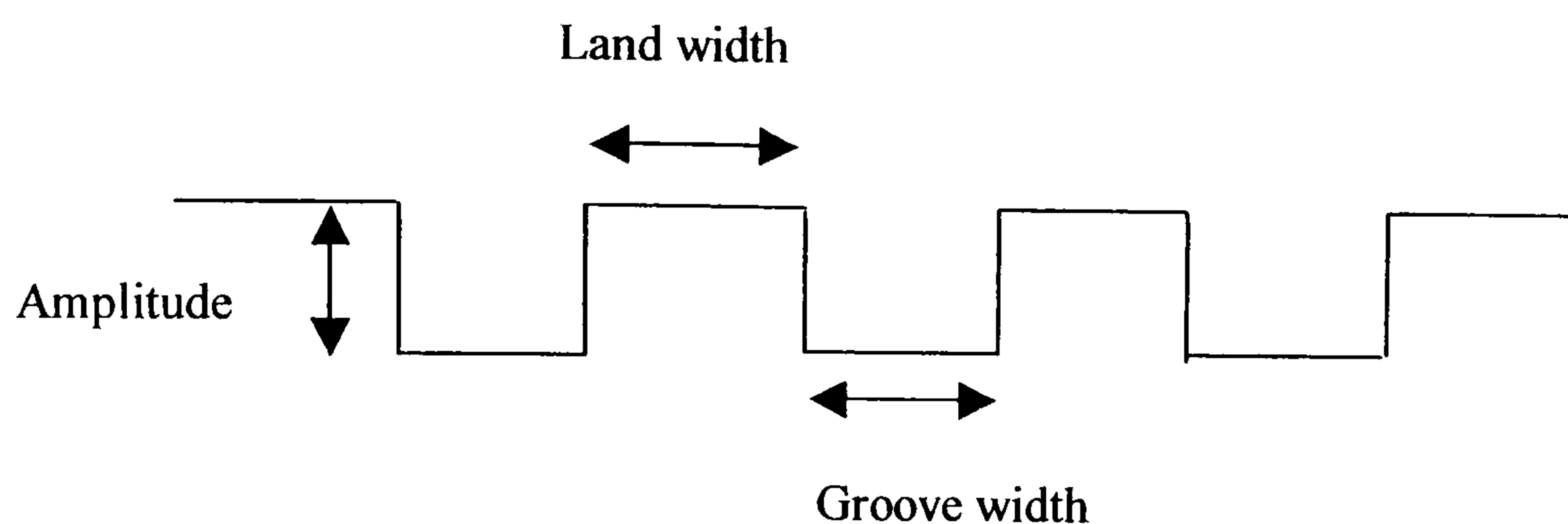
The vast majority of what is known about roughness perception can be credited to the work of Lederman and her colleagues (e.g. Lederman and Taylor, 1972; Lederman, 1974; Lederman, 1981; Lederman, Thorne and Jones, 1986; Lederman and Klatzky, 1999). In a research programme ongoing for some 30 years, Lederman and her colleagues have conducted numerous experiments to determine the role of the physical parameters of texture stimuli and the parameters relating to a participant's interaction with the texture stimuli, on the perception of roughness. The following sections overview the literature on both the stimulus related and interaction related determinants of perceived roughness. Unless otherwise stated, the reader can assume that the texture stimuli used was metal plates featuring a section of rectangular waveform grooves of a given specification etched into them (shown in figure 1.5).



**Figure 1.5 An illustration of a rectangular waveform texture. Picture taken from Lederman and Taylor (1972)**



This type of texture stimuli is specified by three physical parameters: the width of the grooves (groove width); the width of the spaces that separate the grooves (land width); and the depth of the grooves (amplitude). These parameters are shown in figure 1.6 on the following page.



**Figure 1.6 Enlargement of the profile of a rectangular waveform texture**

### **1.4.2 Stimulus related determinants of perceived roughness**

- Groove width

Groove width has consistently been shown to be the most important determinant of perceived roughness (Lederman, 1974; Lederman, 1981; Lederman and Taylor; 1972; Taylor and Lederman, 1975). In these experiments, participants were asked to sweep one or more fingers across a series of rectangular waveform textures and give magnitude estimates of their perceived roughness. The textures differed in their respective groove widths (between .125mm and 1.4 mm), the amplitude of the textures was held constant. The results of these experiments invariably indicated that groove width had a highly significantly affect on the participants perception of

the roughness of the respective textures, with perceived roughness increasing as a function of increasing groove width.

- Spatial period

With the rectangular waveform stimuli, an increase or decrease in groove width results in a concomitant increase in what Loomis and Lederman (1986) refer to as 'spatial period', this is, "the sum of groove width and land width" (1986, p31-28). In order to distinguish the effect of increments in groove width per se from the effect of increments in spatial period, Lederman and Taylor (1972) asked participants to examine the effect of two sets of reciprocal textures. The groove width specifications for the first set of textures, in which groove widths were varied, but the land width was held constant became the specifications for the land widths of the second set of textures, in which the land widths varied across the textures, but the groove width was held constant. Thus, spatial period increased with groove width in the first set of textures and with land width in the second. If spatial period were the primary determinant of perceived roughness, the participants' perception of the roughness of the corresponding plates in the two sets would not differ significantly. The results of the experiment indicated that in the set of textures in which groove width was increased and land width was held constant, perceived roughness increased with increases in groove width. However, in the set of textures in which land width was manipulated and groove width held constant, perceived roughness decreased with increasing land width. The impact of increments in land width on perceived roughness was less notable than equal increments in groove width, suggesting that "although, both variables influence apparent roughness, groove width is the more influential of the two" (Lederman and Taylor, 1972, p405).

- Friction

An individual might intuitively believe that the amount of friction between a person's fingers and a textured surface is a primary determinant of perceived roughness. Friction is, "the ratio between a force along the interface and a force across (perpendicular to) the interface. The forces may be determined when the surfaces are in smooth relative motion, in which case the coefficient is called the dynamic coefficient of friction, or they may be measured in the condition where the lateral force is the largest force that does not cause the objects to slide against one another, in which case the coefficient is called the static coefficient of friction" (Taylor and Lederman, 1975, p35). To investigate the role of friction in perceived roughness, Taylor and Lederman (1975) asked participants to make magnitude estimates of the roughness of rectangular waveform textures under two conditions: a low friction condition, in which the textures were lubricated with a detergent; and a high friction condition, in which the participants examined the same textures dry. The participants' magnitude estimates of roughness did not differ significantly between these conditions, indicating that friction is not an important determinant of perceived roughness.

### **1.4.3 Exploration related determinants of perceived roughness**

Any examination of a textured surface involves parameters relating to the person's interaction with the parameters of the stimuli. For example, individuals may vary the force they apply to the surface of the texture, or the rate at which they move their fingers across the textured surface. The question is: do these interaction related parameters affect perceived roughness. The literature on this issue is reviewed in this section.

- Contact force

Lederman and Taylor (1972) investigated the impact of the amount of contact force participants apply to a texture on roughness perception. This was achieved by asking participants to examine rectangular waveform textures under three contact force conditions: 1 oz, 5 oz and 25 oz. Control over the contact force being applied to the textures was achieved by a balance arm apparatus. This featured a texture on one end of the arm and a weight corresponding to the desired contact force on the other end of the arm. By counterbalancing the weight whilst examining the textured plates, the participants were exerting the desired amount of contact force.

The results indicated that contact force had a significant effect on perceived roughness: the perceived roughness of a given texture increased with increasing contact force. The interaction between groove width and contact force was also significant; the impact of contact force became more pronounced as groove width increased.

Lederman (1974) examined the impact of contact force in more detail. Specifically, she addressed the questions of how much contact force individuals normally apply to a texture in making a judgment of its roughness when left to their own devices, and if there was any relationship between the variables of contact force and groove width. Lederman (1974) asked participants to examine a series of rectangular waveform textures in three contact force conditions. In a 'low force' condition, a contact force of 1oz, was imposed upon the participants examination of the textures. In a 'high force' condition, a contact force of 16oz, was imposed upon the participants examination of the textures. In the remaining condition, participants were allowed to determine the contact force they wished to apply to the textures, which was monitored by the experimenter.

Contact force was, once again, found to be a significant determinant of perceived roughness. The high force condition yielded the greatest estimates of perceived roughness, followed by the free force condition, then the low force condition. The average force applied by the participants in the free force condition was slightly higher than that of the low force condition (2.44 vs 1 oz). With regard to the question of the relationship between groove width and applied contact force, the results indicated that finger force increased significantly with groove width.

- Scanning velocity

Another parameter relating to an individual's interaction with a textured surface is that of the velocity of the relative motion between the individual's finger/s and the texture. Relative motion between the hand and a textured surface had long been held as a prerequisite for roughness perception (Katz, 1925, cited from Lederman 1982). However, the implications of different scanning velocities on roughness perception had not been comprehensively investigated.

Further impetus to examine the variable of scanning velocity came from the notion that the frequency of the vibrations generated by the leading edges of the lands of the textures might be the critical determinant of roughness perception. Lederman and Taylor (1972) had already gone so far as to suggest that vibratory frequency is not significantly implicated in determining perceived roughness. In that experiment, two reciprocal sets of textures were used, with spatial period increasing with groove width in the first set and a directly corresponding increase in spatial period with land widths in the second set. Thus, the temporal frequency of the vibrations between the two sets were identical, yet perceived roughness increased with groove width, but decreased with land width.

However, there was a more ecologically valid method of assessing the impact of vibratory frequency on perceived roughness, which entailed manipulating the scanning velocity at which the participants examined the textures. Lederman (1974) asked participants to examine rectangular waveform textures, at three exploratory rates: 1,5 and 25 cm. per second. The results indicated that scanning velocity significantly affected perceived roughness. The textures examined at the highest scanning velocity were judged as smoother than the same textures examined at the lowest and intermediate scanning velocities, which yielded similar estimates of roughness for the respective textures. Although the effect of exploratory speed was statistically reliable, Lederman (1974) noted that its effect on perceived roughness was small compared to the effect of groove width. The effect of exploratory speed was equivalent to 1 tenth of 1 log unit increase in perceived roughness for a twenty-five fold change in scanning velocity. This contrasts with a four tenths of a log unit increase in perceived roughness per doubling of groove width and a 1-2 tenths increase in perceived roughness per nine fold alteration in contact force (Lederman 1974).

- Active vs passive movement

It could be argued that the relatively small impact of scanning velocity does not necessarily indicate that vibratory frequency does not exert a significant influence on perceived roughness, but rather that participants are simply able to take scanning velocity into account when making their judgments based on vibratory frequency. Lederman (1983) reasoned that if this were the case, then differences in the impact of scanning velocity on roughness perception should be evident according to whether participants moved their fingers over the textures or had the textures moved under their stationary fingers. To test this hypothesis Lederman (1983) conducted an experiment in which participants made magnitude estimates of the roughness of rectangular waveform stimuli at three scanning velocities (1.7, 6.6, 20.6 cm per second).

For each scanning velocity, Lederman also manipulated whether the participants moved their finger across the textured surface (active condition); or the surface was moved beneath the participant's stationary finger, which was secured by a brace (passive condition). "If the speed constancy explanation is correct there should be relatively little effect of hand speed on roughness perception with active touch; however there should be a strong effect when speed was varied by moving the gratings under the stationary skin" (Lederman, 1983, p500).

The results of the experiment indicated that there were no significant differences between the active and passive conditions under any of the scanning velocity conditions, in terms of either the perceived roughness of the respective textures, or the consistency of the participants' responses between different experimental sessions. This result undermined the notion that participants were using vibratory information in making roughness judgments and simply taking account of scanning velocity in the process. Lederman (1981) conducted a study to establish if active versus passive movement qualified the impact of contact force on perceived roughness. In this study, participants made magnitude estimates of the textures using three contact forces (28, 112, 224g) under the same active and passive conditions used in Lederman (1983). There was no significant effect of exploration mode for any of the contact force conditions. Thus Lederman (1981) concluded that the finding that active and passive modes of exploration do not yield not significantly different roughness judgments.

#### **1.4.4 A model of roughness perception in the real world**

Taylor and Lederman (1975) posited a model of roughness perception based on the results of Taylor and Lederman (1972), and Lederman (1974). The

model stated that the sensation of roughness could be attributed to the deformation of the skin caused by the surface irregularities that characterize a texture. Taylor and Lederman (1975) examined the shape that the skin assumed when subjected to the various forces inherent in examining a textured surface. This examination yielded a total of 11 parameters of skin deformation that could give rise to the percept of roughness. The effect of variables such as groove width, land width and applied contact force on these parameters of skin deformation, could then be contrasted with the effect of those variables on perceived roughness.

Taylor and Lederman (1975) found that the parameter of skin deformation that best accounted for the effects of, for example, groove width and contact force was the cross sectional area of the deviation of the skin from its resting area. This parameter increased as a function of groove width and applied contact force and decreased as a function of land width. It also accounted for why fundamental vibratory frequency per se did not exert a significant impact on perceived roughness (Lederman, 1974). The model also yielded the hypothesis that friction would not exert a significant effect on perceived roughness, which was supported (Taylor and Lederman, 1975).

## **1.5 The haptic perception of extent**

The perception of extent i.e. “lengths or distances that vary along a single spatial dimension” (Armstrong and Marks, 1999, p 1211) has long been of interest to researchers. However, Appelle (1993) notes that, “Only a small number of investigations have looked at judgments of extent as a function of haptic activity” (p176).

Some studies of the haptic perception of extent have compared estimates of extent gained from the use of different methods of haptically examining the stimulus. For example, Jastrow, (1886, cited in Appelle 1993 and Seizova-



Cajic, 1998) asked participants to make estimates of various extents in the form of cubes, with edge lengths ranging between 1 and 11cm. The estimates were made under a number of conditions. In one condition, the participants held the cubes between their thumb and forefinger. In another condition, participants guided a pencil over the same distances. In a final condition, the participants had their arm moved over the extents by the experimenter. Jastrow (1886) found that the type of movement influenced the participants' judgment of extent. For example, Appelle (1993) cites that Jastrow found that, "a distance between thumb and forefinger appeared to be equal to an objectively shorter (by 68%) distance covered by the moving arm" (Appelle, 1993, p176).

Hohmuth, Phillips and Van Romer (1976) asked participants to haptically examine wooden dowels measuring 20mm, 30mm and 45mm under two conditions. In one condition, the participants grasped the stimuli between the thumb and index finger (referred to as the kinaesthetic condition). In the other condition, the participants stroked the stimuli from end to end with the index finger (referred to as the haptic condition). Having explored the stimuli, the participants' task was to visually choose a match to that stimulus from a series of comparison dowels. Both modes of exploration produced underestimates of extent, however the condition in which the dowels were explored via the thumb and forefinger consistently produced smaller estimates. In both conditions the magnitude of the error tended to decrease with increasing stimulus size.

Stanley (1966) asked participants to give magnitude estimates of the extent of haptically examined rods, ranging between .70 and 33 inches (1.78 - 83.82 cm), under two conditions. In one condition, the participants held the stimuli between their index fingers. In the other condition, the participants had their index fingers separated by experimenter such that the distance between them corresponded to the extents of the rods used in the study. The

exponents relating perceived extent to actual extent obtained for the participants in the latter condition were consistently smaller than the former condition. The perceived extent of the rods was greater in the latter than the former condition, however this effect diminished with increasing stimulus size. However, it should be noted that this experiment confounded the availability of both cutaneous and kinaesthetic information with the active/passive nature of the exploratory movements. This was because the participants in the haptic condition provided the movement used in exploring the stimuli, whereas the experimenter provided the movement in kinaesthetic condition.

Roeckelein (1968) also asked participants to make magnitude estimates of the perceived size of a series of cubes, with edge lengths ranging between 3-4.5 inches (7.62-11.43 cm) and spheres, with diameters ranging between 1.25-5 inches (3.17-12.70 cm). No instructions were given as to what type of method of exploration the participants should use in examining the stimuli. Roeckelein (1968) found similar exponents for the size estimation of spheres and cubes. Interestingly, he also noted that participants were spontaneously using their fingers "in the manner of a ruler" (p296) i.e. as a fixed reference against which the size of the stimuli could be judged. Jones (1983) asked participants to give magnitude estimates of a series of blocks with widths ranging between .39-8.89cm. He found a positive exponent relating actual block width to perceived extent for blocks perceived with one hand and a slightly higher positive exponent when the combined width of 2 blocks (one held in each hand) was determined. Teghtsoonian and Teghtsoonian (1970) also found a positive exponent relating the perceived width of blocks grasped between the thumb and forefinger.

Seizova-Cajic (1998) asked participants to reproduce verbally specified extents by drawing a line of corresponding extent, without the aid of vision. The results of the experiment indicated that participants underestimated the

verbally specified extents. The degree of underestimation was found to increase with increasing stimulus size.

Appelle and Graveter and Davidson (1980) asked participants to determine whether the lengths of wooden dowel rods ranging between 4.8 and 19.2 cm were the same or different to a series of comparison rods, the size of which varied between 1.2 to 36.6 cm. Participants examined the stimuli under one of three conditions. In one condition, referred to as the 'unrestricted condition', participants were allowed to examine the rods in any way they wished. In another condition, referred to as the 'no measuring condition', participants were allowed free exploration of the stimuli, with the exception that the use of their hands or fingers as a measuring device to compare the pairs of rods to directly was prohibited. In a final condition, referred to as 'the measuring condition', participants were told to orientate their scanning activity in order to measure the stimulus extents. However, they were not told how to achieve this. The results indicated that participants were most accurate in matching the identifying whether the standard rods were the same or different from the comparison rods in the "measuring" condition. The results also indicated that the accuracy of the participants' responses increased with stimulus size.

Lederman Klatzky and Barber (1985) Conducted a series of experiments in which participants made haptic judgments of Euclidean line extents ranging from 2.5 to 15.2cm, under two conditions. In one condition, the participants traced their right index finger back and forth along the Euclidean line as often as they required. This was referred to as the 'no anchor' condition. In the remaining condition, participants were permitted to place their left index finger on the start of the line while they used their right index finger to explore the length of the line as before. This was referred to as the 'anchor' condition. Their responses to the various length lines were gauged under two conditions. In one condition, the participants placed their left index finger on

a marker and placed their right index finger directly (without sliding the finger) to a distance from the left finger that they felt represented the length of the stimulus. This was called the 'static response condition'. Alternatively, participants slid their right index finger from their left finger to the position such that the distance between their fingers corresponded to their perception of the length of the line. This was called the 'dynamic response condition'. The participants' estimates of extent in the anchor condition were more accurate than the estimates of participants in the no anchor condition when participants used the static response method. However, they were marginally worse in the dynamic response condition. In all instances, the estimates of line extent tended to become more accurate with increasing line extent.

There is a small amount of literature that indicates that perceived extent varies according to the speed of exploratory motions in both passive movement (Wapner, Weinberg, Glick and Rand, 1965) and active movement (Hollins and Goble (1988)). Wapner et al (1965) asked participants to explore a 40cm horizontal extent divided into two equal 20cm portions. The experimenter manipulated the speed at which the participants explored each of the portions (either 4cm or 5cm per second). Participants were asked to adjust a marker to indicate at what point the two extents seemed equal. Participants tended to shift the marker in the direction of the portion of the extent explored at a slower speed, thus a 20 cm extent appeared shorter when explored at a faster speed than the same extent explored at the slower speed. Hollins and Goble (1988) asked participants to give magnitude estimates of a series of metal rods, of lengths varying between 1.5 and 65.7 cm. The participants were asked to examine the rods by sliding their index finger along their extents at different speeds, specified by the experimenter. Magnitude estimates of extent increased with actual extent, but decreased with increasing velocity.

## 1.6 The haptic perception of angular extent

Lakatos and Marks (1998) state the importance of the veridical perception of angular extent pointing out that any object “can be reduced to a series of lines or curves intersecting at select locations to form contours edges and vertices” (p738). They go on to say that, “an error in estimating the angle between two lines, for example, would bias one’s interpretation of the spatial locations of all subsequent features” (p378).

However, the haptic perception of angular extent has not received a great deal of attention from researchers (Lakatos and Marks, 1998). Appelle (1971) conducted a study in which subjects were asked to haptically examine and reproduce a series of angles. These angles were formed by two wooden arms, joined at their ends. The arms were mounted on a board with one of the arms fixed in a horizontal orientation. Moving the remaining arm in a clockwise or counter clockwise arc could create any angle between 0 to 180 degrees. Using this apparatus, the experimenter gave the participants a series of angles ranging from 30 to 150 degrees (in 15° increments) to examine. The participants’ task was to adjust a second pair of arms to a point where the angle they formed corresponded to that of the first set of arms. The results indicated that participants tended to underestimate the angle of the standard stimulus for all but the most acute angle presented (40 degrees). The magnitude of the participants’ errors in reproducing the standard angular extents also tended to increase with increasing angular extent.

Lakatos and Marks (1998) conducted an experiment in which participants were asked to haptically examine the apex angle of a series of wooden triangles and raised line depictions of these triangles. The angles used ranged between 60 and 115 degrees in equal increments of 5 degrees. The

participants were asked to examine the apex angles by sweeping their fingers across the upper two sides of the triangles. They were then asked to verbally estimate the apex angle. The results indicated that participants tended to underestimate the angular extent of the apex of the triangles, for all but the most obtuse angles. The participants estimates also tended to be inversely related to angular extent i.e. the bigger the angle the smaller the underestimate. The experimenters also noted “a modest tendency to underestimate to a greater extent with two hands as opposed to one” (p744). There was no significant difference in the estimates derived from the 3-D stimulus and the 2-D raised line depictions.

MacLean and Stacy (1971, cited from Stacy and MacLean, 1972) reported similar results to those of Lakatos and Marks (1998). In this instance, participants gave verbal estimates and haptic reproductions of haptically examined angular stimuli. MacLean and Stacy (1971) found that, “the verbal estimation and matched response modes yielded judgments proportional to, and on average an underestimation of angular extent” (Stacy and MacLean, 1972, p296).

The majority of the work on the haptic perception of angular extent has been directed at the haptic ‘Oblique effect’. This refers to the finding that the haptic perception of vertical and horizontal stimulus orientations are perceived more accurately than oblique orientations (e.g. Lachelt and Verenka, 1980; Gentaz and Hatwell, 1995; Gentaz and Hatwell, 1998; Kappers and Koenderink, 1999; and Kappers, 1999). Lachelt, Eliuk and Tanne 1976, (cited from Appelle, 1991) asked participants to examine the orientation of a rod, which could be rotated through 360 degrees, with one hand and adjust a comparison rod to the same orientation with the other hand. “Participants were significantly more accurate in matching horizontal and vertical standards, whether by scanning the two rods simultaneously (one with each hand) or by setting the comparison rod to an angle specified by the

experimenter” (Appelle, 1991, p178). Lechelt and Verenka (1980) obtained the same outcome under conditions whereby participants examined the standard rod and then adjusted the comparison rod successively, as opposed to simultaneously.

Appelle and Countryman (1986) argued that the oblique effect could be attributed to the fact that in Lachelt and Verenka’s (1980) study, observers used different hands to match the response rod to the standard. They argued that under such ‘bilateral’ scanning conditions, the type of movements performed by the two hands were different for matching oblique orientations, but not for matching vertical or horizontal orientations. They replicated Lachelt and Verenka’s (1980) experiment and added a ‘unilateral’ condition, whereby subjects interacted with the standard and response rods using the same hand. The oblique effect was apparent in the bilateral condition, but absent in the unilateral condition.

Gentaz and Hatwell (1995) conducted a study in which participants were asked to match rod orientations in either the “horizontal plane (like the surface of a table), as in Appelle and Countryman (1986), or in the frontal plane (like the surface of a blackboard on a wall), as in Lachelt and Verenka (1980), or in the sagittal plane (in the median plane, passing through the midline of the subject’s head)” (Gentaz and Hatwell, 1998, p158). In the sagittal plane, the same pattern of movements are produced by the hand/s when exploring the standard and subsequently adjusting the response rod. However, the oblique effect was found in the sagittal plane, irrespective of whether the matching task was performed with one or two hands. The effect was not evident in the horizontal plane, however. These results did not support the conclusions reached by Appelle and Countryman (1986). Gentaz and Hatwell (1995) indicated that the oblique effect might be due to the magnitude and variability of gravitational cues provided by the hand and arm when interacting with the stimulus, as these were not consistent between the

different planes of exploration. Specifically, they argued that if gravitational cues as to vertical and horizontal orientations were reduced, as was the case when the rods appeared in the horizontal plane, then the oblique would disappear.

Gentaz and Hatwell (1996) conducted an experiment to clarify the role of such gravitational cues. Participants were asked to use the same hand to reproduce the orientation of a standard stimulus rod in the horizontal plane under two conditions. In one condition, the participants' forearms were supported by a horizontal surface, as had been the case in Appelle and Countryman (1986) and Gentaz and Hatwell (1995). In the other condition, the participants' forearms were unsupported i.e the participants had to suspend their arm in mid air. In the latter condition, the participant's interaction with the stimuli involved greater gravitational cues as to vertical and horizontal orientations. As Gentaz and Hatwell (1996) predicted, the oblique effect was absent in the supported forearm condition, but present in the unsupported forearm condition. Gentaz and Hatwell (1998) also tested participants in the horizontal, frontal and sagittal planes in either an unsupported forearm condition or a 'lightened forearm condition' in which the weight of the participants' arms was partially counterbalanced. The magnitude of the oblique effect was lowered in the latter condition. Gentaz and Hatwell (1996) and Gentaz and Hatwell (1998) make a persuasive case for gravitational cues being implicated in the causality of the oblique effect. However, their explanation does not account for why the oblique effect was observed in Appelle and Countryman (1986).

## **1.7 The isotropy of haptic perception: perceived extent**

In examining the literature on perceived extent, an issue of theoretical and applied interest was brought to the author's attention. Armstrong and Marks



(1999) have referred to this issue as, “The isotropy of perceptual space: how uniform is perceptual space over its several possible axis?” (p1211). In the case of HVR, the perceptual space in question is the workspace of the device, which corresponds to what Lederman, Klatzky, Collins and Wardell (1987) refer to as ‘manipulatory’ space or, “small scale layouts explored via the arm system” (p606).

Manipulatory space can be specified in relation to the 3-D axes: x (horizontal), y (vertical) and z (depth). Each of these axes is comprised of two possible directions of movement: left and right in the x-axis, up and down in the y-axis and forwards and backwards in the z-axis. Manipulatory space can also be specified in relation to an individual’s body, “ Consider a cylinder of non-zero radius, the axis of which coincides with that of the upper torso of a person’s body. Radial lines are lines orthogonal to the axis while tangential lines are lines that are tangent to the cylindrical surface” (Loomis and Lederman, 1989, 31-25). Under this definition, for a stimulus placed in front of an individual, a motion in the x (horizontal) or the y (vertical) axes involves tangential movement and a motion in the z (depth) axis involves radial movement.

A good deal of the literature on the haptic perception of extent relates to this issue. Reid (1954) conducted an experiment in which participants were asked to use a stylus to examine one side of a square laid flat on a table surface. Having examined one side, their task was to reproduce the extent on the orthogonal axis of the square. Reid found that participants systematically overestimated the length of the vertical component of the square relative to the horizontal component. He argued that this was a haptic version of the horizontal vertical illusion found in vision. (e.g. Avery and Day, 1969).

Davidon and Cheng (1964) also conducted an experiment in which blindfolded participants were asked to reproduce a series of haptically explored horizontal and vertical extents, presented in the horizontal plane. In agreement with Reid (1954), the results indicated that vertical extents were overestimated relative to equivalent horizontal extents. However, Davidon and Cheng (1964) argued that this was not evidence of a haptic horizontal vertical illusion, but rather a radial tangential illusion (RTE), as vertical extents were examined and reproduced via radial movements, whereas horizontal extents were examined and reproduced via tangential movements. Cheng (1968) extended the findings of Davidon and Cheng (1964) by determining that the RTE persisted regardless of whether the standard and response extents were adjacent or separated by 90 degrees.

Day and Wong (1971) asked participants to adjust the horizontal and vertical components of an L figure to subjective equality under two conditions. In one condition, the L figure was placed in the fronto-parallel plane (i.e. stood upright on its base). In this plane, movement along the vertical and horizontal aspects of the figure was tangential. In the other condition, the L figure was placed in the horizontal plane (i.e. laid flat on the table surface). In this plane, movement along the horizontal aspect of the L figure was tangential and movement along the vertical aspect of the figure was now radial). There was no significant difference between the participants' perception of equality between the vertical and horizontal components and objective equality of these two components when the L figure was presented in the fronto-parallel plane. However, when the figure was laid flat (as had been the case in Reid, 1954), the participants perceived the vertical component of the L figure as being equal to the horizontal component only when they had adjusted the vertical component such that it was, on average, 4.42% greater than the horizontal component. This experiment confirmed the findings of an earlier study by Day and Avery (1970), which also indicated no overestimation of

the vertical component of an L figure relative to the horizontal component when it was presented in the fronto-parallel plane.

The findings of Day and Avery (1970) and Day and Wong (1971) supported the argument of Davidon and Cheng (1964) and Cheng (1968) in that they indicated that it is not the vertical or horizontal components of the stimuli per se that are responsible for the RTE, but rather the type of movement (radial or tangential) that the exploration of these components entails.

Wong (1977) attempted to determine why radial movements were overestimated relative to objectively equal tangential movements. Wong found that participants executed radial movements at a slower speed and for a longer duration than tangential movements. Furthermore, Wong's results indicated that, more often than not, participants were aware that the duration of their radial movements was greater than for tangential movements. However, the participants did not attribute the longer durations of radial movements relative to tangential movements to slower exploration speeds. Therefore, Wong (1977) posited that the RTE could be attributed to the fact that, unbeknownst to the participants, their radial movements are executed more slowly than tangential movements, which they perceive to have been executed at the same speed. This leads to a systematic overestimation of radial extents. Wong (1977) suggested that the slower radial movements could be attributed to the greater moments of inertia associated with radial movements than with tangential movements of equivalent extent.

Marchetti and Lederman (1983) also found that participants performed radial movements at a slower speed and for a longer duration than objectively equivalent tangential movements. However, they systematically altered the moments of inertia associated with radial and tangential movements by, for example, changing the mass of the exploring hand. The results indicated that

the RTE could not be accounted for by differences in the moments of inertia associated with radial and tangential movements.

Despite recent demonstrations of the RTE, in both 3-D objects and raised line stimuli in addition to further verification that radial movements are executed for longer durations than objectively equivalent tangential movements (Armstrong and Marks, 1999), the basis of the RTE remains a mystery (Loomis and Lederman, 1986; Barac-Cikoja and Turvey, 1995).

## **1.8 Haptic perception and vision**

An issue to be considered in characterising haptic perception in the real world concerns the interaction between haptic perception and vision. There are two predominant research issues stemming from this topic. The first issue concerns the nature of the interaction between the visual and haptic modalities in sighted individuals; the second issue is concerned with establishing if there are any differences in haptic perception between blind and sighted individuals. The focus of the empirical work in this thesis is on addressing the second issue. Therefore the former issue is not taken up in this literature review. It will, however, be briefly addressed in the general discussion (chapter 5).

### **1.8.1 Haptic perception and blindness**

The World Health Organisation defines blindness as: “visual acuity of less than 3/60m or corresponding visual field loss in the better eye with best possible correction” (<http://www.who.int/pbd/pbl/data.htm#definitions>). This means that at a distance of 3 meters, the individual would be unable to discern a figure that an individual with ‘normal vision’ could discern at 60 metres. An individual who meets this criterion is eligible to be registered as being blind in the UK. Use of the term ‘blind’ in this thesis can be taken to

refer to such individuals. The World Health Organisation also identifies the concept of 'low vision', which corresponds to, "visual acuity of less than 6/18m, but equal or better than 3/60m in the better eye with best possible correction" (<http://www.who.int/pbd/pbl/data.htm#definitions>). This means that individuals who meet this criterion would not be able to discern a figure at a distance of six meters that an individual with normal vision could discern at 18 metres. However, they could discern, with the assistance of glasses or contact lenses, a figure at three metres, that an individual with normal vision would be able to discern at 60m. This definition corresponds to individuals whom the RNIB term 'partially sighted' (<http://www.rnib.org.uk/wesupply/fctsheets/shortgu.htm#ps>). The author uses the term partially sighted to encompass individuals who meet the low vision criteria set out by WHO. The term 'visually impaired' will be used to refer to blind and partially sighted individuals as a whole.

An important dimension in defining blindness is the age at which the individual loses their vision. According to Davidson (1986) "the most common distinction made in psychological research is between congenital and adventitious blindness" (1986, p347). Congenital blindness refers to individuals who were "born without sight", (Heller, 1991, p240). Adventitious blindness refers, rather generally, to individuals who "lose their sight later in life" (Heller, 1991, p240).

Some researchers have also made the distinction between 'early blind' and 'late blind' individuals (Worchel, 1951; Davidson, 1976; Heller, 1989a; Heller and Kennedy, 1990) the age at which the distinction is made between these two categories is set at "a somewhat arbitrary age of two years" (Davidson, 1976, p23). The arbitrary distinction between early and late blind individuals is the result of ambiguity as to when infants acquire the capacity for visual imagery, and to what extent any residual elements of visual imagery that remain after infants lose their sight, have an impact upon subsequent

development of haptic perception. This thesis is not dealing empirically with this issue. Therefore, in the descriptions of the participants used in the experimental work reported in this thesis, the term congenitally blind will be reserved for individuals who were blind at birth. The term adventitiously blind will be applied to the participants who lost their vision at any point after birth.

Although there is a wide-ranging literature on haptic perception in blind individuals, it should be noted that experimentation on haptic perception in blind individuals comparable to the experiments reported in this thesis is very scarce. Indeed, investigations into the haptic perception of object attributes such as extent and curvature in blind individuals is very rare per se. Thinus-Blanc and Gaunet (1997) made the distinction between studies of haptic perception in blind individuals that occur in 'manipulation' and 'locomotor' space (p25). This appears to correspond to the distinction between what Lederman, Klatzky and Wardell (1987) refer to as 'manipulatory' space or, "small scale layouts explored via the arm system" (p606) and 'ambulatory' space or, "large scale layouts explored on foot, with the leg system" (p606). This section will concentrate on the literature concerning haptic perception in blind individuals that occurs in manipulatory space, as this describes the space explored by users in VR with a force feedback device.

Some research into haptic perception in blind individuals within manipulatory space have addressed what Thinus-Blanc and Gaunet (1997) refer to as spatial memory tasks, or experiments that have, "examined spatial relationship set-ups that have been actually experienced by participants in proximal spaces... through the haptic modality" (p24). An example of such a study would be that of Hollins and Kelly (1988). In this experiment, congenitally blind and blindfolded sighted participants were asked to memorise the location of five successively presented objects on a circular table. After being asked to use a pointer to indicate the position of these objects from the location in which they were memorised, the participants

were then asked to move to different location around the table and point to the position of the objects. The performance of congenitally blind participants was significantly poorer than that of their sighted counterparts. However, the blind participants' performance increased to that of the sighted participants when the same task involved replacing, as opposed to pointing, to the objects. This was deemed to be because when participants replaced the objects, they could also examine the contour of the table, thus using it as a reference point against which to judge the location of the objects. Dodds and Carter (1983) also found equivalent performance between blindfolded sighted and blind individuals when the participants were asked to verbally describe the position of objects from different locations.

Some experiments have also addressed the 'inferential spatial abilities' of blind individuals. This is defined as "the computation of spatial relationships that have not been actually experienced, but based on those already known (i.e. those belonging to the spatial memory type)" (Thinus-Blanc and Gaunet, 1997, p24). For example, Klatzky, Golledge, Loomis, Cicinelli and Pellegrino (1995) asked blindfolded sighted, congenitally blind and adventitiously blind participants to examine two components of a triangle by tracing their fingers along the extents as many times as they wished. Their task was to infer the length of the third leg of the triangle by positioning their hands such that the distance between them corresponded to the inferred length of the third leg of the triangle. The results indicated that there was no significant difference between both groups of blind participants and the sighted participants in terms of their absolute errors in inferring the length of the third leg of the triangle. Barber and Lederman (1988) and Carreiras and Codina (1992, cited from Thinus-Blanc and Gaunet, 1997) obtained the same outcomes in similar spatial inference tasks.

There is evidence to indicate that blind individuals can identify small patterns (about the size of the fingertip) more efficiently than sighted individuals

(Heller 1989b; Heller and Kennedy, 1990). For example, Heller (1989b) asked blindfolded sighted, early blind and late blind participants to examine a series of simple embossed 2-D figures (measuring 12.5 mm square), such as an 'x' or a '+' with their index finger. They were then asked to select a match from a comparison array. Both groups of blind participants and the sighted participants were not found to differ with respect to the accuracy with which they identified the figures. However, both groups of blind participants performed the matches significantly quicker than the sighted participants.

As has been demonstrated with sighted individuals, (e.g. Magee and Kennedy, 1980), the identification of 2-D depictions larger than the fingertip can also present problems for blind individuals. For example, Kennedy and Fox (1977) found that blind individuals could identify only 12.5% of the raised line drawings presented. Heller (1989b) asked blindfolded sighted, early and late blind individuals to haptically explore raised line drawings of common objects, such as an umbrella, a key and a coat hanger. Initially, the participants were not given any feedback about the drawings; the rate of correct identification was predictably poor for all groups. However, the late blind individuals outperformed the early blind and sighted individuals, whose performance was not significantly different. The participants were then asked to identify the depictions a second time. On this occasion, prior to examining any of the pictures, a list of the names of the objects depicted in the pictures was read out to the participants, (i.e. the object names were not paired with the pictures). The late blind participants significantly outperformed the early blind participants and the sighted participants. Heller argued that the superiority of the late blind subjects probably reflected the fact that they possessed better tactual skills than sighted participants and had more experience of drawings and the rules of pictorial representation, before losing their sight, than did the early blind individuals.



Turning to the perception of angular extent, Gentaz and Hatwell (1998) asked early and late blind adults to examine the orientation of a rod that could be rotated through 360 degrees and then reproduce its orientation on a response rod, using the same hand. The rod was presented in the horizontal plane and the vertical plane. The results indicated that the both groups of blind participants exhibited the oblique effect in the frontal plane, but not the horizontal plane. This was in agreement with a similar previous study involving sighted individuals (e.g. Gentaz and Hatwell, 1995). Lechelt (1998) also observed the oblique effect in blind individuals.

There have been a number of studies that have compared the perception of curvature between blind and sighted individuals. e.g. Blumfield (1937, cited from Davidson, 1986); Hunter, 1954; Davidson, 1972b). All of these studies have indicated that curvature is judged more accurately by blind individuals than their sighted counterparts. Numerous studies have indicated that, in sighted individuals, subjective straightness is actually a concave curve (Rubin, 1936; Crewsdon and Zangwill, 1940; Hunter, 1954; Goodnow, Baum and Davidson, 1971, Davidson, 1972). Hunter (1954) and Goodnow, Baum and Davidson (1971) argued that this was due to the sighted participants confusion between stimulus curvature and the natural concave radial curve of the arm. Davidson (1972) asked sighted and blind participants to examine a series of concave and convex curves ranging in arc height from  $-2$  to  $-8$ mm, in addition to a straight edge. The participants' task was to classify the stimulus as being concave, convex or straight. The blind participants were significantly more accurate than the sighted individuals in classifying the stimuli. Davidson (1986) attributed this to the fact that blind individuals used a more efficient method of exploration for judging curvature more frequently than sighted individuals. This method, referred to as 'gripping', involved the participant curling 3 or 4 fingers around the edge of the curve and sweeping their hand back and fourth. The more veridical perception of curvature using this method was thought to be due to the fact that the gripping strategy

yielded information about surface curvature independent of the radial sweep of the arm (Davidson, 1972). When the sighted participants were instructed to use this method of judging curvature, the performance of the blind and sighted participants was no longer significantly different.

With respect to the perception of extent, Hermelin and O'Connor (1975, cited from Thinus-Blanc and Gaunet, 1997) asked early blind and blindfolded sighted children (between the ages of 10-15) to examine and reproduce a vertical extent. The reproduction was achieved either by the participants reproducing the movement from the same location, indicating the terminus of the movement from a different starting point, or by reproducing the same distance from a different starting point. The results indicated that, "the blindfolded sighted children and early blind children performed similarly in both the reproduction and endpoint location tasks, but early blind children underestimated distance reproduction" Thinus-Blanc and Gaunet, 1997, p26).

Comparisons between blindfolded and sighted participants with respect to their susceptibility to haptic illusions that involve the judgment of extent have also been reported. For example, Hatwell (1960, cited from Davidson 1972b) noted that blind individuals were less susceptible to a tactual version of the horizontal vertical illusion than sighted individuals. In common with Davidson (1972), Hatwell (1960) indicated that the difference between sighted and blind individuals could be attributed to the different scanning styles used between the two groups of participants. The blind individuals tended to avoid using a single finger tracing style of exploring the illusory figure, opting instead to press their palms on the figure. When another group of blind participants were restricted to the single finger tracing style of exploration most frequently used by the sighted participants, they proved significantly more susceptible to the illusion. Tsai (1967) and Patterson and Deffenbacher (1972) found that sighted blindfolded participants experienced the Muller-Lyer illusion to a lesser extent than their blind counterparts. However, it is not

clear from these two studies whether the difference between the sighted and blind participants is due to different methods of exploring the illusory figure or some other factor.

Research comparing roughness perception in blind and sighted individuals is also very scarce. Heller (1989a) conducted an experiment in which early blind, adventitiously blind and sighted participants were asked to feel a series of pairs of sandpaper samples, the grit values of which ranged between 80 and 400. The participant's task was to identify which of a given pair was the smoother. Participants were asked to perform this task in an 'active touch' condition and a 'passive touch' condition. In the active touch condition, participants examined the textures using a contact force and scanning velocity of their own choosing. In the passive touch condition, the participants' finger was guided over the textures at a constant contact force and scanning velocity determined by the experimenter. There was no significant difference between the sighted and blind individuals in terms of the number of correct identifications of the smoother stimuli. The effect of the nature of participants' examination of the textures (active or passive) was also non-significant, as was the interaction between this variable and the variable of visual status.

## **1.9 Touch in VR**

An individual cannot simply use touch in VR the same way as they would in the real world. Touching within VR is achieved via a haptic device. A haptic device is a "device that enables manual interaction with VEs." (Srinivasan, 1995, p161). Exactly what touch in VR entails is, therefore, inextricably linked to the type of haptic device being used. The term 'haptic virtual reality' (HVR) will henceforth be used as a generic term for VR that involves touch. It encapsulates haptic devices and VEs that involve both purely haptic

information and haptic information in conjunction with visual and/or auditory information

The following section provides an overview of the main types of haptic devices. A comprehensive source of up-to-date information about haptic interfaces can be obtained at the haptics community web page gallery (<http://haptic.mech.nwu.edu/intro/gallery/>). This section ends with a characterisation of touch with the particular haptic device used in the reported experiments.

Haptic devices can be most broadly classified in terms of whether they convey tactile or kinaesthetic information to the user, “the corresponding difference in VEs is whether the direct touch and feel of objects contacting the skin is simulated or the interactions are felt through a tool.” (Srinivasan and Basdogan, 1997 p395).

### **1.9.1 Tactile devices**

These devices function by using an individual’s capacity to perceive properties such as pressure and vibration by their physical effect on the skin via tactile perception. Simulated tactile contact between the user and the virtual object can be achieved in a number of ways. Srinivasan (1995) identifies three classes of tactile interface: ‘shape-changing devices’, ‘electrotactile devices’ and ‘vibrotactile devices’. This section will not provide examples of shape changing devices and electrotactile devices, as they are still in the experimental stages and are not commercially available. Furthermore tactile devices will only be given a very brief coverage, since this types of device are not used in the reported experimentation.

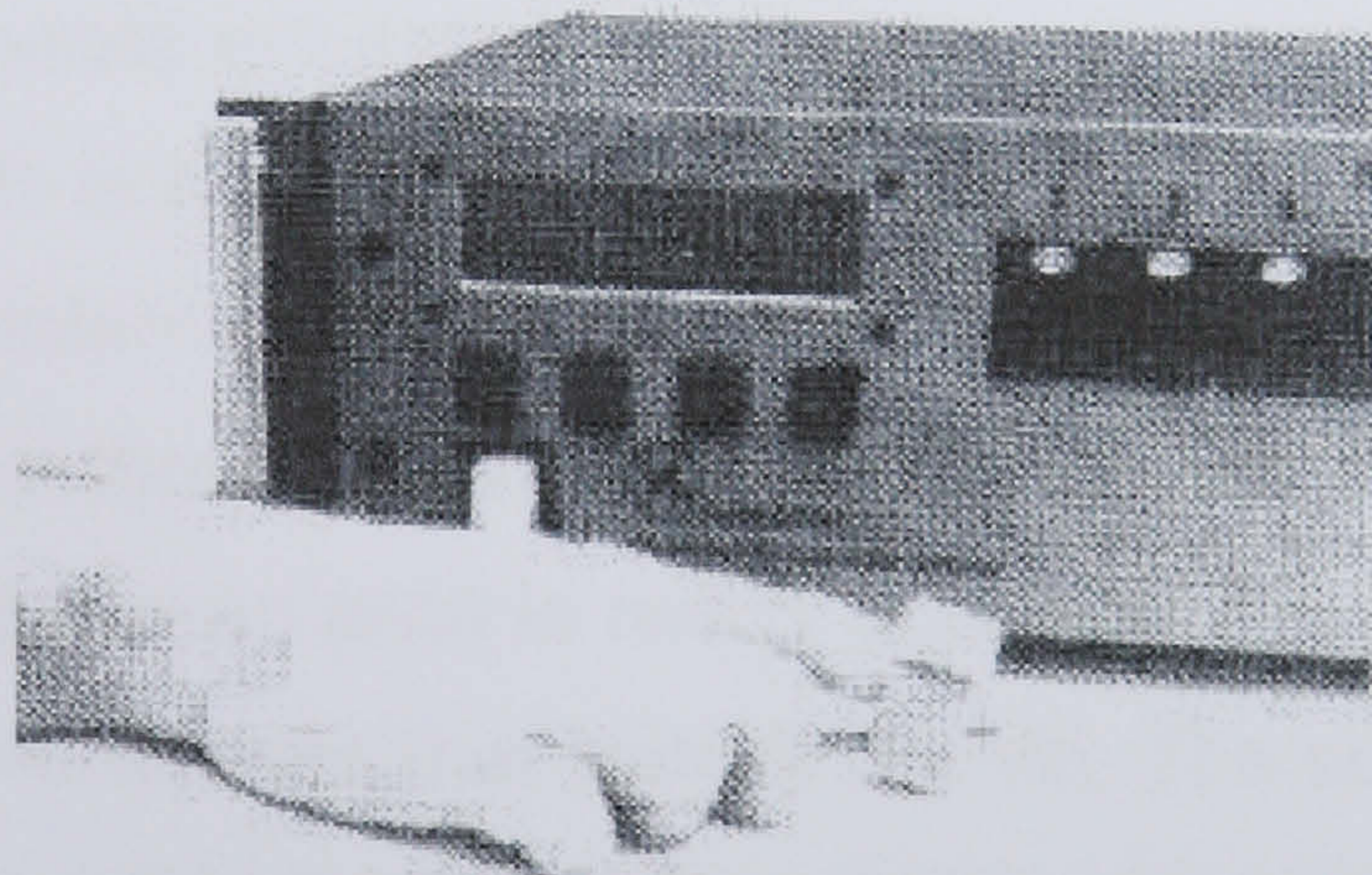
The Immersion Corporation ([www.immersion.com](http://www.immersion.com)) has developed the CyberTouch system, shown in figure 1.7. It features 6 pin matrices (one for

each finger and one located in the palm), each of which can be operated independently.



**Figure 1.7 The CyberTouch system<sup>10</sup>**

More recently, developers of tactile devices have begun to explore conveying sensations other than pressure and vibration to the users fingertips. The Displaced Temperature Sensing System (DTSS) is shown in figure 1.8.



**Figure 1.8 The Displaced temperature sensing system<sup>11</sup>**

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<sup>10</sup> Picture taken from the following URL

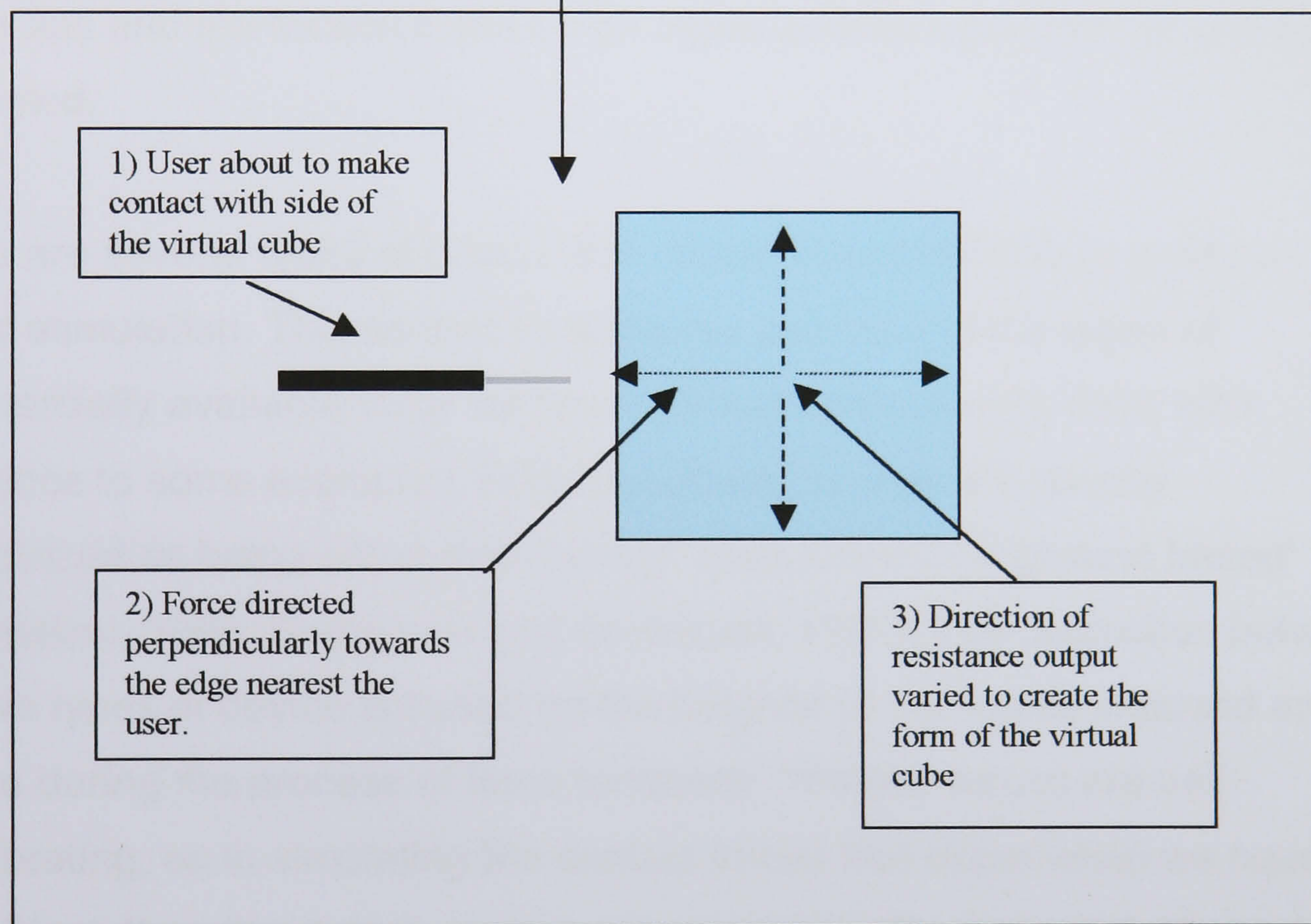
<http://www.immersion.com/products/3d/interaction/cybertouch.shtml> More information about the CyberTouch can also be obtained at this address

<sup>11</sup> This picture was obtained from the following URL: <http://www.cmresearch.com/haptic.html> More information about the DTSS can also be obtained at this address.

The DTSS is a tactile device that allows the property of temperature to be added to VEs. The interface works via a 'thermode', which is attached to the user's finger. A thermode is an assembly of a thermoelectric heat pump, a temperature sensor and a heat sink. The heat pump increases or decreases the temperature in the heat sink within a range of 10c to 45c to produce a temperature at the surface of the thermode and the user's finger. The interface can either replicate the temperature of whatever object the sensor is placed on, or can accept commands from a PC to create a temperature for objects in a VE.

### **1.9.2 Force feedback devices**

The majority of haptic devices function by using the process of force feedback. Force feedback works by using an individual's ability to perceive the presence and form of an object by monitoring the direction and magnitude of its resistance to his/her probing, via kinesthetic perception. Force feedback devices emulate the resistance to probing that a real object would produce. This is achieved by representing the contact point between the user and the content of a VE as a series of co-ordinates in two-dimensional (2-D) or three-dimensional (3-D) space. The individual uses the haptic device to explore an area in reality corresponding to the space identified by the co-ordinates that specify the VE. The software monitors the individual's position within this area. Should the individual make contact with the co-ordinates that define a virtual object or the boundaries of the VE, it instructs motors on the device to output resistance of a direction and magnitude appropriate to simulate the contact between the user and the VE.



**Figure 1.9 An illustration of the force feedback process**

Figure 1.9 depicts a user exploring a single virtual 3-D cube with the PHANTOM™ haptic device from Sensable technologies ([www.sensable.com](http://www.sensable.com)). In this example: 1) The 3-D co-ordinate representing

the contact point of the device is about to make contact with a co-ordinate representing a point on the left face of the virtual cube 2) The device outputs a force to prevent the co-ordinate representing the contact point of the device occupying the co-ordinate representing the part of the cube nearest to it. 3) By varying the direction of the force output for each of the cube's component faces, the simulation of a whole virtual cube is created.

By varying the direction and magnitude of the forces exerted, a haptic device can create an object of any shape and can simulate object attributes such as hardness, viscosity and texture. Dynamic objects can also be modelled and attributes such as the impact of gravity, the weight of an object, its inertial properties and the friction between an object and its surroundings can be simulated.

There are several types of device that utilize force feedback to produce haptic stimulation. This section provides an overview of the types of commercially available force feedback devices produced to date, with reference to some examples. Force feedback devices are usually categorized as being either 'body based' (exoskeletal) or 'ground based' (Srinivasan, 1995; Srinivasan and Basdogan, 1997). The distinction between the two types of device is based on the balance of the forces imposed on the device during the process of force feedback: "If these forces are self-equilibrating, as in simulating the contact forces that occur when we squeeze and object, then the device need not be mechanically grounded. However, if the forces are unbalanced, as in pressing a virtual object with a single finger pad, the equilibrium of the device requires that it be attached somewhere". (Srinivasan, 1995, p173).

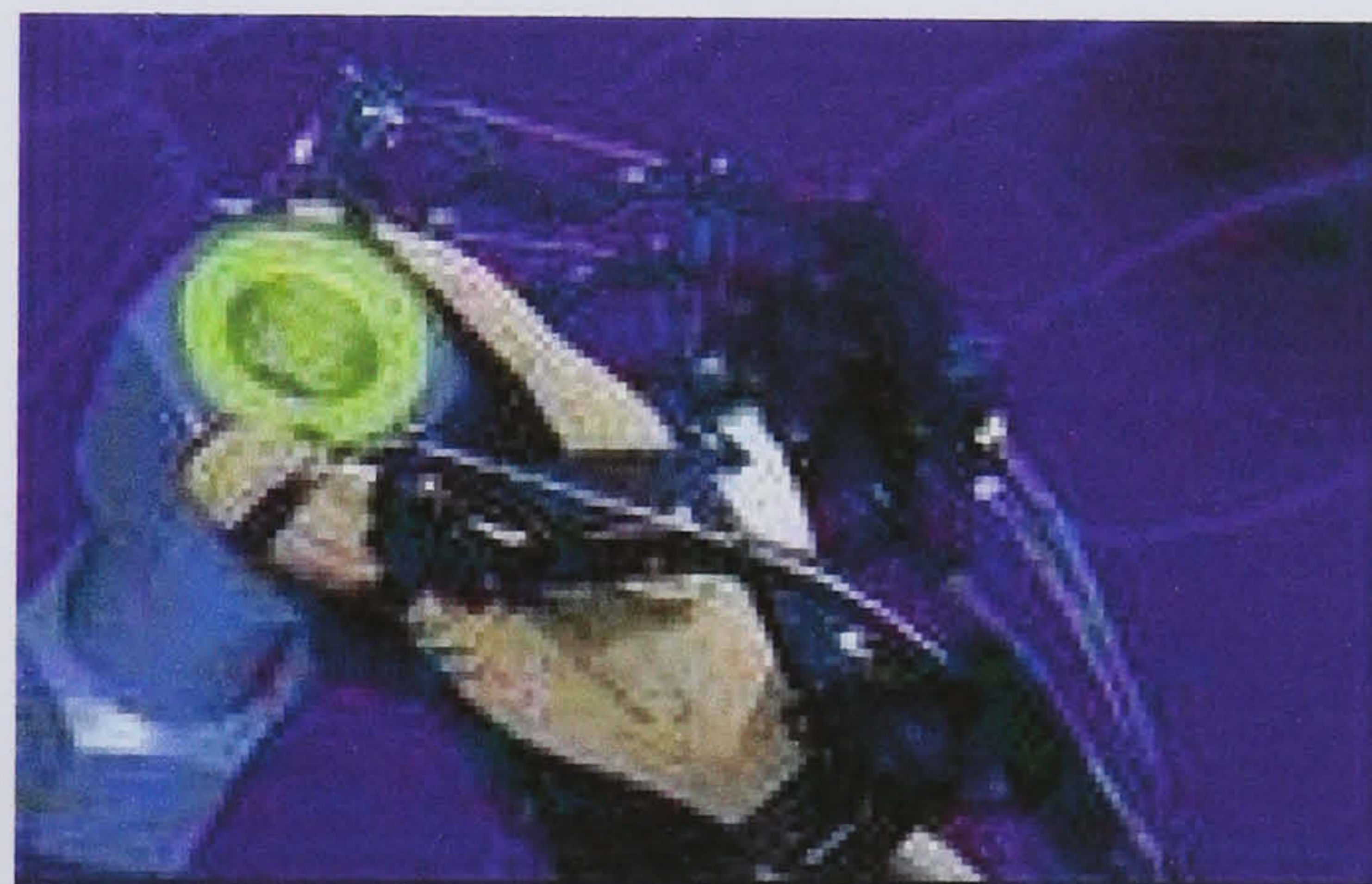
Body based devices are designed to be attached to, and accommodate, the range of movement that is achievable by a specific portion of the user's anatomy. Force feedback information can then be relayed to any one or



combination of the limbs and joints attached to the device. An example of such a device is the Cyber Grasp™, (depicted in figures 1.10 and 1.11), developed by Immersion corporation ([www.immersion.com](http://www.immersion.com))



**Figure 1.10 The Cybergrasp system<sup>12</sup>**



**Figure 1.11 An illustration of the Cybergrasp glove being used to feel a virtual object.<sup>13</sup>**

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<sup>12</sup> This picture was taken from the following URL:  
[www.sensable.com/products/3D/interaction/cybergrasp.shtm](http://www.sensable.com/products/3D/interaction/cybergrasp.shtm) More details about the CyberGrasp can also be obtained from this site.

<sup>13</sup> This picture was taken from the following address:  
[www.sensable.com/products/3D/interaction/cybergrasp.shtm](http://www.sensable.com/products/3D/interaction/cybergrasp.shtm)

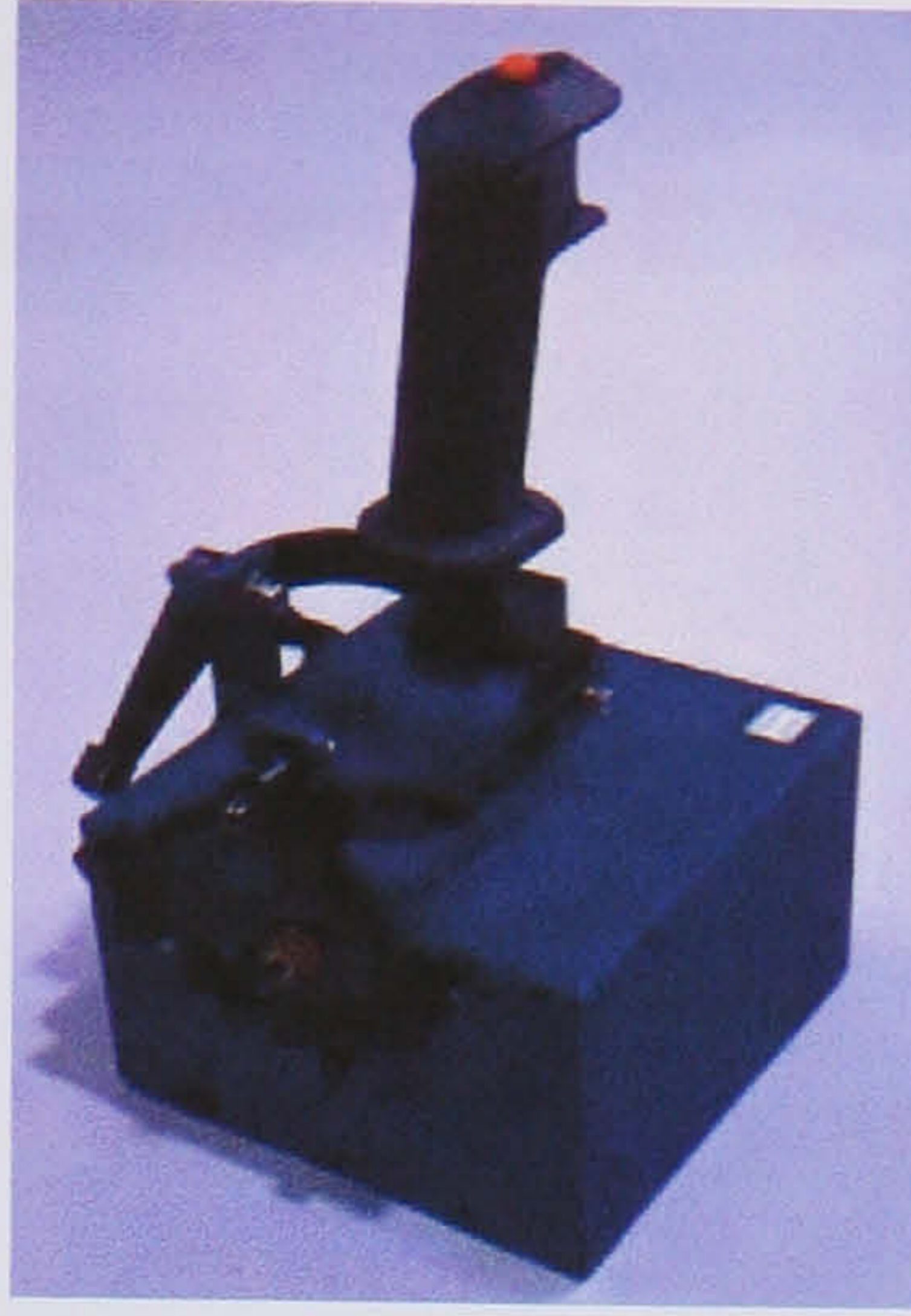
Ground based devices can broadly be placed into one of two categories: two-dimensional (2-D) devices or three-dimensional (3-D) devices. 2-D haptic devices are operated in much the same way as a conventional mouse or joystick: the user moves the device over a horizontal two-dimensional plane and this movement is transposed into two-dimensional movement on the vertical plane of the monitor. The device tracks the user's position in relation to any virtual objects in the virtual environment. Should the user come into contact with any virtual object, the device outputs force feedback appropriate to creating the desired object attribute. There are two main types of two-dimensional force feedback device: haptic mice and haptic joysticks, examples of which are depicted in figures 1.12 and 1.13 respectively.



**Figure 1.12 The Logitech Wingman Mouse<sup>14</sup>**

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<sup>14</sup> This picture was taken from the following URL <http://www.logitech.com/cf/products/productfeatures.cfm/79> more information on this product can be obtained at [http://www.logitech.com/lang/eng/products/pdfs/ifeel\\_mouse.pdf](http://www.logitech.com/lang/eng/products/pdfs/ifeel_mouse.pdf)



**Figure 1.13 The IE2000 haptic joystick<sup>15</sup>**

3-D ground based haptic devices create 3-D VEs and 3-D virtual objects. The Impulse Engine 3000, manufactured by Immersion Corporation ([www.immersion.com](http://www.immersion.com)), seen in figure 1.14, is an example of a 3-D ground based device



**Figure 1.14 The Impulse Engine 3000**

The Impulse Engine 3000 is controlled via a probe, protruding from the device's chassis, which the user can move in the x, y and z axes. The device features three encoders and three motors (one for each 3-D axis). The

encoders track the position of the probe in a VE and monitor any contact between the user and objects within the VE, the motors output resistance to the users movements appropriate to creating virtual object being examined. The device has a workspace of 13x23x23 cm<sup>3</sup> and can exert a maximum force of 9N.

The PHANTOM™ haptic device, shown in figure 1.15, is another example of a 3-D ground based device and is the device used in the experimentation reported in this thesis.



**Figure 1.15 The PHANTOM™ haptic device (thimble endpoint shown)**

The PHANTOM™ device also works via by three motors with integrated encoders, which track the 3-D position of the user within a VE. The encoders relay information to motors to generate resistance in the 3-D planes appropriate to creating the desired virtual object. The force feedback is relayed to the user via a linkage arm with a 'gimble' attached to its end. The gimble is a joint that allows the endpoint that the user grasps to rotate 360 degrees around it's own axis and in both the horizontal and vertical planes. This means that the device does not restrict the user's range of wrist movement and that they are free to adjust the orientation of the endpoint to

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<sup>15</sup> Picture taken fro the following URL <http://haptic.mech.nwu.edu/intro/gallery/immersionstick.jpg>

one that is comfortable for the exploration they are carrying out. The PHANTOM™ can be used with one of two endpoints: a thimble or a stylus, depicted in figure 1.16. The device provides a workspace of 12.7 x 17.7 x 25.4cm and its motors can output a maximum force of 8.5N.



**Figure 1.16 The thimble and stylus endpoints to the PHANTOM™ device**

### **1.9.3 The differences between haptic perception in VR with a force feedback device and haptic perception in the real world**

Haptic interaction with VEs via the PHANTOM™ device differs from haptic interaction in the real world in a number of respects. The first important difference relates to the lack of cutaneous contact with the virtual object being touched with the PHANTOM™. One may, therefore, wonder if the term ‘kinaesthetic virtual reality’ would be more appropriate than HVR when referring to force feedback devices such as the PHANTOM™. The use of the HVR in the literature is probably due to the overlap between cutaneous and kinaesthetic perception, highlighted in section 1.2. In the context of haptic interaction with the PHANTOM™ and other force feedback devices, the kinaesthetic information indicating contact with an object is accompanied by

the cutaneous sensation of pressure on the finger/s the user is using to interact with the devices.

The cutaneous information available when interacting with force feedback devices is very limited, serving only to indicate contact with an object. The cutaneous information corresponds to the properties of the endpoint that the individual uses to interact with the device, as opposed to the virtual objects that they are interacting with. In the case of the PHANTOM™, the cutaneous stimulation corresponds to the properties of either the thimble or stylus endpoints. It should also be noted that the cutaneous stimulation is incidental; the force feedback process itself does not output any cutaneous information. However, the term haptic virtual reality is now established in the literature, so having made the above qualifications the author will continue to use it as a generic term that encompasses touch in VR with any haptic device.

Another distinguishing characteristic of haptic interaction with a VE via the PHANTOM™ is the point of contact between the user and the VE being represented as a single point. This means that the user has only one point of haptic contact with any object in a virtual environment. This is clearly a marked deviation from reality, in which one would be free to interact with an object using any number of fingers on one or both hands. One very apparent implication of single point based interaction is for the exploratory procedures (EPs) that an individual can use when interacting with virtual objects via the PHANTOM™. Any exploratory procedure involving the use of more than one finger is precluded.

The user cannot perceive the size of the single point of interaction with the VE either visually or haptically. A visual representation, in the form of a cursor, can be used to indicate the user's position in relation to virtual objects, but its size does not correspond to actual point of contact between

the user and the virtual object, which is infinitesimal. As previously noted, either a stylus or thimble endpoint can be used in interacting with PHANTOM™, however, the virtual contact point between the user and the virtual object remains constant irrespective of the endpoint used. Once again, this is a notable discrepancy between haptic interaction with the PHANTOM™ device and haptic interaction in the real world. In reality, an individual would generally interact with an object using their hands and should they use an intermediary tool, they would be able to haptically and visually perceive the size of the area of contact between that tool and the object of interest. The size of the contact point between the individual and reality would also not be independent of the tool being used to explore the object, as is the case with the thimble and stylus endpoints to the PHANTOM™.

Finally, there are the physical aspects of the device itself to consider: the PHANTOM's moving parts have inherent friction, weight and inertial values associated with them. These values are different from those of those associated with joints and muscles. Therefore, when a person interacts with a virtual object via the PHANTOM™, they are subject to different forces than they would encounter by exploring its real counterpart.

What becomes clear when one examines what touch in HVR entails with any particular haptic device, is that researchers cannot assume that knowledge obtained about haptic perception in the real world will apply without qualification to HVR. This point is underlined by some recent research that has begun to address the consequences of haptic exploration with an intermediary link (a rigid probe, or a glove) imposed between the participant's hand and the experimental stimulus. This approximates the lack of cutaneous information and single point based interaction characteristics of haptic interaction with virtual objects via any 3-D grounded, force feedback device, including the PHANTOM™.

Klatzky, Lederman and Metzger (1985) found that participants could identify common 3-D objects by touch both accurately and rapidly. However, when Lederman and Klatzky (1998) asked participants to identify a selection of the same objects via a probe, performance deteriorated significantly. The efficiency with which an individual can haptically sort objects according to properties such as size and texture with a rigid probe has also been reported to be inferior to when bare fingers are used (O'Modhain, 1999).

Over the last couple of years there has been also some experimentation to ascertain how roughness is perceived when the person uses a tool other than their finger in exploring a textured surface (Klatzky and Lederman 1999; Lederman, Klatzky, Hamilton and Ramsay, 1999). These experiments have indicated that the relationship between the size of the point of contact between the probe and the texture surface is critical in determining the psychophysical function relating perceived roughness to inter-element spacing. Perceived roughness was found to increase more rapidly as a function of inter-element spacing when a bare finger, as opposed to a probe was used in examining the textures. When using a probe, perceived roughness was also found to peak at textures featuring an inter-element spacing roughly corresponding to the contact diameters of the probe being used. After this peak, perceived roughness would begin to decrease as a function of increasing inter-element spacing. Klatzky and Lederman (1999)

Clearly, research into haptic perception in HVR needs to be undertaken. Srinivasan and Basdogan (1997) point out that, "any rational basis for the design of the hardware and software has to depend on human perception and performance.....therefore a bootstrap approach where the current VEs help perform human experiments, which, in turn, help design the next generation of VE systems seems to be necessary" (p401).



To date, this kind of approach has been largely lacking in research. A situation has arisen, whereby the development of haptic devices has occurred largely independently of a body of research that addresses the fundamentals of haptic perception in HVR. Therefore, it would seem prudent for research to make a concerted effort to studying the fundamentals of haptic perception in VR with one particular device. The results from this research will then provide a basis for the development of future haptic devices and applications for HVR.

## **1.10 Studies of haptic perception in HVR and rationale for the reported experimentation**

This section provides an overview of the status of the literature on haptic perception in HVR relevant to the work reported in this thesis and, in doing so, provides the rationale for the reported research. In common with the ordering of the literature on haptic perception in the real world, this section first considers studies involving the perception of the object attribute of roughness in HVR before moving onto the perception of size and angular extent, followed by the isotropy of perceived extent in 3-D space. This section then moves on to consider the rationale for the examination of parameters of haptic perception in VR yielded by a consideration of the real world and VR based literature.

### **1.10.1 The perception of roughness in HVR**

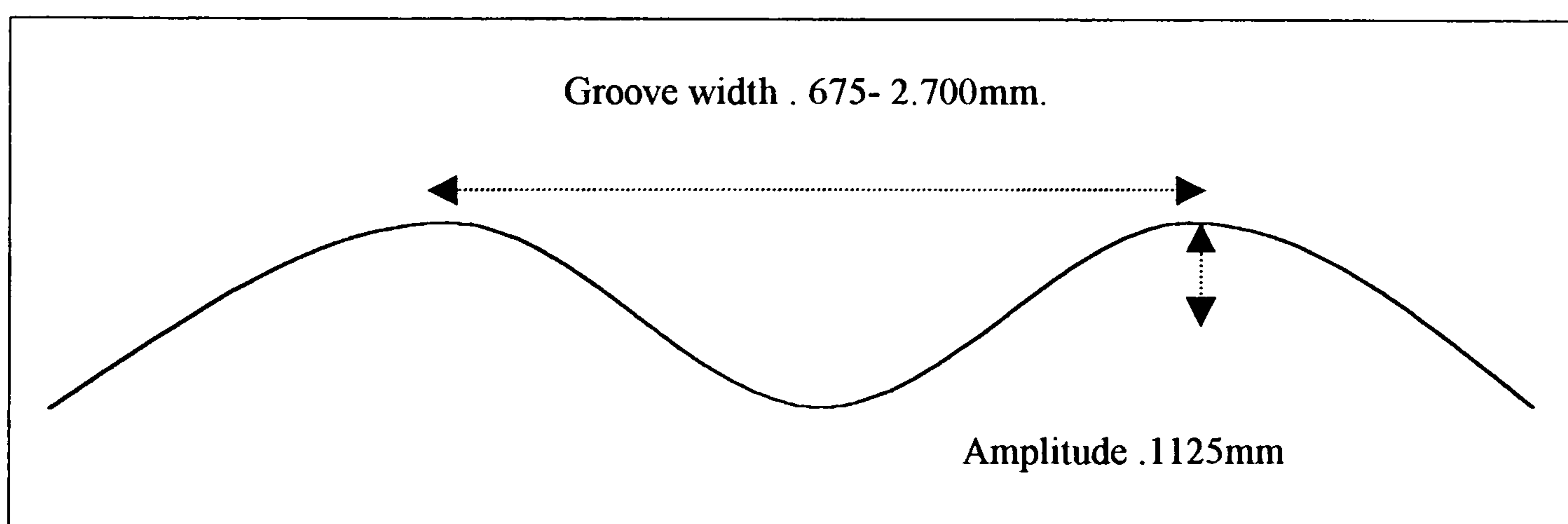
Over the last few years, there has been some interest in the subject of roughness perception in HVR. The preliminary work on the subject was conducted to ascertain whether the 2-D haptic devices that were available at the time could create convincing simulations of three dimensional object properties, such as texture. (e.g. Minsky, Ouh-young, Steele, Brooks and

Behensky 1990). Texture was an ideal medium with which to investigate this issue, as the 2-D haptic devices could only output forces in the x (horizontal) and z (depth) planes. However, since texture is characterized by distortions to a surface in the vertical plane, a 2-D of freedom device would have to convincingly create the illusion of movement in the vertical plane to produce viable textures.

Minsky, Ouh-young, Steele, Brooks, Behensky (1990) developed the Sandpaper system for experimenting with virtual textures. The principle behind the system is very simple. In reality, owing to the influence of gravity, the amount of resistance encountered upon movements up the sides of the raised elements of which a texture is composed is greater than the resistance experienced upon movements down the side of such elements. Minsky et al's two degree of freedom haptic joystick (see fig 1.13) used this principle to create virtual textures by modulating the amount of lateral forces acting upon the user, such that the lateral resistance encountered by the user was proportional to the height of the corresponding virtual elements. This process gave the person the impression that they were interacting with a surface that featured distortions in the vertical plane. Minsky and Lederman (1996) found that the perceived roughness of textures simulated in this way increased with increases in the amplitude of the lateral forces being exerted on the user. However, this finding is difficult to compare with studies of roughness perception in the real world, as it is not clear which, if any, stimulus related determinant of roughness in the real world force amplitude is equivalent to.

The subsequent advent of 3-D devices that can simulate all of the dimensions of a textured surface permitted the impact of stimulus parameters that have been investigated in reality, such as groove width, to be directly addressed in HVR. However, there is still relatively little research of this kind.

Colwell, et al (1998a;1998b), were responsible for the seminal work on the perception of roughness with a 3-D haptic device. This study utilised the IE3000 (see figure 1.14) Unfortunately, the infinitesimal size of the contact point of the haptic device precluded the use of the rectangular waveform textures that had been used by most of the real world based research (e.g. Lederman, 1974; Lederman, 1981; Lederman and Taylor; 1972; Taylor and Lederman, 1975). This was because the user would get caught in the corners of the grooves of the texture, making smooth and continuous movement along the virtual texture surface almost impossible. However, it was possible for users to explore regular sinusoidal waveforms. Unlike rectangular waveform stimuli these are defined by two physical parameters: groove width and amplitude (see figure 1.17)



**Figure 1.17 Illustration of a sinusoidal groove profile**

In the authors opinion, the use of this type of stimuli is preferable to sandpaper-like stimuli, as it avoids the problem of inconsistent stimuli presentation inherent such textures; the participant can "ride" around the base of the raised dots that constitute the surface, or fall off the side of them. Colwell et al (1998) gave sighted and blind participants a series of ten virtual sinusoidal textures to examine. Each texture differed in terms of the width of

its sinusoidal grooves, the amplitude of the grooves was held constant between the textures (see figure 1.17). Participants examined six runs of the ten randomly ordered virtual textures and gave magnitude estimates of how rough they perceived each texture to be.

The results of Colwell et al (1998) revealed that groove width was a significant determinant of perceived roughness. However, the results deviated from what would have been anticipated on the basis of the real world based literature on roughness perception in an important respect. As has been noted in section 1.4.1 of this chapter, experiments on the perceived roughness of real textures in the real world indicate that perceived roughness correlates positively with groove width i.e. as groove width increases, so does perceived roughness. However, in Colwell (1998) none of the sighted participants exhibited this relationship. In this experiment, perceived roughness correlated inversely with groove width, that is to say that perceived roughness decreased with increasing groove width. This was also the case for four of the eight blind participants, the remaining four exhibited the conventional positive correlation between groove width and perceived roughness.

The results of Colwell et al (1998) also indicated that variations in the physical parameters of the stimulus that determine perceived roughness in reality do not necessarily have the same impact in HVR.

What was not clear at the time of conducting this research was how roughness would be perceived with the PHANTOM™ device and how this would compare with perceived roughness with the IE3000 device.

Furthermore, it was not known if perceived roughness with the PHANTOM™ device would differ as a function of the endpoint being used with the device, or between sighted and blind individuals. Experiment one was conducted to resolve these questions.

### **1.10.2 The perception of 3-D object size and angular extent in VR**

Colwell et al (1998a; 1998b) conducted the first investigations into the perception of size and angular extent in HVR. This experiment involved sighted and blind individuals feeling a series of virtual three-dimensional cubes, spheres and sheared cubes (trapezoids) via the IE3000 haptic device. The Cubes and spheres were presented in three sizes: 2.7 cm, 3.6 cm and 4.5 cm.

Each object type/size permutation was presented in an external orientation, in which the participants explored the objects from the outside and in an internal orientation, in which the participants explored the internal dimensions of hollow versions of the objects. The sheared cubes appeared in the internal exploration format only and featured three degrees of shearing: 18, 41 and 64 degrees. The size of the sheared cubes was held constant at 3.6 cm. After the sighted participants had explored the virtual cubes and spheres, they were asked to visually select a match to the object they had just explored from 3-D depictions of the virtual objects. The blind participants were asked to feel a series of fuzzy felt representations of the objects and choose the one that corresponded to the size/angle of shear of the virtual object they had just explored.

Bruns (1998) also conducted an investigation of size perception in HVR with the IE3000 device. He replicated the methodology of Colwell et al (1998), with the exception that the participants were asked to reproduce the size of the virtual objects rather than visually or tactually selecting a match from comparison objects. As had been the case in Colwell et al (1998), Bruns (1998) found that the size and angular extent estimates of sighted and blind

individuals did not differ significantly and that virtual objects presented in the internal orientation were perceived as significantly larger than the same sized object presented in the external orientation (the Tardis effect<sup>16</sup>).

Unfortunately the analyses conducted by the above authors did not provide a particularly comprehensive characterization of perceived size or angular extent in VR. For example, it is not clear from their work whether the linear increase in the size and angular extent of the stimuli was matched by a corresponding linear increase in perceived size and angular extent.

At the time of conducting the experimental work for this thesis, it was not clear how individuals would perceive the size and angular extent of 3-D objects with the PHANTOM™ device. Experiment 3 was therefore conducted to provide a general characterisation of perceived size and angular extent with this device. Furthermore the experimenter was interested to ascertain if the perception of these attributes would differ between the thimble and stylus endpoints of the PHANTOM™ device or between sighted and blind individuals. Of course, the issue of whether the distortion in the perceived size of 3-D objects known as the Tardis effect would also be evident with the PHANTOM™ was also of interest.

### **1.10.3 The isotropy of haptic space in VR: perceived extent**

Section 1.7 noted that an important issue in haptic perception in the real world is the uniformity of the perception of an attribute over the axes that specify manipulatory space. The real world based literature clearly indicated that perceived extent is not isotropic, but is subject to a reliable anisotropy known as the Radial Tangential effect (e.g. Cheng, 1968; Wong, 1977; Armstrong and Marks, 1999).

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<sup>16</sup> The Tardis was the name given to the time travel machine featured in the popular science fiction series Dr. Who. Externally, the machine appeared to be no larger than a phone box, but its internal dimensions were far greater than its external appearance suggested.

However, this issue has not been addressed by previous research in HVR. Therefore, it is not known whether perceived extent in HVR with a 3-D force feedback device is subject to the Radial Tangential effect, or whether it is consistent over the 3-D axes that define a virtual environment. Experiments five and six were conducted to examine if the perception of linear extent in HVR is uniform over the 3-D axes (x, y and z) and within both directions of each axis.

In addition to determining whether the RTE would be present in HVR, these experiments also aimed to determine whether the notion that the effect might be due to radial movements being unintentionally performed slower than equivalent tangential movements (e.g. Wong, 1977; Marchetti and Lederman, 1983; and Armstrong and Marks, 1999).

#### **1.10.4 The effect of the endpoint used with the PHANTOM™ on haptic perception**

Section 1.9.2 noted that the PHANTOM™ device could be interacted with via thimble or stylus endpoint. Jansson (1999) and Jansson and Billberger (1999) have compared the stylus and thimble endpoints of the PHANTOM™ in terms of the identification of simple geometric objects and found no difference between them. However, in the light of literature on the identification of common 3-D objects, this result is to be expected. Although the identification of 3-D objects via touch alone can be fast and accurate (Klatzky, Lederman and Metzger, 1985), accuracy is severely compromised when the number of fingers a participant can use in examining the stimulus is reduced, performance being at it's worst when only one finger or an intermediary probe is used (Klatzky, Loomis, Lederman, Wake and Fujita, 1993; Lederman and Klatzky, 1998). Since both the stylus and thimble endpoints of the PHANTOM™ impose a single point of interaction on the participant, it could be argued that the participants are equally disadvantaged

in identification tasks and that any other differences between the two endpoints are of much less significance.

However, neither Jansson nor any other previous research has addressed whether the perception of a particular object attribute differs between these two endpoints. It may, for example, be the case that the single point nature of the interaction with virtual objects with the two endpoints is not the most important factor when perceiving other object attributes, such as roughness. Other potential differences in participants' use of the endpoints might exert an effect.

Therefore, the PHANTOM's stylus and thimble endpoints were compared in terms of the perception of roughness, in experiments one and two, and 3-D object size and angular extent, in experiment three.

#### **1.10.5 Comparisons between different force feedback devices**

Section 1.9.2 also identified a number of types of 3-D force feedback devices. However, the consistency of haptic perception between different 3-D force feedback devices has not been addressed by previous research. One can distinguish between haptic devices in terms of a number of difference technical specifications, a full review is beyond the scope of this thesis, but the interested reader is directed to Hayward and Astley (1996). As an example, some of the specifications of the PHANTOM™ device and the IE3000 device are summarised in table 1.1 (on the following page).



**Table 1.1 Some performance measures for the IE3000 and PHANTOM™ device**

	Impulse Engine 3000	PHANTOM™ 1.0
Workspace size	13 x 23 x 23 cm	13 x 18 x 25 cm
Maximum exertable force	9.0 Newtons	8.5 Newtons
Nominal position resolution	.023 mm	.030 mm

It is evident from table 1.1 that the PHANTOM™ and the IE3000 differ slightly in respect of each of the featured technical specifications. However the implications of such differences for haptic perception in VR are not understood. As Biggs and Srinivasan (2001) put it: “a device might perform brilliantly at displaying shoulder torque (a physical measurement), but if this parameter is not very effective at helping the user complete many tasks or feel immersed, the device may not really be good” (p23-24). Furthermore, Hayward and Astley (1996) note that the ambiguity of the descriptions of the specifications for haptic interfaces “makes evaluation and comparison difficult” (1996, p1).

Therefore, the comparisons between the results obtained with the PHANTOM™ device and the IE3000 device reported in this thesis are gross in nature. They simply seek to determine if the perception of roughness and 3-D object size and angularity differs appreciably between these two 3-D force feedback devices.

The device comparisons were not undertaken to determine the effectiveness of variations of different technical parameters of a haptic device. Should perceptual differences between the IE3000 device and the PHANTOM™ device become evident, subsequent research can begin to elucidate which differences in the technical specifications of the devices might be responsible

for such differences. The perception of roughness and 3-D object size and angular extent was compared between the PHANTOM™ and IE3000 devices in experiments one and three respectively.

### **1.10.6 Haptic perception in VR with the PHANTOM™ vs haptic perception in the real world**

Section 1.9.3 indicated that haptic interaction with the PHANTOM™ device differs from touch in the real world in terms of a number of characteristics, such as the lack of cutaneous information inherent in haptic interaction via the PHANTOM™. However, at this time it is not clear which, if any, of these differences between VR and the real world impact significantly on the perception of object attributes (Biggs and Srinivasan, 2001).

Therefore, experiment four was conducted to compare the perception of the size and angular extent of 3-D objects between HVR and the real world. The experimental methodology involved manipulating the conditions under which the participants haptically interacted with the real world counterparts to the virtual objects such that the results would allow some preliminary inferences to be made as to which aspects of interaction with a force feedback device might be of perceptual consequence. This is the kind of bootstrap approach advocated by Srinivasan and Basdogan (1997).

The other advantage to manipulating the conditions under which the participants examine the real counterparts to the virtual objects is that it is potentially informative in identifying the mechanism for any findings, such as the Tardis effect, that might occur.

### **1.10.7 The impact of exploratory variables of haptic perception in VR with the PHANTOM™**

Section 1.2.2 of the literature review noted that exploring an object by touch involves a number of exploratory variables, such as whether individuals control their exploratory movements, the contact force they apply to an object and so on.

The impact of exploratory variables on haptic perception in VR has received very little attention from researchers to date. Therefore, the impact of an exploratory variable on the perception of roughness (i.e. contact force) was examined, in addition to the impact of an exploratory variable on the perception of extent (i.e. active and passive movement).

The justification for the selection of these particular variables is covered in the introduction to experiments two and four respectively. Suffice to say here that they were chosen for the novel contribution they would make in understanding the role of exploratory variables on haptic perception in VR. They were also chosen due to their potential to contribute to our understanding of the endpoint used with the PHANTOM™, in the case of contact force, and the mechanism underlying the Radial Tangential effect, in the case of active vs. passive movement.

### **1.10.8 The effect of visual status on haptic perception with the PHANTOM™**

Section 1.8 identified that the impact of visual status on haptic perception is an important issue in the real world based literature. However, aside from the work of Colwell et al (1998a; 1998b) there has been little work that addresses the implications of visual status in HVR.

There are two good reasons for the study of the impact of visual status in HVR. The first is that the issue is of theoretical interest and, as has been noted above, has received very little attention from researchers. The second reason is that there are also practical reasons for studying this issue. As has been identified in section 1.1.1, one of the applications of HVR is as an accessibility tool for blind individuals. It stands to reason that such an application should be informed by research that addresses haptic perception in VR in blind individuals. Therefore, sighted and blind individuals are compared with respect to roughness perception in experiments one and two, the perception of 3-D objects size and extent in experiments three and four and the perception of linear extent in experiments five and six.

However, the reported research goes beyond just examining the perception of virtual object attributes in blind individuals. It also incorporates blind participant samples in investigating all of the parameters covered in this section, whether related to the issue of the isotropy of perceived extent in 3-D virtual space, the impact of device variables, or the impact of exploration variables.

## **1.11 Plan of Thesis**

A total of six experiments into HVR are described in chapters two through four. This section outlines the subject matter and variables examined in each of these empirical chapters

- Chapter 2: Roughness perception in haptic virtual reality

Chapter two encompasses experiments one and two, which examine the perception of the textural attribute of roughness with the PHANTOM™ device. Magnitude estimation was used to determine the perceived

roughness of the virtual textures *and* the psychophysical function relating the groove widths of the virtual textures to perceived roughness. Experiments one and two investigated whether variations in the groove widths of virtual sinusoidal textures would allow participants to discriminate between these textures on the basis of perceived roughness.

Both experiments compared roughness perception with the PHANTOM™ via both the thimble and stylus endpoints to ascertain whether the endpoint used with the PHANTOM™ affects roughness perception. Experiments one and two also compared roughness perception in blind and sighted individuals to determine the implications of visual status for roughness perception in HVR.

In addition to the above issues, experiment one compared the perceived roughness of identical virtual textures between the PHANTOM™ device and another 3-D force feedback device (the IE3000).

Experiment two examined the impact of the exploration variable of the amount of contact force applied to the virtual textures by participants on perceived roughness in HVR. It also examined the relationship between this variable and those of the groove widths of the virtual textures, the endpoint used with the PHANTOM™ (stylus vs. thimble) and the visual status of the participants (sighted vs. blind).

- Chapter three: The perception of virtual and real 3-D object size and angular extent in HVR

Chapter three encompasses experiments three and four. In both experiments, participants were asked to examine a series of 3-D objects and reproduce their perceived size. Two types of objects were used (cubes and spheres), in order to determine whether the perception of size was uniform across different object types. Participants were also asked to examine and

reproduce the angular extent of several sheared cubes (trapezoids). In both experiments, the cubes and spheres were presented in such a way that they would be explored from the outside or the inside. Sheared cubes were always examined from the inside.

In experiment three, the objects were virtual and examined via the PHANTOM™ device. The perception of the size of the virtual cubes and spheres was compared between the stylus and thimble endpoints of the PHANTOM™ to determine whether the endpoint used had a significant effect on perceived size and angular extent. Experiment three also examined the impact of the specific device used on perceived size and angular extent by comparing the results obtained with the PHANTOM™ device to those obtained using identical stimuli explored via the IE3000 device in Colwell (1998).

In experiment four, participants were asked to examine and reproduce the size or angular extent of real counterparts to the virtual objects. The participants were asked to examine these objects under a number of exploration conditions, which either replicated some of the characteristics of the exploration of virtual objects with the PHANTOM™ device, or permitted the participants to explore the real objects in any way they wished. Thus, this experiment sought not only to provide a direct comparison between real and virtual perception of analogous stimuli, but also to determine which, if any, of the characteristics of interaction with virtual objects via the PHANTOM™ device might be responsible for any differences observed in the perception of 3-D object size and angular extent between HVR and the real world.

- Chapter four: The isotropy of 3-D space in HVR

Chapter four encompasses experiments five and six. Experiments five and six were conducted to examine if the perception of extent was consistent

over the 3-D axes (x, y and z) that specify the PHANTOM™ 's workspace. Both experiments examined the impact of the whether the participants or the PHANTOM™ device provided the movement required to traverse the lines i.e. the impact of active vs passive movement on perceived extent. Experiments five and six also examined the impact of visual status in the consistency of perceived extent by comparing the data obtained from sighted and blind individuals.

In experiment five, participants explored the virtual lines via bi-directional exploration along each of the 3-D axes. The aim was to determine whether the perception of extent with the PHANTOM™ device was consistent along each of the 3-D axes per se.

Experiment six, extended the results of experiment five by asking participants to examine the virtual lines via uni-directional movements along each of the 3-D axis. These uni-directional movements were used in order to determine whether perceived extent in HVR differs as a function of the directions of the exploratory movements within each of the 3-D axes.

Finally, chapter 5 draws together the empirical findings and their implications for the psychology of touch and for the design of prospective haptic devices and applications.

## **1.12 Summary**

This thesis broadly addresses the topic of haptic perception in HVR and the real world. The reported experimentation concerns both the perception of virtual object attributes by sighted and blind individuals, in addition to various parameters associated with the characteristics of haptic exploration with a force feedback device and participants' exploration of the virtual stimuli. The reported experimentation contributes to our understanding of haptic

perception in VR in all of these respects. It can be used to inform the development of future HVR devices and applications and, more generally, to inform future literature on haptic perception in the real world



## **2. Chapter 2: Experimental studies of roughness perception in VR**

This chapter reports two experiments in which the perception of the textural attribute of roughness in HVR is examined with the PHANTOM™ device. Experiment one aimed to establish the relationship between the physical parameter of the groove width of virtual textures and perceived roughness. Additionally, experiment one examined the impact of the endpoint used with the PHANTOM™ on perceived roughness and the implications of visual status for perceived roughness with the PHANTOM™ device. Finally, experiment one investigated whether the perception of roughness was comparable between two force feedback devices (i.e. the PHANTOM™ device and the IE3000).

Experiment two was conducted to examine the impact of a variable related to an individual's interaction with virtual textures on perceived roughness, namely, the amount of contact force users apply to virtual textures. The effect of this variable was examined with respect to the variables of groove width, endpoint and visual status addressed in experiment one.

### **2.1 Experiment 1: The perception of Roughness with the PHANTOM™ device**

#### **2.1.1 The effect of groove width on perceived roughness with the PHANTOM™ device**

Real world based studies of roughness perception have indicated that “the magnitude of the roughness percept is a strongly increasing function of the

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original

with the PHANTOM™ device, although they did use sinusoidal waveforms with a higher amplitude 2.5mm than Colwell et al (.1125).

Experiment one was conducted to examine the impact of the stimulus parameter of groove width on roughness perception with the PHANTOM™ device. Furthermore, by replicating the methodology and stimulus used by Colwell et al (1998a; 1998b) with the PHANTOM™ device, experiment one aimed to determine if the perception of roughness would be consistent between two 3-D haptic devices i.e. the PHANTOM™ and IE3000 devices.

### **2.1.2 The impact of the endpoint used with the PHANTOM™ device on perceived roughness**

As has been noted in section 1.7.3. the PHANTOM™ device can be interacted with via either a thimble or stylus endpoint. This raises the question of whether the endpoint with the PHANTOM™ has a significant effect on the perception of roughness. Previous research on perceived roughness with the PHANTOM™ device (e.g. Jansson, 1998; Wall and Harwin, 2000) has not addressed this issue. For the user, the two endpoints are distinguished by the distribution of the forces relayed by the device: the force feedback is either directed to the tip of a single finger with the thimble endpoint or to the combination of fingers the individual uses in grasping the stylus.

Whilst the actual output from the device itself does not differ as a result of the endpoint being used, it may be the case that the two endpoints precipitate differences in one or more parameters relating to an individual's interaction with a virtual texture. For example, an individual may unwittingly or otherwise apply more contact pressure to virtual textures with the thimble than the stylus endpoint, which might influence perceived roughness.

Therefore, in experiment one, participants were asked to examine the virtual textures with both the thimble and stylus endpoints in order to ascertain if the endpoint used with the PHANTOM™ would exert a significant effect on perceived roughness.

### **2.1.3 The impact of Visual status on perceived roughness with the PHANTOM™ device**

The work of Colwell et al (1998) was noteworthy for its use of blind participants. With the exception of Heller (1989), previous research had not examined whether the perception of roughness differed between blind and sighted individuals in the real world, let alone HVR. Colwell et al (1998) found that the exponents describing the rate at which perceived roughness changed as a function of increments in groove width did not vary significantly between sighted and blind individuals. However, the relationship between groove width and perceived roughness was significant for eight out of nine of the blind participants, but only seven out of thirteen of the sighted participants.

At the time of the preparation of this manuscript, researchers had not addressed the impact of visual status on roughness perception with the PHANTOM™ device. Therefore, experiment one includes a sample of blind participants to ascertain whether perceived roughness of virtual textures with the PHANTOM™ device differs significantly between sighted and blind individuals.

## **2.2 Method**

### **2.2.1 Participants**

This experiment utilised a total of 23 participants, 13 participants were sighted and the remaining 10 were blind. The sighted participant sample consisted of six males and seven females, all of who reported having no sensory-motor impairments. Their ages ranged from 19 to 36, with the mean age being 27. The sighted participants were all University students recruited from various disciplines.

The blind participant sample consisted of 8 males and 2 females, all of who reported having no other sensory-motor impairments. 5 of the blind participants were congenitally blind the remaining 5 lost their sight between the ages of 8 and 42. The ages of the blind participants ranged from 19 to 54, with the mean age being 46. The blind participants were all volunteers recruited from a list of visually impaired individuals who had expressed an interest in participating in the Sensory Disabilities Research Unit's research.

### **2.2.2 Design**

This experiment utilised a four factor mixed design, consisting of one between subjects factor and three within subject factors. The between subjects factor Visual Status consisted of two levels, blind and sighted participants. The within subjects factor Endpoint consisted of two levels, the stylus and thimble endpoints of the PHANTOM™ device; the within subjects factor Groove Width consisted of 10 levels, corresponding to the 10 groove widths utilised; the within subjects factor Run Number consisted of six levels, corresponding to the six occasions on which each texture was presented.

Participants examined six runs of the ten virtual textures. The order in which the textures were presented was randomised within each run. This process

applied to both the thimble and stylus endpoints. Therefore, each participant underwent a total of 120 trials (10 textures x 6 runs x two endpoints).

### **2.2.3 Apparatus**

The stimuli were presented via the PHANTOM™ haptic device (depicted and described in chapter 1, section 1.9.2) connected to a Pentium II 400 Mhz computer with 64MB of RAM running the Windows NT operating system. Both the stylus and thimble endpoints to the PHANTOM™ (depicted in chapter one, p28) were used in this experiment. Interaction with the PHANTOM™ via the thimble and the stylus endpoints is depicted in Figures 2.1 and 2.2 respectively.



**Figure 2.1 Interaction with the PHANTOM™ device via the thimble endpoint**

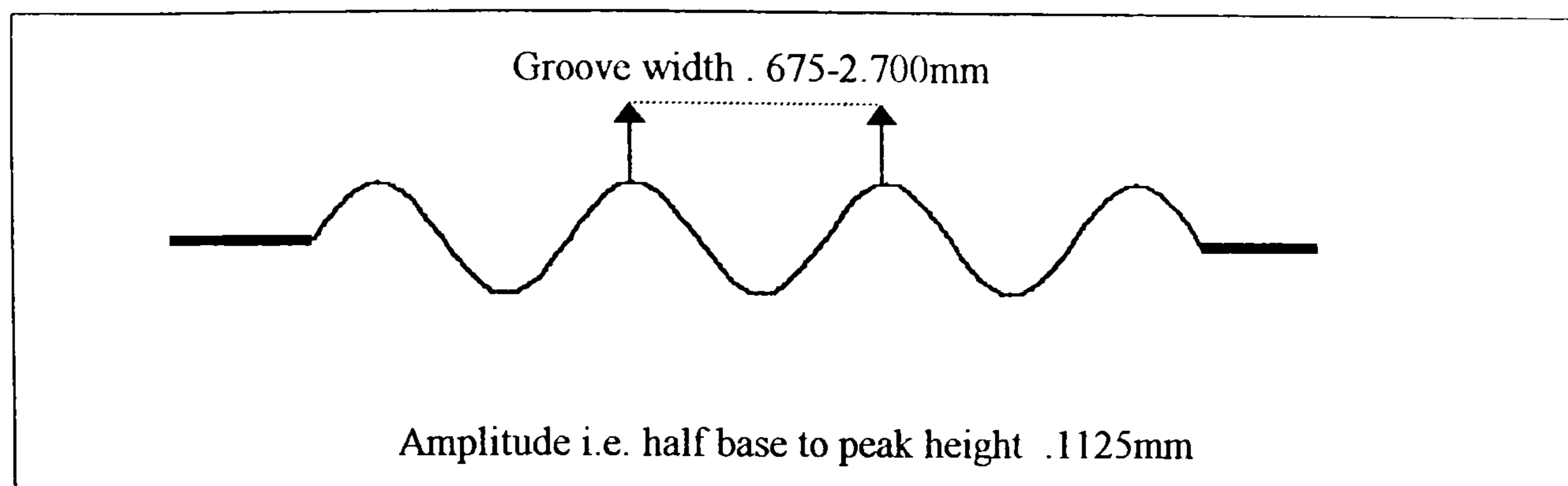


**Figure 2.2. Interaction with the PHANTOM™ device via the stylus endpoint**

A depiction and description of the IE3000 device used by Colwell (1998) can also be found in the chapter one, section 1.9.2. The software for both devices was identical, it was written by Andrew Hardwick of the BT Exact laboratories (Hardwick et al, 1998). A set of Sanyo PH 200N headphones relayed white noise to the participants for the duration of the experiment in order to prevent any auditory cues from the PHANTOM™ influencing their judgments of the virtual textures.

#### **2.2.4 Stimuli**

The stimuli consisted of the same ten sinusoidal waveform virtual textures featuring smooth planes at each end used by Colwell et al (1998). Figure 2.3 (on the following page) depicts part of an enlarged sinusoidal waveform with smooth planes at each end.



**Figure 2.3 Drawing of a sinusoidal groove profile.**

The amplitude of the sinusoidal grooves, i.e. half their peak to peak height, was constant across the virtual textures at .1125mm. The ten virtual textures differed in the width of their respective sinusoidal grooves, which ranged between .675mm and 2.700mm in 10 equal increments of .225mm. The dimensions of the virtual textures are shown in table 2.1 (on the following page). The texture featuring a groove width of 1.575 (highlighted in bold font in table 2.1) was used as the baseline texture, as had been the case in Colwell et al (1998). The 1.5mm baseline texture also appeared in the run of the 10 textures that were to be compared to the baseline. The values for the 1.5mm texture that appear in subsequent graphs are the magnitude estimates for this texture relative to when it was presented as the baseline, not the value ascribed to it as the baseline.



**Table 2.1 The dimensions of the virtual textures used in experiment one**

Texture number	Groove width (mm)	Amplitude (mm)
1	.675	.1125
2	.900	.1125
3	1.125	.1125
4	1.350	.1125
<b>5</b>	<b>1.575</b>	<b>.1125</b>
6	1.800	.1125
7	2.025	.1125
8	2.250	.1125
9	2.475	.1125
10	2.700	.1125

### **2.2.5 Procedure**

Participants were seated with the PHANTOM™ device in front of them in the horizontal plane. Participants were asked to sit at a distance whereby they could comfortably explore the device's entire workspace without needing to change their seating position. Participants were also asked not to change their seating orientation relative to the PHANTOM™ throughout the course of the experiment. The Sighted participants were blindfolded for the duration of the experiment.

The participants were informed that the experiment would involve them making judgments about the roughness of a series of virtual textures. They were given a pair of headphones, which they were asked to wear for the duration of the experiment. The headphones relayed static noise to the participants in order to mask any noises produced by the PHANTOM™. As an additional precaution, the participants were also told that such noises

were not a reliable source of information about the virtual textures. The participants were not given any visual representations of the virtual textures during the experiment; they had to reach their judgments using only the information relayed to them via the PHANTOM™ device.

To introduce the participants to the virtual textures, they were sequentially presented with two virtual textures of the kind used in the experiment proper. They were asked simply to judge which one they perceived as being rougher. The experimenter then explained the magnitude estimation procedure that the participants were to use in judging the roughness of the virtual textures. To ensure that the participants understood the procedure, they were then asked to respond to a hypothetical example given by the experimenter. The participants were then told that they would first be presented with the baseline texture, followed by a run of ten further virtual textures. They were informed that they would be permitted as much time as they required for interacting with each virtual texture, but they would only be permitted to feel each virtual texture, including the baseline texture, once per run. The participants were also instructed that for every virtual texture, apart from the baseline texture, they should sweep the PHANTOM™ 's endpoint from left to right once only. The participants were then given the opportunity to practice the experimental procedure on a series of virtual textures with dimensions not utilised in the experiment itself.

The participants were then presented with the baseline virtual texture, which was identical for all participants and for all runs. They were asked to ascribe any positive non-zero number to it. The participants were then sequentially presented with the ten virtual textures, randomly ordered by the computer. After each virtual texture had been presented, the participants were asked to use the magnitude estimation technique to describe its roughness. This procedure was repeated on 6 consecutive occasions (runs) of the 10 virtual textures. Participants were given the option of being reminded about any

aspect of the experimental procedure after each run of the virtual textures. They were also told that they could ask for a break between any of the runs of the virtual textures if they felt fatigued.

Upon the completion of each run of the virtual textures, the participants were once again presented with the baseline virtual texture and told to remind themselves of how it felt. They were given the option of retaining the number they had ascribed to the baseline for the previous run or ascribing it an alternative number. This procedure was repeated for both the thimble and stylus endpoints of the PHANTOM™ with each participant. The endpoint that the participant used first was counterbalanced.

## 2.3 Results

The raw data was prepared for analysis in the following way. First, every magnitude estimate made by a participant was divided by the baseline specified by the participant for that particular run of the virtual textures. The geometric mean for the participant's magnitude estimates for each of the ten virtual textures over the six runs was then established. The natural logarithms of these means were then calculated. Two types of statistical analysis were applied to this data: regression analysis and analysis of variance. Inferential tests were all conducted to the 95% confidence level.

Regression analysis provides the psychophysical function (exponent), which describes the relationship between the groove widths of the virtual textures and perceived roughness. Exponents were obtained by regressing log (magnitude estimates) on log (groove width/groove width standard). Thus, the values for the 1.575mm texture that appear in subsequent graphs are the magnitude estimates for this texture relative to when it was presented as the standard, not the value ascribed to it as the standard.

An exponent of less than one indicates that as groove width increases, greater differences in groove width are needed to produce the same difference in perceived roughness. An exponent of more than one indicates that as groove width increases, smaller differences in groove width are required to produce the same difference in perceived roughness. The positive or negative nature of the exponent indicates the direction of the relationship between groove width and perceived roughness: a positive exponent indicates that as groove width increases, so does perceived roughness; a negative exponent indicates that as groove width increases, perceived roughness decreases. This was the type of analysis used by Colwell et al (1998).

Applying the same data (not collapsed over the 6 runs of the virtual textures) to an analysis of variance, indicates whether the participants' magnitude estimates of perceived roughness of the virtual textures significantly differ as a result of the variables of Groove Width, Run Number Visual Status and Endpoint. This is the type of analysis most frequently used by Lederman and her colleagues. The results section begins by looking at the effect of experimental variables on the participants' exponent data before moving on to consider the effect of the experimental variables on the participants' magnitude estimates of the roughness of the virtual textures

### **2.3.1 Analysis of the participants' exponents**

Table 2.2 (on the following page) displays individual blind and sighted participants' exponents associated significance levels, for both the stylus and thimble endpoints.

**Table 2.2 Individual exponents, levels of significance and adj  $r^2$  for sighted and blind individuals with both stylus and thimble endpoints**

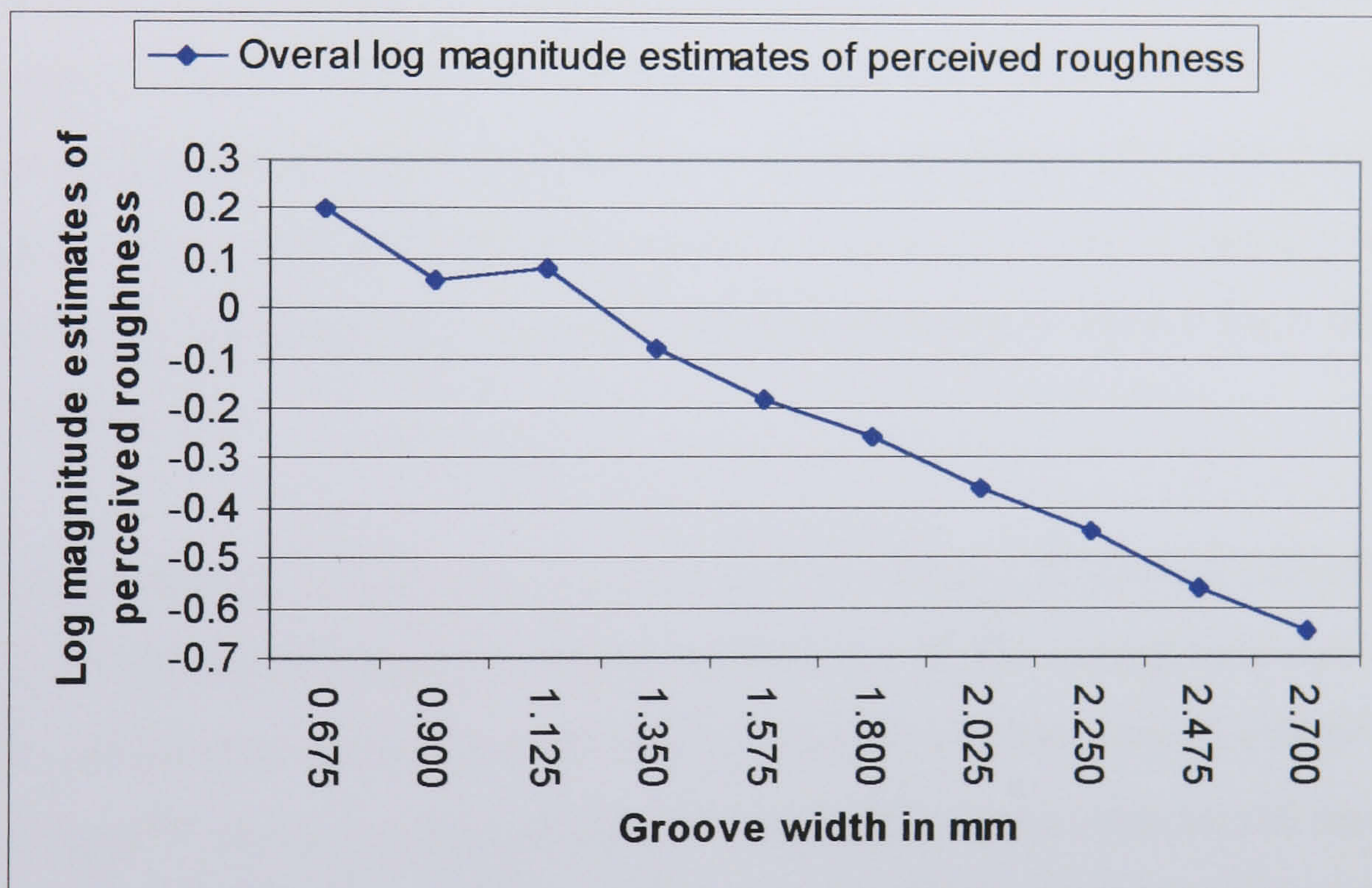
Participant Number	Stylus endpoint			Thimble endpoint		
	Exponent	(Adj) $r^2$	Sig. Of P	Exponent	(Adj) $r^2$	Sig. of P
<b>Sighted</b>						
1	-.708	.831	.0005	-.832	.610	.005
2	-1.08	.865	.0005	-1.55	.953	.0001
3	-.774	.655	.005	-.470	.581	.01
4	-1.06	.797	.0005	-1.34	.869	.0005
5	-.585	.557	.01	-.887	.910	.0001
6	-.573	.294	ns	-1.53	.912	.0001
7	-.687	.672	.005	-.601	.889	.0001
8	-.696	.716	.005	-.237	.143	Ns
9	-.646	.647	.01	-1.10	.805	.0005
10	-.352	.190	ns	-.560	.601	.01
11	-.389	.388	.05	-.381	.338	.05
12	-.036	.088	ns	.104	.070	ns
13	-.229	.872	.0001	-.592	.972	.0001
<b>Blind</b>						
1	-.827	.751	.001	-1.46	.895	.0001
2	-.420	.845	.0005	-.597	.906	.0001
3	-.446	.584	.01	-.700	.877	.0001
4	-.231	.425	.05	-1.48	.903	.0001
5	-.730	.824	.0005	-.846	.859	.0005
6	-.403	.775	.001	-.159	.143	ns
7	-.515	.600	.01	-.607	.788	.0005
8	.463	.913	.0001	.608	.928	.0001
9	-.514	.688	.005	-.766	.889	.0001
10	-.431	.648	.005	-.893	.924	.0001

Table 2.2 indicates that 10 out of 13 of the sighted participants exhibited an exponent reliably different from zero for each of the end points, and 1 sighted participant exhibited an exponent not reliably different from zero for the thimble endpoint only. The statistically reliable exponents from the sighted participants for both the stylus and the thimble endpoints were all negative.

Table 2.2 also indicates that all of the blind participants exhibited an exponent reliably different from zero for the stylus endpoint. One blind participant exhibited an exponent reliably different from zero with the stylus

endpoint only. 9 out of 10 of the statistically reliable exponents returned by the blind participants with the stylus endpoint were negative. 8 out of the 9 of the statistically reliable exponents obtained by blind participants with the thimble endpoint were negative.

A regression analysis was applied to participants' logged magnitude estimates of perceived roughness collapsed across the factors of Visual Status and Endpoint in order to establish the overall relationship between groove width and perceived roughness. Perceived roughness decreased as a function of increasing groove width,  $F(1, 21) = 139.21$   $p < .0005$  with an exponent of  $-.615$ . This is illustrated in figure 2.4

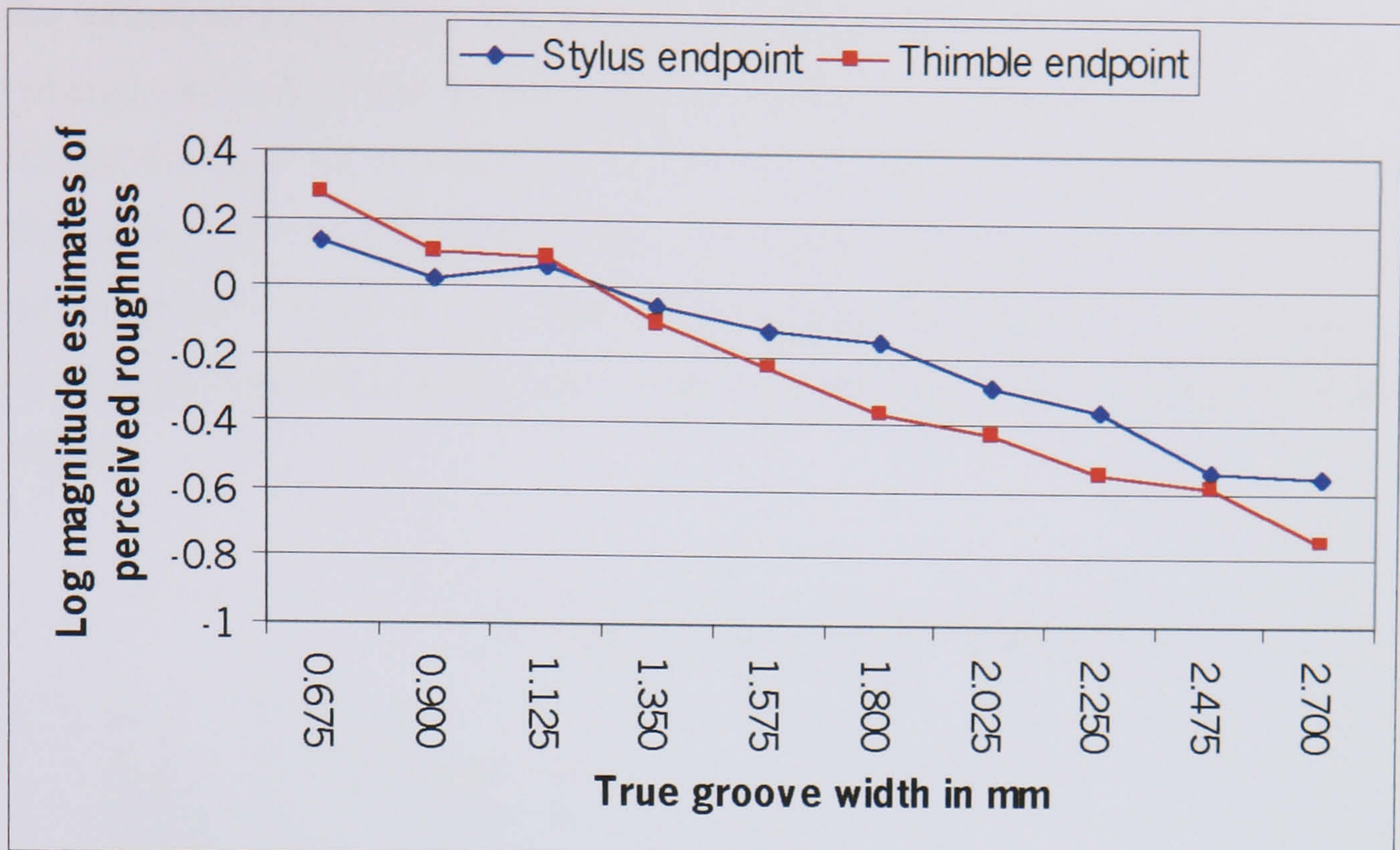


**Figure 2.4 Log magnitude estimates of perceived roughness collapsed across the factors of Endpoint and Visual Status plotted against the true groove widths of the respective virtual textures**

To look for any effects of the factors of Endpoint and Visual status on the relationship between groove width and perceived roughness, a two factor

mixed design analysis of variance was applied to the participants' exponents. The between subject factor was Visual Status (Sighted or blind participants) and the within subjects factor was Endpoint (stylus or thimble). There was no statistically reliable difference between the exponents returned by sighted and blind participants,  $F(1, 21) = .65$   $p = .427$ . However, the exponents returned by the participants between the stylus and thimble endpoints were found to differ reliably,  $F(1, 21) = 7.30$   $p = .013$ . Accordingly, a regression analysis was applied to the data from the stylus and thimble endpoints separately, collapsed across visual status, to return overall exponents for each endpoint. Perceived roughness decreased as a function of increasing groove width for the stylus endpoint,  $F(1, 9) = 58.25$   $p < .0005$  with an exponent of  $-.50$ . Perceived roughness also decreased as a function of increasing groove width for the thimble endpoint,  $F(1, 9) = 241.31$   $p < .0005$  with an exponent of  $-.730$ . The higher negative exponent for the thimble endpoint means that perceived roughness decreased more rapidly as a function of increasing groove width with the thimble endpoint than with the stylus endpoint.

The experimental results are summarised in figure 2.5 (on the following page), which depicts the perceived roughness of the virtual textures as a function of groove width for both the stylus and thimble endpoints of the PHANTOM™. Since no statistically reliable difference was found between the sighted and blind participants' exponents, the results have been collapsed across the factor of Visual Status.



**Figure 2.5 Log magnitude estimates of perceived roughness collapsed across blind and sighted individuals for the respective groove widths with the stylus and thimble endpoints**

### **2.3.2 Analysis of the participants' magnitude estimates of perceived roughness**

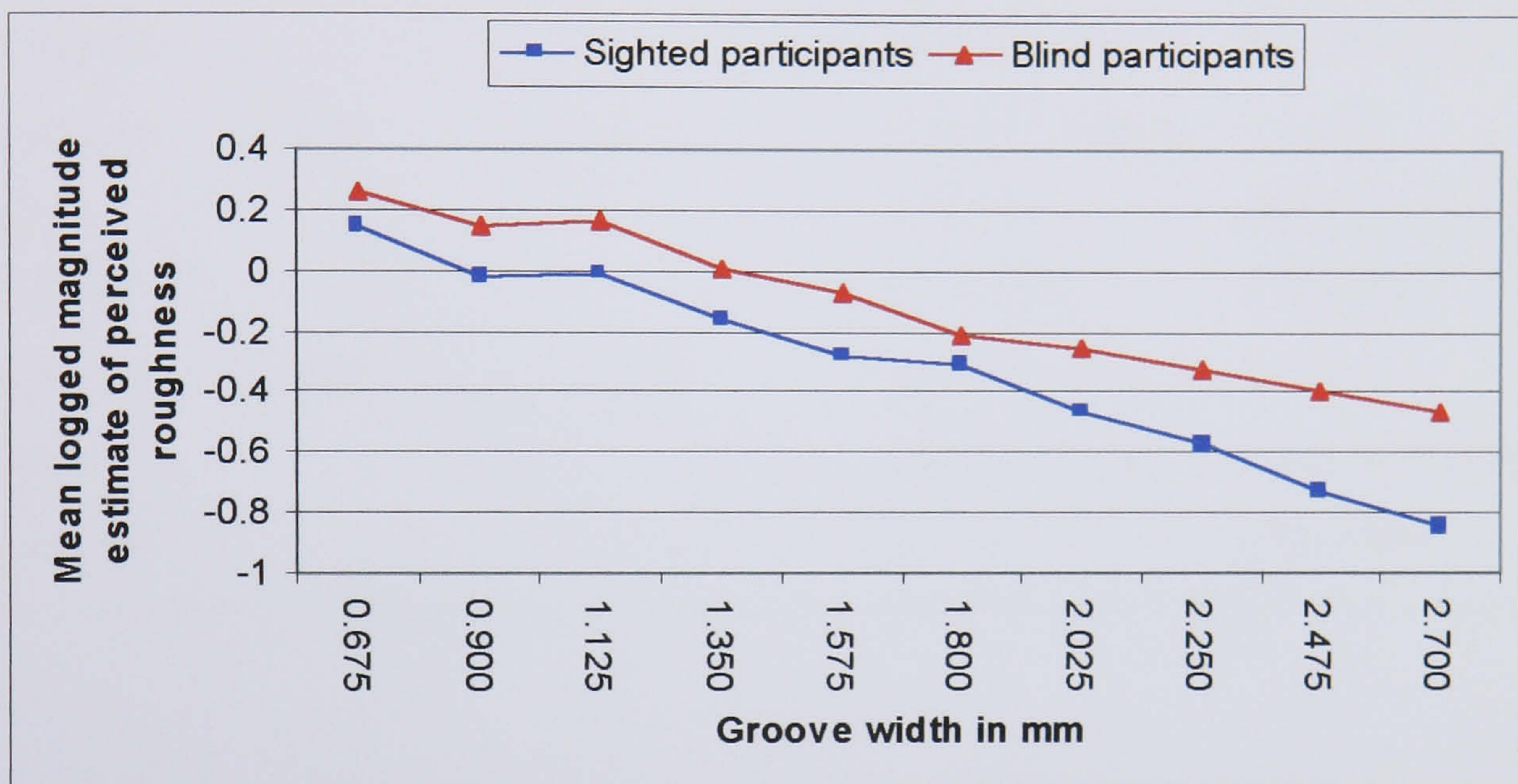
In order to ascertain whether the factors of Groove Width, Endpoint and Visual Status had a significant effect on the participants' magnitude estimates of the roughness of the respective virtual textures, an analysis of variance was then applied to the data.

A four factor mixed design analysis of variance was used, consisting of one between subjects factor (Visual Status) and three within subject factors (Groove Width, Run Number and Endpoint).

Only the variable of groove width was found to have a statistically reliable effect on the participants' magnitude estimates of the perceived roughness of



the virtual textures,  $F(9, 13) = 54.37$   $p < .0005$ . However, a statistically reliable interaction was found between the factors of Groove Width and Visual Status,  $F(9, 13) = 5.74$   $p < .0005$ . This is illustrated in Figure 2.6, which indicates that the difference in the magnitude estimates of the roughness of the respective textures provided by the sighted and blind participants gets more pronounced over the four virtual textures featuring the largest groove widths.



**Figure 2.6 Perceived roughness as a function of groove width for Sighted and blind individuals collapsed across the stylus and thimble endpoints**

### 2.3.3 Comparison of the data obtained with the PHANTOM™ and IE3000 devices

The exponents obtained with the PHANTOM™ device were then compared with those obtained by Colwell et al (1998) with the IE3000 device. Table 2.3 (on the following page) summarises the relative incidence of significant positive and negative exponents between the two devices.

**Table 2.3 The incidence of significant positive and negative exponents for sighted and blind participants between The IE3000 as reported in Colwell (1998) and The PHANTOM™ device**

	IE3000, Sighted participants	IE3000, Blind participants	PHANTOM™, Sighted participants	PHANTOM™, Blind participants
Overall	7 of 13	8 of 9	10 of 13	10 of 10
significant exponents			(Stylus) 11 of 13 (Thimble)	(Stylus) 9 of 10 (Thimble)
Significant positive exponents	2 of 7	4 of 8	0 of 13 (Stylus) 0 of 13 (Thimble)	1 of 10 (Stylus) 1 of 9 (Thimble)
Significant negative exponents	5 of 7	4 of 8	100% Stylus 100% Thimble	9 of 10 (Stylus) 8 of 9 (Thimble)

Table 2.3 indicates that only 7 out of 13 of sighted participants yielded statistically reliable exponents with the IE3000 device. This contrasts with 10 out of 13 of the sighted participants with the stylus endpoint of the PHANTOM™ and 11 out of 13 of the sighted participants with the thimble endpoint of the PHANTOM™. 5 out of 7 of the statistically reliable exponents returned by the sighted participants with the IE3000 device were negative. The statistically reliable exponents from the sighted participants using the PHANTOM™ were exclusively negative, irrespective of the endpoint used.

Table 2.3 also indicates that the number of blind participants individually exhibiting statistically reliable exponents was 8 out of 9 for the IE3000 device compared to 10 out of 13 with the stylus endpoint of the PHANTOM™ and 11 out of 13 for the thimble endpoint of the PHANTOM™.

4 out of 8 of the statistically reliable exponents for the blind participants with the IE3000 were negative, whereas 9 out of 10 of the statistically reliable exponents returned by the blind participants with the stylus endpoint and 8 out of 9 with the thimble endpoint of the PHANTOM™ were negative.

The incidence of statistically reliable positive and negative exponents between the IE3000 device and the PHANTOM™ device were compared with a Chi-square. There were no statistically reliable differences between the IE3000 and the PHANTOM™ device with the stylus or thimble endpoint with respect to the incidence of either positive or negative exponents.

The exponents obtained from the stylus and thimble endpoints of the PHANTOM™ device were then compared to the exponents obtained by Colwell et al (1998) with the IE3000. Since the data from this experiment and that of Colwell's indicated no statistically reliable difference between the exponents obtained for the sighted and blind individuals, a simple one-way ANOVA was performed. The independent variable was the device used i.e. the IE 3000, the PHANTOM™ (with the thimble endpoint attached) and the PHANTOM™ (with the Stylus endpoint attached). The dependent variable was the participants' exponents. The difference in the exponents obtained for each device was not found to be statistically reliable.

Unfortunately, it was not possible to compare the magnitude estimates of perceived roughness for the virtual textures obtained with the PHANTOM™ to those obtained with the IE3000, as the raw data from Colwell et al (1998) was not available to the author.

## 2.4 Discussion

### 2.4.1 The effect of groove width on perceived roughness with the PHANTOM™ device

Experiment one showed an overall negative exponent relating virtual groove width to perceived roughness with the PHANTOM™ haptic device: as virtual groove width increased, perceived roughness decreased. The results of this experiment appear largely comparable with those obtained by Colwell et al (1998) with the IE3000 device, in that the negative exponent relating groove width (inter-element spacing) to perceived roughness observed in Colwell et al (1998) also predominates here. There was no significant difference in the exponents relating groove width to perceived roughness obtained between the IE3000 device and the PHANTOM™ device, with either the thimble or the stylus endpoint. This means that, overall, participants were not significantly more sensitive to changes in groove with one device than with the other.

The results obtained in this experiment are also consistent with those of Wall and Harwin (2000), in which participants were asked to judge the roughness of sinusoidal textures with the PHANTOM™ device. In both experiments, for the majority of the participants, perceived roughness decreased with increasing groove width.

It could be argued that the negative exponent relating inter-element spacing to perceived roughness found in this study, Colwell et al (1998) and Wall and Harwin (2000) makes sense when viewed in the context of the findings of Klatzky and Lederman (1999). Klatzky and Lederman found that the perceived roughness of real quasi-sandpaper textures explored with

intermediary probes increased with increasing inter-element spacing until the point at which the inter-element spacing of texture surface was greater than the contact diameter of the probe. Further increases in inter-element spacing over and above the contact diameter of the probe then yielded *decreases* rather than increases in perceived roughness. Since the virtual contact diameter of both the IE3000 and PHANTOM™ devices is smaller than any of the groove widths of the virtual textures, it could be argued that it makes sense that perceived roughness should decrease with increases in groove width from the outset.

The above explanation would seem to conflict with the findings of Jansson (1998). After all, the contact point of the PHANTOM™ was smaller than any of the inter-element spacing values used in his study too, yet the perceived roughness of the virtual textures presented was found to increase as a function of increasing inter-element spacing. However, Jansson used virtual replicas of sandpaper of varying grit values, variations in the inter-element spacing of the stimuli were accompanied by concomitant variations in the amplitude of the particles of which the textures were comprised. This was not the case in either Klatzky and Lederman (1999), Colwell (1998), Wall and Harwin (2000) or this experiment, where only inter-element spacing was manipulated. Therefore, it seems very likely that the inconsistency between the results of Jansson (1998) and the aforementioned studies can be attributed to the relationship between probe size and inter-element spacing being confounded by the lack of control over the variable of stimulus amplitude.

Clearly, a study in which the type of stimuli used by Klatzky and Lederman (1999) is examined with the PHANTOM™ device is required to conclusively determine the reason for the inconsistency between the results of this experiment and those of Jansson (1998). If the results of such an experiment indicate that perceived roughness increases with increased inter-element

spacing, we can conclude that the negative exponent found in Colwell et al 1998a; 1998b; Wall and Harwin 2000 and this experiment would appear to be attributable to the sinusoidal stimuli used. However, if the results indicate that perceived roughness decreases with increasing inter-element spacing, then the relationship between the probe size and the inter-element spacing of the stimulus would seem to be the best candidate for accounting for the negative exponent. If this were the case, the results of Jansson (1998) could be attributed to the relationship between probe size and inter-element spacing being confounded by the lack of control over the variable of stimulus amplitude. Either way, the results of this experiment indicate that one should not assume that roughness perception with the PHANTOM™ device invariably increases as a function of inter-element spacing regardless of the type of texture used.

A study of roughness perception with sinusoidal stimuli in the real world would be very useful in establishing if the negative exponent relating groove width to perceived roughness can be attributed to the sinusoidal textures per se, or is limited to sinusoidal waveform textures presented in HVR. Unfortunately, the fabrication of sinusoidal textures of the dimensions used in this experiment in the real world remains highly problematical.

Interestingly, although the overall exponent relating groove width to perceived roughness was highly significant, not all of the participants individually demonstrated a significant relationship (exponent) between groove width and perceived roughness. Colwell et al (1998a; 1998b) also found that the relationship between groove width and perceived roughness was not significant for all her participants. These findings are difficult to put in context, since the vast majority of experiments investigating roughness perception have not reported individual data. It would be interesting to replicate this experiment's methodology using a texture waveform that could

be presented to participants in HVR and in the real world to determine whether the incidence of non significant exponents occurs in HVR specifically, or in roughness perception in the real world too. In any case, the results of this experiment and those of Colwell et al (1998) certainly serve as a caution that, in HVR, the relationship between groove width and perceived roughness is not meaningful for every individual.

#### **2.4.2 The effect of the Endpoint used with the PHANTOM™ device on perceived roughness**

The impact of the endpoint used with the PHANTOM™ device on roughness perception in HVR was difficult to anticipate, as this variable had not previously been addressed by research. It transpired that the stylus and thimble endpoints were comparable in terms of the number of significant exponents they yielded. This indicates that both endpoints are roughly equal in terms of their amenability to being used in roughness perception with the PHANTOM™ device. Statistical analysis revealed that the perceived roughness of the respective virtual textures did not differ significantly between the two endpoints; in other words, the virtual textures explored with the stylus endpoint did not feel significantly rougher or smoother when they were examined with the thimble endpoint, and vice versa. However, the thimble endpoint yielded a significantly larger overall negative exponent than the stylus endpoint. This means that perceived roughness decreased more rapidly with increases in groove width for the thimble than it did for the stylus endpoint for both sighted and blind participants. Put another way, the participants were more sensitive to changes in groove width with the thimble endpoint than with the stylus endpoint.

An explanation for this effect may lie in an amount of contact force an individual applies to the virtual textures with the respective endpoints. For

example, when using the thimble endpoint, the individual might, intentionally or unintentionally, apply more contact force to the virtual textures. This might occur simply because it is easier to apply more contact force with the thimble endpoint than with the stylus endpoint, as the individual's finger is secured and will not slip, as might occur with the stylus. If participants were applying more force to the virtual textures with the thimble endpoint, it is odd that this was not reflected in significantly higher magnitude estimates of roughness for the thimble endpoint, which is what would be predicted by Lederman (1974). However, since Lederman (1974) did not compare participants' exponent data, the notion that contact force might significantly affect the exponent relating groove width to perceived roughness is not at odds with the real world based literature.

The fact that the thimble and stylus endpoints returned significantly different exponents provide impetus to examine whether the two endpoints can be distinguished in terms of an interaction related determinant of perceived roughness. The variable of the contact force that the individual applies to the virtual textures seems particularly worthy of further investigation in this regard.

### **2.4.3 The effect of visual status on perceived roughness with the PHANTOM™ device**

The results of this experiment indicated that the exponents returned by sighted and blind participants were not significantly different. This was also the case in Colwell et al (1998). This means that sighted and blind participants were not significantly different in terms of their sensitivity to variations in the groove widths of the virtual textures with either device. In this experiment, the magnitude estimates of the perceived roughness of the virtual textures were also not found to significantly differ between sighted and



blind participants. This means that, overall, the sighted participants did not perceived the respective virtual textures as being significantly rougher or smoother than the blind participants and vice versa. However, an interaction was found between the variables of visual status and groove width: the difference between sighted and blind individuals magnitude estimates of perceived roughness tended to increase with increasing groove width. This is a difficult result to put into context, as Colwell et al (1998) did not incorporate comparisons of the sighted and blind participants' magnitude estimates of perceived roughness. Heller (1982) posited that the role of vision in texture perception was to guide the exploratory motions of the hand, presumably to ensure that the lateral sweep EP, optimal for texture perception, was being performed efficiently. Being deprived of vision might have meant that the sighted participants in this experiment were less able to control tangential movements running parallel to, rather than across, the ridges and grooves of the sinusoidal groves than the blind participants. Such movements might have made the respective virtual textures feel nominally smoother to the sighted participants than to their blind counterparts. The extent of such tangential deviations in movement might have increased with increasing groove width. This explanation is speculative at this time, an experiment in which the PHANTOM™ device precisely monitors the exploratory movements of sighted and blind participants' when exploring the virtual textures would be required to test its validity.

The nature of the significant exponents relating groove width to perceived roughness with the PHANTOM™ device was very consistent between blind and sighted participants. All but one blind participant exhibited a negative exponent relating groove width to perceived roughness with both the thimble and the stylus endpoints of the PHANTOM™. There was nominal difference in the number of statistically reliable exponents yielded by sighted and blind participants: overall, the blind participants yielded more statistically reliable exponents than the sighted participants. This is in broad agreement with

Colwell et al (1998) who found a higher incidence of statistically unreliable exponents in the sighted participants than in the blind participants. Thus, the results of this experiment and those of Colwell et al (1998) have indicated that it might be the case that, in HVR, the relationship between inter-element spacing and perceived roughness is slightly more robust for blind individuals than for sighted individuals. At this stage it is a little premature to state this conclusively, but it is certainly a trend that warrants vigilance in any prospective experiments of the impact of visual status on roughness perception in HVR. It would be interesting to see if the results obtained from sighted and blind individuals in this experiment and that of Colwell et al (1998) also applied to different types of virtual textures.

In summary, the results of experiment one indicated that perceived roughness decreased as a function of increases in the groove width of virtual textures presented via the PHANTOM™ device for most, but not all, users. This is the opposite of what has been found in real world based research on roughness perception, but is in agreement with research on perceived roughness in HVR.

The endpoint used with the PHANTOM™ device was found to exert a significant impact on the exponent relating groove width to perceived roughness: specifically, perceived roughness decreased more rapidly as a function of increasing groove width with the thimble endpoint than with the stylus endpoint. However, the perceived roughness of the respective virtual textures per se did not differ significantly between the stylus and thimble endpoints of the PHANTOM™ device.

Roughness perception in HVR was found to be comparable between the PHANTOM™ device and the IE3000 device, irrespective of the endpoint used with the PHANTOM™. The exponents relating groove width to perceived roughness did not differ significantly between the devices and the

incidence of positive and negative exponents was also found to be comparable between the devices.

Finally, perceived roughness in HVR with the PHANTOM™ device was found to be similar between sighted and blind individuals. The exponents returned by both groups of participants were not found to be significantly different, which is in agreement with the results of Colwell et al (1998). However, the difference between sighted and blind individuals' magnitude estimates of perceived roughness of the virtual textures increased with increasing groove width. This was not noted in Colwell (1998).

Having investigated the relationship between a physical parameter of virtual texture and perceived roughness, the experimenter wanted to make some progress in ascertaining the impact of a variable related to a participant's interaction with virtual texture on perceived roughness in HVR. This is undertaken in experiment two.

## **2.5 Experiment 2: The impact of applied contact force on the perception of roughness in virtual reality.**

### **2.5.1 The effect of contact force on perceived roughness with the PHANTOM™ device**

Having investigated the impact of a stimulus related determinant of perceived roughness, the thesis now moves on to address the effect of a variable related to an individual's interaction with virtual textures on perceived roughness.

A review of the literature revealed that contact force is the most important interaction related determinant of perceived roughness in the real world, (Lederman and Taylor, 1972; Lederman, 1974; Lederman, 1981; Lederman, 1983). Users are free to vary the amount of contact force they apply to virtual textures with a force feedback device such as the PHANTOM™. However, the amount of contact force individuals chose to apply to virtual textures and the impact of variations in contact force on perceived roughness in HVR has not been examined. Extra impetus to examine the effect of contact force on perceived roughness in HVR is provided by possibility that differences in the amount of contact force being applied to the virtual textures might account for the significant difference in the exponents yielded by the stylus and the thimble endpoints in the previous experiment.

In formulating the questions addressed by this experiment, the questions posed by Lederman (1974) and the main findings of that experiment bear reiteration. Lederman (1974) sought to examine the effect of the imposition of specified amounts of contact force on the perception of roughness, in addition to establishing how much contact force an individual normally applies to real textures when judging their roughness. She also wanted to

ascertain if there was any relationship between the variable of groove width and the amount of contact force participants chose to apply to the textures.

Lederman (1974) found that the perceived roughness of a given texture increased with increasing contact force, the impact of contact force became more pronounced as groove width increased. The average force applied by the participants was found to be .68N. In the force condition where participants were free to modulate the amount of force they applied to the textures, their use of contact force and their magnitude estimates of perceived roughness were found to be consistent over a number of presentations of the textures. With regards to the question of the relationship between groove width and applied contact force, the results indicated that contact force increased significantly with groove width. Unfortunately, Lederman only analysed the impact of contact force on the perceived roughness of the respective textures per se and did not also examine the impact of contact force on the psychophysical function (exponent) relating groove width to perceived roughness.

Taylor and Lederman (1975) posit that increases in contact force, increase the depth to which the individuals finger/s can descend into the gaps between the raised elements of which a texture is comprised. This results in increases in the cross sectional area of the deviation of the skin from its resting position, which is said to be responsible for determining perceived roughness. However, in interacting with virtual textures, increases in contact force are no longer accompanied by the concomitant increases in the cross sectional area of the deviation of the skin from its resting position. Would the lack of cutaneous information negate the effect of contact force, or would there be an effect of contact force on perceived roughness in the absence of cutaneous deformation thought to be underpinning its effect in the real world?

This experiment sought to answer much the same questions posed by Lederman (1974) in the context of HVR. The experiment was devised to determine the impact of the imposition of two different applied forces on participants' perception of the perceived roughness of virtual textures and the psychophysical function relating groove width to perceived roughness. The experiment was also designed to indicate the amount of contact force that individuals would normally apply to the virtual textures of their own volition and whether there would be a relationship between groove width and contact force.

### **2.5.2 The interaction between the variables of contact force and the endpoint used with the PHANTOM™ device**

It is possible that the impact of the exploratory variable of contact force might differ between the thimble and stylus endpoints of the PHANTOM™ device. Experiment one clearly indicated that the perception of roughness with the PHANTOM™ device is significantly affected by the endpoint utilised with the device. Since the physical nature of the interaction between the user and the virtual texture is identical regardless of the specific endpoint being used, it is logical to assume that the perceptual differences might be attributable to a difference in one or more of the interaction related variables highlighted in chapter two induced by the endpoint.

The interaction related variable of contact force would appear to warrant investigation first, not only because it is significantly implicated in mediating perceived roughness in reality, but also because there reason to believe that the degree of contact force that users apply to the virtual textures may differ as a function of whether they use the thimble or stylus endpoint (outlined on section 2.4.2).

### **2.5.3 The interaction between the variables of contact force and visual status**

The results of the previous experiment and that of Colwell (1998) have indicated that exponent data relating perceived roughness to groove width from sighted and blind individuals is not significantly different. One may intuitively conclude that this means that there is no significant effect of any variations in contact force on the psychophysical function between sighted and blind individuals. However, it might also be reasonable to maintain that contact force might well exert a significant influence the psychophysical function, but the application of contact force is homogenous between sighted and blind individuals, thus no difference is manifest between their exponents. Whether the perceived roughness of virtual textures at given contacts forces would vary between blind and sighted individuals is even more difficult to predict. The experimental design of Lederman (1974) did not include a sample of blind participants. Thus there is no data on whether the effects of contact force on the perceived roughness of texture are comparable for blind and sighted participants in reality, let alone in HVR.

In order to investigate the aforementioned issues, an experimental design similar to that of the previous experiment was used, with the addition of a contact force factor, featuring a number of levels. In two of these levels, the PHANTOM™ device imposed different contact forces on the participants during their interaction with the virtual textures. In the remaining level, the participants were free to apply the degree of contact force that they felt was appropriate to the virtual textures, as the participants in the previous experiment had done. However, on this occasion the contact force being applied to the virtual textures was being monitored and recorded by the PHANTOM™ device.

## **2.6. Method**

### **2.6.1 Participants**

This experiment utilised a total of 20 participants, 10 participants were sighted and the remaining 10 were blind. The sighted participant sample consisted of four males and six females, all of who reported having no sensory-motor impairments. Their ages ranged from 24 to 42, with the mean age being 33. The sighted participants were all University students/staff recruited from various disciplines.

The blind participant sample consisted of eight males and two females, all of who reported having no other sensory-motor impairments. Four of the blind participants were congenitally blind; the remaining six lost their sight between 1 and 30 years of age. The ages of the blind participants ranged from 33 to 55, with the mean age being 47. The blind participants were all volunteers recruited from a list visually impaired individuals who had expressed an interest in participating in the S.D.R.U.'s research.

### **2.6.2 Design**

This experiment utilised a five factor, mixed design consisting of one between subjects factor and four within subjects factors: The between subjects factor Visual Status featured two levels, blind and sighted participants. The within subjects factor Endpoint featured two levels, the thimble and stylus endpoints of the PHANTOM™ device; the within subjects factor Contact Force consisted of three levels, 1.49N, 2.99N and participant mediated force; the within subjects factor Groove Width featured eight levels, corresponding to the eight groove widths used; finally, the within subjects factor Run Number featured three levels, corresponding to the three occasions on which each texture was presented.



Participants examined three runs of the eight virtual textures under each of the contact force levels. The ordering of the contact force levels was randomised for each participant, as was the order in which the textures appeared within each run. This process was repeated for both the thimble and stylus endpoints. Therefore, each participant underwent 144 trials (8 textures x 3 runs x 3 contact force levels x 2 endpoints).

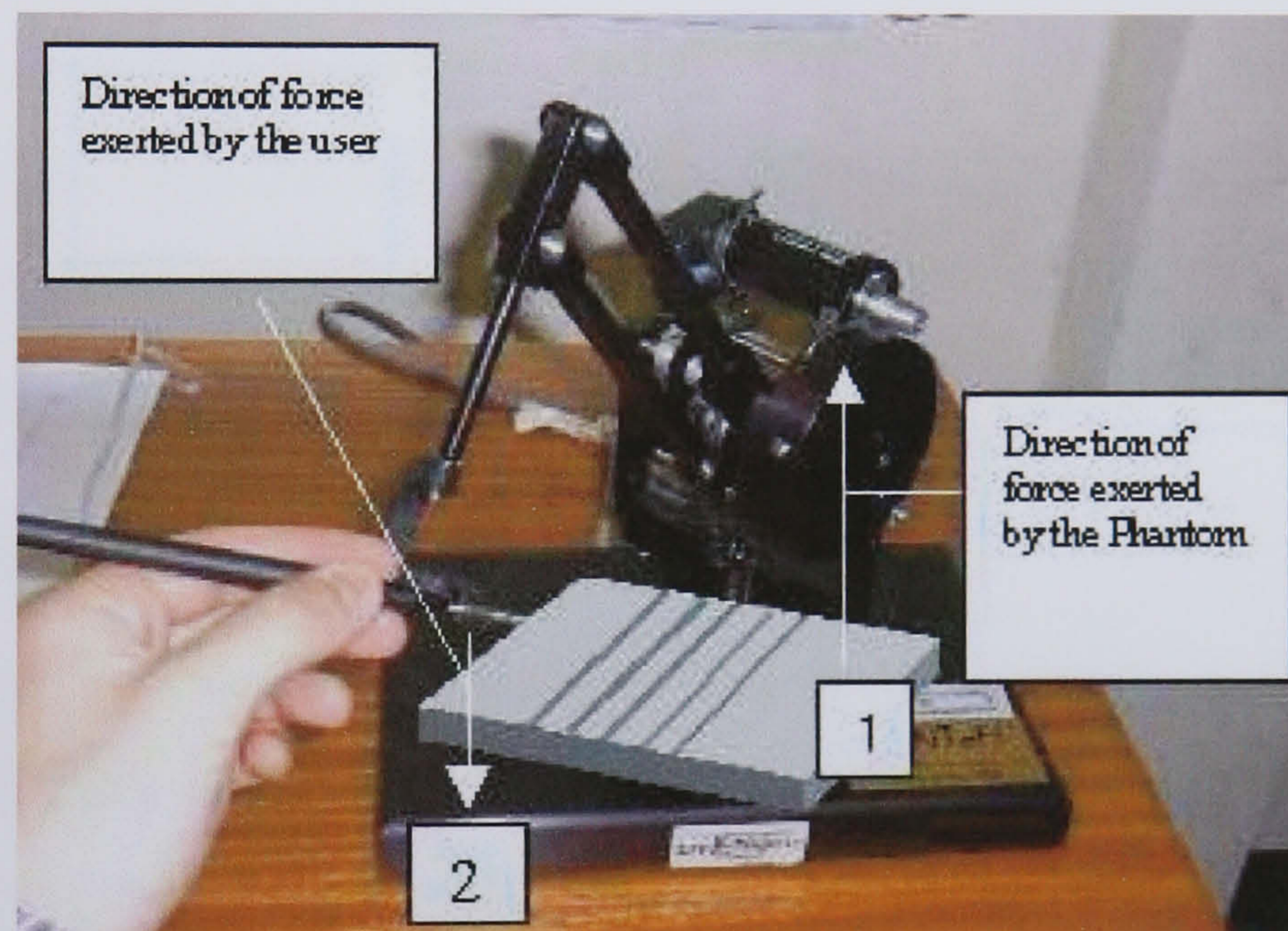
### **2.6.3 Apparatus/Stimuli**

The apparatus and stimuli used in this experiment were identical to that used in experiment one (refer to sections 2.2.3 and 2.2.4). The only differences being that only 8 of the textures used in experiment one were used here; the textures featuring groove widths of .675mm and .900mm were omitted. This action was taken in order to partially offset the increase in the number of trials each participant would have to undertake as a result of the two extra contact force levels. The baseline virtual texture used in this experiment was the one featuring a groove width of 1.800mm, in order that baseline texture fell in the middle of the range of the virtual textures to be presented. As with experiment one, the baseline texture also appeared in the run of the 10 textures that were to be compared to the baseline. The values for the 1.8mm texture that appear in subsequent graphs are the magnitude estimates for this texture relative to when it was presented as the baseline, not the value ascribed to it as the baseline.

The other difference was that, in addition to allowing the participants to feel the virtual textures using as much force as they wished, participants examined the textures under two applied force levels. The imposition of an applied contact force on the participants' interaction with the virtual textures was achieved by the use of a "counterbalancing" method. In reality this method involves the use of a set of scales featuring a weight, corresponding to the desired amount of contact force, on one end of the scales and a texture on the other end of the scales. Maintaining a constant contact force

on the texture is simply a matter of applying sufficient force to keep the weight at the end of the scales within the arc of the scales movement. This was the method used by Lederman (1974).

This method was replicated with the PHANTOM™ and is illustrated in figure 2.7 The PHANTOM™ applies a vertical force, corresponding to the desired contact force, to the virtual textures [1]. In the absence of any opposition from a user, the virtual textures would proceed in an upward motion to the top of the PHANTOM's workspace. The participants simply had to resist this upward motion by applying sufficient force to the virtual textures, such that the endpoint of the PHANTOM™ remained in the device's workspace [2]. In doing so, they were applying the desired amount of contact force.



**Figure 2.7 An illustration of the implementation of the applied force factor with the PHANTOM™ device (the virtual texture is visible for illustrative purposes only and is not accurate in both rendition and orientation)**

In the participant mediated force condition, the position of the virtual textures was constant, irrespective of the contact force the participants chose to

apply. The device simply recorded the amount of force that the participants were applying to the virtual textures.

Ideally, the experimenter would have liked to have used the same contact forces as Lederman (1974). However, pilot studies revealed that replicating her low force condition, which involved a 0.27N force, produced textures that were extremely difficult to discern with the PHANTOM™. Conversely, replicating her high force condition, which involved a 4.39N force, produced virtual textures that seemed unstable and produced aversive vibrations. An informal pilot study suggested that a force of 1.49N be used for the low force condition, as this was the minimum force value at which the participants seemed unanimously able to offer judgments of the virtual textures. The pilot study also suggested that a force of 2.99N be used as the high force condition, as this was the highest force value at which none of the pilot participants complained about the vibrations generated by PHANTOM™ device during their interaction with the virtual textures.

#### **2.6.4 Procedure**

The experimental procedure was very similar to that used in the previous experiment. Therefore, only the procedural additions stemming from the addition of the force levels will be covered here.

As in experiment one, Participants were seated with the PHANTOM™ device in front of them in the horizontal plane. Participants were asked to sit at a distance whereby they could comfortably explore the device's entire workspace without needing to change their seating position. Participants were also asked not to change their seating orientation relative to the PHANTOM™ throughout the course of the experiment. The sighted participants were blindfolded for the duration of the experiment.

The participants were informed that they would be examining the virtual textures under three contact force levels, which would be run separately, one after the other. The experimenter then demonstrated how the applied force levels would work, by presenting the participants with some virtual textures under the contact force level that they would be encountering first. The participants were given the opportunity to practice the experimental procedure on a series of virtual textures with dimensions not utilised in the experiment itself, at the start of each contact force level.

A run of eight randomly ordered virtual textures were given to participants on three consecutive occasions (runs) for each contact force level. The number of runs used in this experiment was half that of the previous experiment. This change was made in order to offset increase in the number of trials each participant would have to undertake as a result of the 2 applied force levels. The order in which the force levels were undertaken was randomly determined for each participant.

## **2.7 Results**

### **2.7.1 Analysis of the participants' exponents**

The exponents obtained from sighted and blind individuals with the stylus and thimble endpoints of the PHANTOM™ device in the high, low and participant mediated contact force levels are displayed in tables 2.4, 2.5 and 2.6 respectively. Inferential tests were all conducted to the 95% confidence level.

**Table 2.4 individual exponents and associated P values for participants in the high force condition**

Participant	Exponent Stylus	R2 Stylus	P value Stylus	Exponent Thimble	R2 Thimble	P value Thimble
Sighted 1	-.744	.799	.003	-.693	.701	.010
Sighted 2	.125	.040	.634	-.032	.008	.837
Sighted 3	2.34	.923	.000	1.64	.908	.000
Sighted 4	-1.74	.928	.000	-1.87	.765	.004
Sighted 5	-.277	.104	.436	.169	.839	.001
Sighted 6	-.418	.699	.010	-.726	.805	.003
Sighted 7	-1.25	.875	.001	-.155	.053	.585
Sighted 8	-.499	.656	.015	-.552	.885	.000
Sighted 9	-.205	.280	.178	-.218	.353	.120
Sighted 10	-.800	.957	.000	-.758	.393	.096
Blind 1	-.509	.826	.002	-.460	.657	.015
Blind 2	-1.73	.981	.000	-1.38	.876	.001
Blind 3	-.752	.811	.002	-.677	.663	.014
Blind 4	-.352	.694	.010	-.194	.141	.360
Blind 5	-1.16	.766	.004	-.757	.680	.012
Blind 6	-.300	.242	.216	-.553	.922	.000
Blind 7	-.753	.671	.013	-.297	.382	.103
Blind 8	-1.04	.564	.032	-1.08	.961	.000
Blind 9	-.958	.772	.004	-.729	.781	.004
Blind 10	-.718	.878	.001	-.129	.041	.629

Starting with the high force condition, table 2.4 indicates that 7 out of 10 of the sighted participants and 9 out of 10 of the blind participants individually exhibited a significant exponent with the stylus endpoint. 6 out of 7 of the statistically reliable exponents returned by the sighted participants were negative. All of the statistically reliable exponents returned by the blind participants with the stylus endpoint were negative. With respect to the thimble endpoint, 6 out of 10 of the sighted participants and 7 out of 10 of the blind participants individually exhibited statistically reliable exponents. 4 out of 6 of the statistically reliable exponents returned by the sighted participants were negative. All of the statistically reliable exponents returned by the blind participants with the thimble endpoint were negative.

**Table 2.5 individual exponents and associated P values for participants in the low force condition**

Participant	Exponent Stylus	R2 Stylus	P value Stylus	Exponent Thimble	R2 Thimble	P value Thimble
Sighted 1	-.687	.783	.003	-.483	.707	.009
Sighted 2	.133	.146	.351	-.750	.822	.002
Sighted 3	1.83	.979	.000	1.34	.680	.012
Sighted 4	-.462	.303	.158	-.006	.000	.983
Sighted 5	.059	.051	.592	.249	.692	.010
Sighted 6	-.342	.741	.006	-.228	.361	.115
Sighted 7	-1.35	.844	.001	.069	.006	.860
Sighted 8	-.482	.905	.000	-.386	.903	.000
Sighted 9	-.265	.394	.096	-.274	.198	.269
Sighted 10	-1.10	.912	.000	-.567	.449	.069
Blind 1	-.308	.543	.037	-.322	.594	.025
Blind 2	-1.46	.898	.000	-.958	.645	.016
Blind 3	-.890	.813	.002	-.797	.710	.009
Blind 4	-.664	.866	.001	-.113	.286	.172
Blind 5	-.840	.488	.054	-1.25	.698	.010
Blind 6	-.472	.601	.024	-.492	.837	.001
Blind 7	-.824	.498	.051	-.803	.661	.014
Blind 8	-1.06	.747	.006	-.714	.768	.004
Blind 9	-1.03	.873	.001	-.412	.445	.071
Blind 10	-.589	.756	.005	-.426	.251	.206

Turning to the Low force condition, table 2.5 indicates that 6 out of 10 of the sighted participants and 8 out of 10 of the blind participants individually exhibited statistically reliable exponents with the stylus endpoint. 5 out of 6 of the statistically reliable exponents returned by the sighted participants were negative. All of the statistically reliable exponents with the stylus endpoint from the blind participants were negative. With respect to the thimble endpoint, 5 out of 10 of the sighted participants and 7 out of 10 of the blind participants individually exhibited statistically reliable exponents. Of the sighted participants who returned statistically reliable exponents, 3 out of 5 exhibited negative exponents. All of the statistically reliable exponents with the thimble endpoint from blind individuals were negative.

**Table 2.6 individual exponents and associated P values for participants in the participant mediated force condition**

Participant	Exponent Stylus	R2 Stylus	P value Stylus	Exponent Thimble	R2 Thimble	P value Thimble
Sighted 1	-.397	.775	.004	-.338	.441	.072
Sighted 2	-.846	.736	.006	-.300	.327	.138
Sighted 3	1.24	.692	.010	2.05	.942	.000
Sighted 4	-.429	.180	.295	-.223	.086	.482
Sighted 5	.245	.905	.000	.186	.622	.020
Sighted 6	-.020	.001	.929	-.190	.151	.341
Sighted 7	-1.12	.814	.002	.280	.022	.724
Sighted 8	-.334	.680	.012	-.233	.371	.109
Sighted 9	-.436	.751	.005	-.103	.037	.649
Sighted 10	-1.39	.811	.002	-1.20	.709	.009
Blind 1	-.502	.723	.008	-.410	.751	.005
Blind 2	-1.90	.840	.001	-2.25	.919	.000
Blind 3	-.399	.250	.207	-.677	.536	.039
Blind 4	-.636	.710	.009	-.346	.348	.124
Blind 5	-1.03	.819	.002	-.804	.586	.027
Blind 6	-.849	.973	.000	-.907	.818	.002
Blind 7	-.752	.600	.024	-.500	.359	.116
Blind 8	-1.27	.901	.000	-.730	.821	.002
Blind 9	-1.15	.832	.002	-.846	.554	.034
Blind 10	-.727	.646	.016	-.411	.321	.143

Turning finally to the participant mediated force condition, table 2.6 indicates that 8 out of 10 of sighted participants and 9 out of 10 of the blind participants individually exhibited statistically reliable exponents with the stylus endpoint. 6 out of 8 of the statistically reliable exponents exhibited by the sighted participants were negative. All of the significant exponents returned by the blind participants with the stylus endpoint were negative. With respect to the thimble endpoint, 3 out of 10 of the sighted participants and 7 out of 10 of the blind participants individually exhibited significant exponents. 2 out of 3 of the statistically reliable exponents returned by the sighted participants were negative. All of the statistically reliable exponents returned by the blind participants with the thimble endpoint were negative.

In order to facilitate comparisons between the force conditions, a summary of the incidence of significant positive and negative exponents derived from tables 2.4, 2.5 and 2.6, is provided in table 2.7

**Table 2.7 Incidence of Positive negative and non-significant exponents according to Visual Status, Endpoint and Force factors**

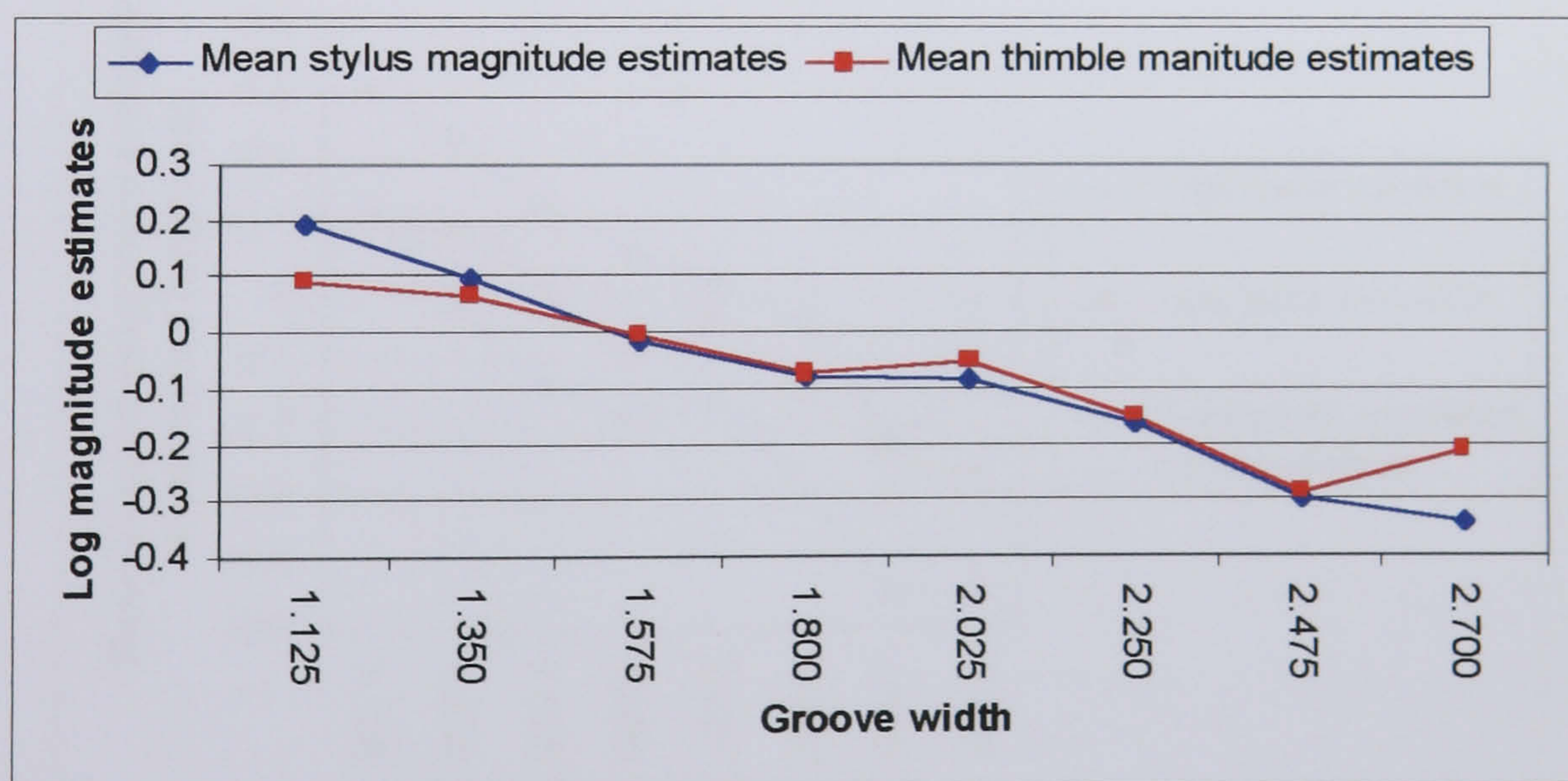
Visual status	Endpoint	Force condition	Significant negative exponents	Significant positive exponents	Non - significant exponents
Sighted	Stylus	High	6	1	3
		Low	5	1	4
		Free	6	2	2
	Thimble	High	4	2	4
		Low	3	2	5
		Free	2	1	7
Blind	Stylus	High	9	0	1
		Low	8	0	2
		Free	9	0	1
	Thimble	High	7	0	3
		Low	7	0	3
		Free	7	0	3

A logistic regression was applied to the data concerning the incidence of significant positive, negative and non-significant exponents shown in table 2.7. There is a statistically reliable effect of visual status, in that blind participants are more likely to produce significant negative exponents ( $p = 47/60$ ) than their sighted counterparts ( $p = 26/60$ ), chi-square (1) = 14.7,  $p = .0001$ . There is also an effect of end-point, in that the stylus endpoint is more likely to produce significant negative exponents ( $p = 43/60$ ) than the thimble endpoint ( $p = 30/60$ ), chi-square (1) = 6.4,  $p = .0116$ . There was no reliable effect of force, nor of any interactions with this factor.



A three factor mixed design ANOVA consisting of one between subjects factor (Visual Status) and two within subjects factors (Endpoint and Contact Force) was applied to the individual participants' exponents from each of the force conditions

There was no statistically reliable difference between the exponents obtained from the sighted and blind participants, ( $F(1, 18) = .536$   $P = .473$ ) or between the contact force conditions ( $F(2, 17) = .880$   $P = .424$ ). However a statistically reliable effect of Endpoint was discovered, ( $F(1, 18) = 8.782$   $P < .008$ ). Accordingly, separate regression analyses were conducted on the mean magnitude estimates of perceived roughness for the virtual textures, collapsed across the factors of Visual Status and Contact Force, for the stylus and thimble endpoints. The stylus and thimble endpoints returned exponents of  $-.707$  and  $-.514$  respectively, meaning that perceived roughness decreased more rapidly as a function of increasing groove width with the stylus endpoint than with the thimble endpoint. This is shown in figure 2.8 on the following page.



**Figure 2.8 Perceived roughness as a function of groove width collapsed across the force factor and visual status for the stylus and thimble endpoints**

## 2.7.2 Analysis of the participants' magnitude estimates of perceived roughness

A five factor mixed design analysis of variance consisting of one between subjects factor (Visual Status) and four within subjects factors (Groove Width, Contact Force, Run Number and Endpoint).

The effect of Groove Width was found to be statistically reliable,  $F(7,12) = 13.064$   $p < .0005$ . As figure 2.9 indicates, perceived roughness decreased as a function of groove width for all but the texture with a groove width of 2.025mm for the participants in the low and participant mediated force conditions and for the texture with a groove width of 2.700mm in the high force condition.

The effect of Contact Force was also found to be statistically reliable,  $F(2,17) = 10.853$   $p < .0005$ . Figure 2.9 shows that the virtual textures were judged roughest in the high force condition, followed by the low force condition then the participant mediated condition.

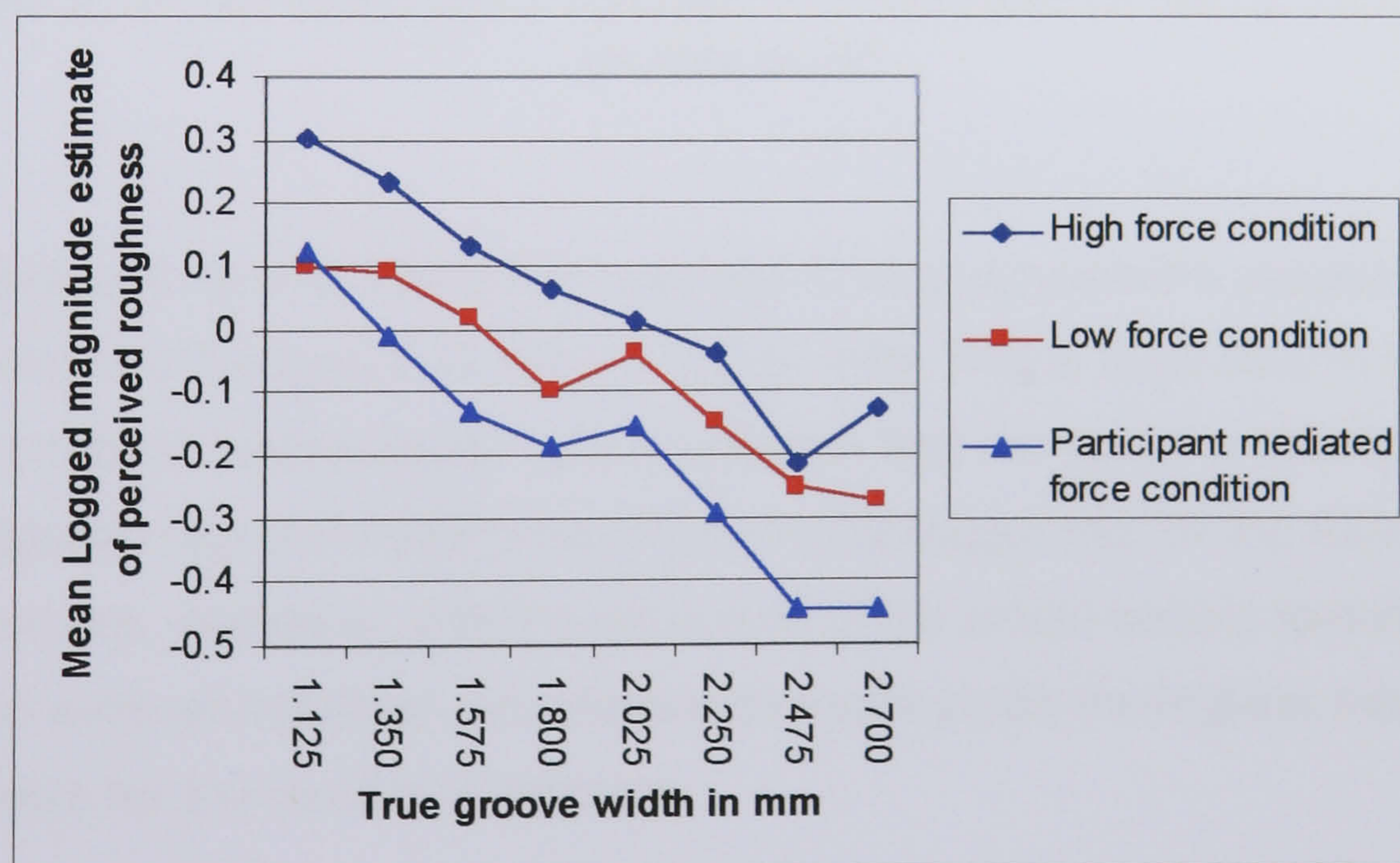
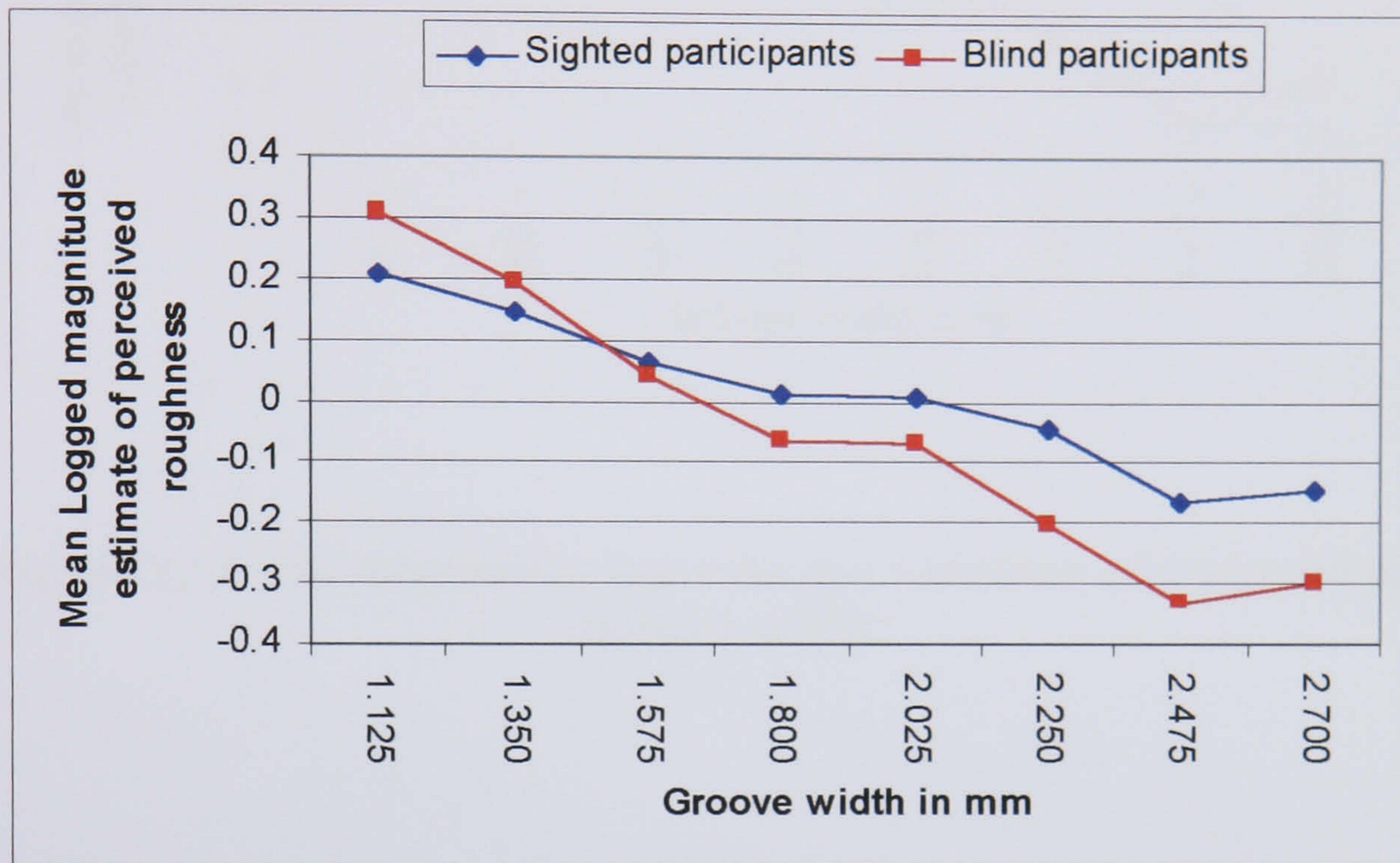


Figure 2.9 The effect of applied contact force on perceived roughness

A statistically reliable interaction was found between the variables of Groove width and Visual Status,  $F(7,12) = 3.663$   $p = .001$ . Figure 2.10 indicates that the discrepancy between the blind and sighted individuals' magnitude estimates of perceived roughness decreases over the first two textures and from that point onwards tends to increase with increasing groove width.



**Figure 2.10 The interaction between the variables of visual status and groove width**

A statistically reliable interaction was also found between the variables of Endpoint and Texture,  $F(7,12) = 3.122$   $p = .005$ . This is illustrated in figure 2.11 (on the following page), which indicates that the stylus endpoint yielded the highest magnitude estimates of perceived roughness for the narrowest two textures. However, with the exception of the virtual texture featuring a groove width of 2.250mm, the thimble endpoint yields the highest magnitude estimates for the remaining textures.

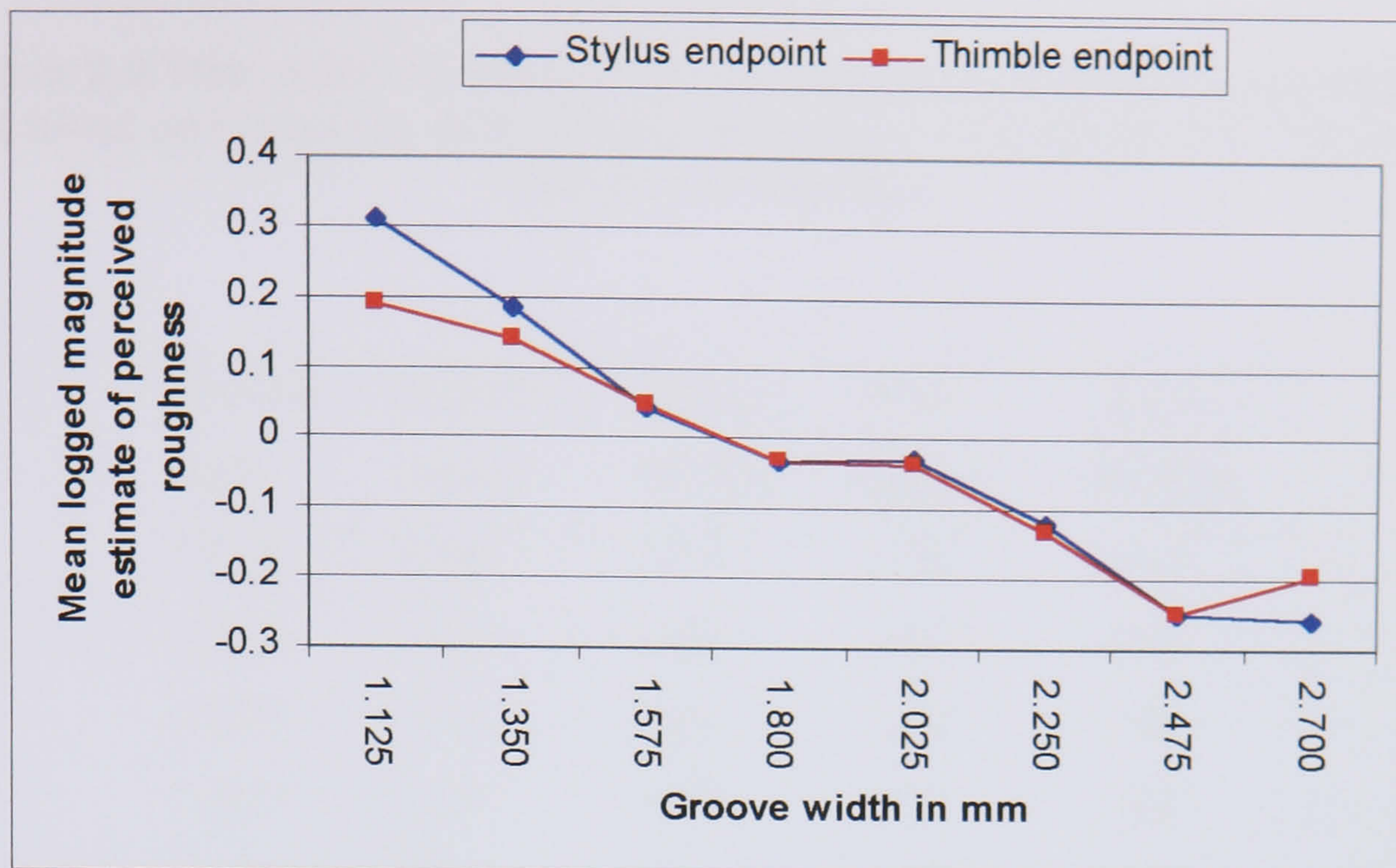


Figure 2.11 The interaction between the variables of endpoint and groove width

### 2.7.3 Analysis of the amount of contact force being applied to the virtual textures by the participants

The mean force applied by the sighted and blind participants with the stylus and thimble endpoints of the PHANTOM™ collapsed over the three runs of each virtual texture is displayed in table 2.8 (on the following page)

**Table 2.8 The mean contact force (in Newtons) applied by the sighted and blind participants with the stylus and thimble endpoints for each of the virtual textures.**

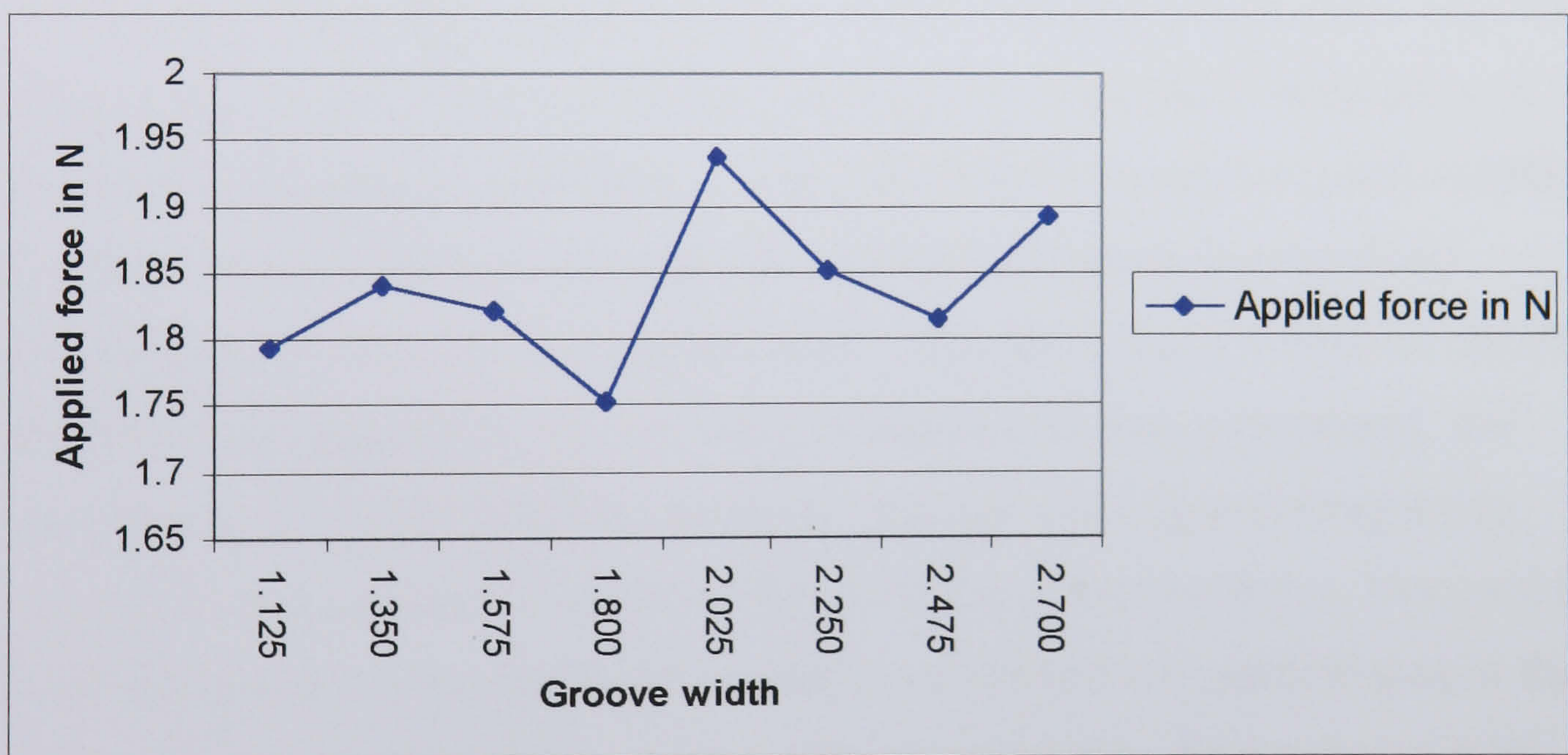
Groove width	Sighted stylus	Sighted thimble	Blind stylus	Blind thimble
1.125	1.99	1.73	1.70	1.74
1.350	1.93	1.80	1.65	1.97
1.575	1.77	1.81	1.76	1.92
1.800	1.91	1.74	1.75	1.60
2.025	2.08	2.01	1.76	1.88
2.250	1.94	1.80	1.81	1.84
2.475	2.16	1.87	1.63	1.58
2.700	2.09	1.74	1.78	1.94
Mean	1.98	1.81	1.73	1.81

Table 2.8 indicates that, for both sighted and blind participants, the mean forces applied to the virtual textures fell between 1.58 and 2.16N. The average force applied by the participants, collapsed over the factors of groove width, visual status and endpoint was 1.83N. For the most part it appears that, with both the stylus and thimble endpoints of the PHANTOM™ device, the mean contact force applied to the virtual textures is slightly higher for the sighted participants than for the blind participants. However, there does not appear to be any totally consistent trends relating fluctuations in applied contact force to the Factors of Groove Width, Endpoint or Visual Status.

A four factor mixed design analysis of variance consisting of one between subjects factor (Visual Status) and three within subjects factors (Groove

Width, Endpoint, and Run Number), was applied to the data indicating the amount of force the participants applied to the virtual textures.

No statistically reliable effects were found between the amount of force participants applied to the virtual textures as a function of either Groove Width, ( $F(7, 12) = .085$   $P = .546$ ), Run Number, ( $F(2, 17) = .074$   $P > .484$ ), Endpoint, ( $F(1, 18) = .043$   $P > .837$ ) or Visual Status, ( $F(1, 18) = .012$   $P > .733$ ). Furthermore, there were no statistically reliable interactions between these variables. Therefore, the data has been collapsed over the Visual Status, Run Number and Endpoint factors in figure 2.12 (on the following page), which illustrates the mean amount of force applied to each of the virtual textures by the participants. Figure 2.12 reinforces the aforementioned observation that there is not a consistent trend relating fluctuations in applied contact force to Groove Width.



**Figure 2.12 The mean force in Newtons applied to the virtual textures as a function of groove width, collapsed across the factors of endpoint and visual status.**

## **2.8 Discussion**

### **2.8.1 The effect of contact force on perceived roughness with the PHANTOM™**

The introductory section of this chapter set out three questions regarding the effect of contact force on roughness perception in HVR (p28-29). These questions mirrored those of Lederman (1974), who addressed the impact of contact force on roughness perception in real world in detail.

The first of these questions concerned the effect of the imposition of different levels of contact force on perceived roughness in HVR. The results of this experiment are in agreement with Lederman and Taylor, 1972; Lederman, 1974; Lederman, 1981 and Lederman, 1983, in that contact force was found to be a significant influence on the participants' magnitude estimates of perceived roughness. However, Lederman (1974) found that participants in the high force condition returned the highest estimates of perceived roughness, followed by the participants in the participant mediated condition, and then participants in the low force condition. In this experiment, the participants in the high force condition returned the highest magnitude estimates of perceived roughness for all of the virtual textures, followed by the participants in the low force condition, and then the participants in the participant mediated force condition. To examine this discrepancy, it is necessary to look at the amount of force the participants chose to apply to the textures in the participant mediated force condition of this experiment and that of Lederman (1974).

When Lederman (1974) examined the amount of force the participants applied to the textures in her participant mediated force condition, she found that the mean force being applied to the textures by the participants was

.68N. This fell between the values of the low and high force conditions, which featured contact forces .27N and 4.39N respectively. Therefore, Lederman (1974) concluded that the ordering of the force conditions was consistent with perceived roughness increasing with increasing contact force.

In this experiment, the mean force applied to the virtual textures in the participant mediated force condition was 1.83N, which also falls between the low force (1.49N) and high force (2.99N) conditions, yet the participants' magnitude estimates of perceived roughness were greater in the low force condition than in the participant mediated force condition.

The most likely reason for this discrepancy between the results of this experiment and those of Lederman (1974) is the difference in applied forces chosen for the respective low force conditions. It may be the case that the absence of cutaneous information in HVR meant that the slightly higher forces applied to the virtual textures in the participant mediated force condition relative to the low force condition were not sufficient to yield higher magnitude estimates of perceived roughness. Perhaps the increased demands on the participants' attention resulting from controlling applied force ameliorated the effect of variations in the groove widths of the virtual textures relative to the low force condition. This possibility could be investigated by conducting an experiment featuring a condition in which the average force applied by the participants in the participant mediated force condition then constitutes the contact force used in an imposed force condition. If the above explanation is accurate, then the magnitude estimates of perceived roughness should be higher for the virtual textures presented in the imposed force condition than in the participant mediated condition.

The relationship between groove width and perceived roughness was similar for all three force groups, the similarity being particularly pronounced for the low force condition and the participant mediated force condition. In all force conditions the participants' magnitude estimates of the roughness of the



virtual textures decreased with increasing groove width, interestingly, with one exception in each force condition. In the high force condition the groove width measuring 2.700 mm actually yields a higher mean magnitude estimate than the groove width measuring 2.475mm, although this appears to be due to the fact that the mean magnitude estimates of perceived roughness for the texture featuring the groove width of 2.475mm is particularly low. The same cannot be said for the low force and participant mediated force conditions, as in both cases the texture featuring the groove width of 2.025 seemed to represent a positive 'blip' in an otherwise negative correlation between groove width and perceived roughness. At this time the author is unable to offer an explanation for this anomalous finding. However, irregularities in data trends in real-world research on roughness perception have also been reported. For example, Heller (1982) reported that participants did not consistently judge sandpaper with a grit value of 240 as being rougher than sandpaper with a higher grit value, thus smaller inter-element, spacing of 280. Lederman (1974) found that, despite an overall trend for contact force to increase with groove width, participants applied an anomalously low amount of force to one texture. Neither Heller (1982), nor Lederman (1974) was able to point to a reason for the anomalies in their data.

Lederman (1972) found that the contrast in the participants' magnitude estimates of perceived roughness between the force conditions tended to increase with increases in groove width. This was not the case in this experiment. This was presumably due to the fact that in Lederman's experiment, the extent to which the participants' fingers could descend into the grooves as a result of increases in contact force would have increased with increases in groove width. Therefore, there would have been a corresponding increasing contrast in the area of the deviation of the skin from its resting position as a result of increasing groove width between the force conditions. However, this would not occur with the virtual textures,

since the extent to which the contact point of the PHANTOM™ could descend into the grooves would be constant between the force conditions.

Contact force did not have a significant effect on the participants' exponents. This means that although contact force exerted a significant effect on the perceived roughness of the virtual textures, it did not significantly affect the psychophysical function relating groove width to perceived roughness. It is not possible to examine this result in the context of real world based research, because none of the studies that have investigated the impact of contact force on texture perception have reported statistical comparisons of exponent data. However, the results serve as a clear indication that a variable can have a significant influence on the perceived roughness of a series of virtual textures independently of a significant effect on the psychophysical function and vice versa. This was also attested to in the previous experiment reported in this chapter, which indicated that the endpoint being used with the PHANTOM™ had a significant effect on the rate at which perceived roughness decreased with increasing groove width, but not on the perceived roughness of the virtual textures per se. At this time it is not clear whether a variable such as contact force exerts a significant effect on perceived roughness independent of a significant effect on the psychophysical function in the real world. However, this can be easily remedied by future real world based studies incorporating analyses of participants' exponent data in addition to their magnitude estimates of perceived roughness.

The second question raised in the introduction to this experiment concerned the relationship between contact force and perceived roughness when individuals are left free to modulate the degree of contact force they apply to the virtual textures. For both sighted and blind participants, the mean forces applied to the virtual textures fell predominantly between 1.58 and 2.16N. The average force applied by the participants, collapsed over visual status

and endpoint, was 1.83N, which is notably higher than the 68N average force applied to the rectangular waveform real textures by the participants in Lederman (1974). It is not clear at this time whether this can be attributed to the differences between examining textures in the real world and HVR per se, or the difference in the texture waveforms used between this experiment and that of Lederman (1974). An easy way to clarify this issue would be to compare the amount of force participants applied to a texture waveform that could be presented in both the real world and HVR.

The results of this experiment indicated there was not a consistent trend relating fluctuations in applied contact force to groove width. The amount of contact force applied by the participants did not differ significantly between sighted and blind participants, the stylus or thimble endpoints, the virtual textures or between the runs of the virtual textures. This contrasts with the findings of Lederman (1974), where contact force was found to increase with increasing groove width. Given that Lederman (1974) speculated that participants applied more contact force in order to “prevent the skin from catching on the leading edge of each land” (p389) it is not surprising that this did not occur in VR; there were no lands with the sinusoidal textures used in this experiment for the PHANTOM’s probe to catch on. Therefore applying more contact force for this purpose would be pointless.

The third question raised in the introduction to this experiment concerned the consistency of the participants’ application of contact force when examining the virtual textures and any effect this might have on perceived roughness. Neither the amount of force that the participants chose to apply to the virtual textures, or their magnitude estimates of perceived roughness differed significantly between the runs of the virtual textures in the participant mediated force condition. This indicates that participants were consistent in their application of contact force and that the perceived roughness of the virtual textures was comparable over several presentations when the

participants were free to modulate their use of contact force. This result is in agreement with Lederman (1974).

### **2.8.2 The effect of contact force compared between the thimble and stylus endpoints of the PHANTOM™**

With respect to the issue of whether the effects of contact force would be consistent between the two endpoints of the PHANTOM™ device. The incidence of significant exponents was higher with the stylus endpoint than for the thimble endpoint, irrespective of the force condition and for both sighted and blind participants. However, this difference was particularly pronounced for sighted participants in the participant mediated force condition; only 30% returned significant exponents with the thimble attachment compared to 80% with the stylus attachment. This finding is rather puzzling since in the previous study reported in this chapter, there was a slightly higher incidence of significant exponents with the thimble than with the stylus. The only explanation that springs to mind is that the random ordering of the force conditions might have meant that, by chance, an inordinate number of the sighted participants underwent the participant mediated force condition with the thimble endpoint last and perhaps were just fatigued.

Negative exponents predominated for both endpoints in all of the force conditions. In all force conditions the stylus endpoint yielded more significant negative exponents than the thimble. When the participants' exponents from the three force conditions were compared, a significant effect of endpoint was found. The exponents yielded by the stylus endpoint over the force conditions were significantly greater than those yielded by the thimble endpoint. This finding clearly contrasts with the previous experiment, in which the exponents yielded by the thimble endpoint were significantly

greater than those of the stylus. It seems, therefore, that although the endpoint used is consistently exerting an effect on the exponent relating groove width to perceived roughness, the nature of this effect can vary between groups of participants; it is not simply the case that perceived roughness invariably increases more rapidly as a function of decreasing groove width with one endpoint than the other. The mechanism for the effect of endpoint on the participants' exponent data is not clear at this time. It was thought that such an effect could be attributed to participants applying more contact force to the virtual textures with one endpoint than with the other. However, this was not the case: the amount of contact force applied to the virtual textures was not found to be significantly different between the stylus and thimble endpoints. It might be the case that another variable, perhaps the speed of the scanning motion across the virtual textures, might account for the significantly different exponents yielded by the thimble and stylus endpoints.

The participants' magnitude estimates of perceived roughness obtained from the three force conditions were not found to significantly differ between the stylus and thimble endpoints. This is in agreement with the previous study and consolidates the conclusion that the endpoint used with the PHANTOM™ does not have a significant effect on the perceived roughness of the virtual textures per se. However, there was an interaction between the endpoint used and groove width. The stylus endpoint yielded the highest magnitude estimates of perceived roughness for the narrowest two textures, however the thimble endpoint yielded the highest magnitude estimates from the texture featuring a groove width of 1.575mm upwards. This was not the case in the previous experiment. This result cannot be accounted for by a corresponding interaction between the variables of groove width and endpoint in the data documenting how much contact force the participants applied to the virtual textures. Therefore, at this stage it is hard to account for

this finding. However, it would be interesting to see if any other parameters of participant's interaction with the textures could account for this interaction.

### **2.8.3 The effect of contact force compared between sighted and blind individuals**

The issue of whether the effects of contact force would be consistent between blind and sighted individuals had not been previously addressed by research. With respect to the incidence of significant positive and negative exponents, a number of trends between sighted and blind participants remain constant over the force conditions. For example, blind participants returned more significant exponents than the sighted individuals. This trend was noted in the previous experiment reported in this chapter and in the work of Colwell et al (1998). It would appear, therefore, that blind individuals find judging the roughness of sinusoidal textures in HVR easier than sighted individuals. The relationship between groove width and perceived roughness also appears more robust in blind individuals, in that negative exponents predominate over positive exponents to a greater extent with blind individuals than with sighted individuals. Indeed, every significant exponent returned by the blind individuals in this experiment was negative. A similar outcome was obtained in the previous experiment.

The exponents obtained from sighted and blind individuals over the three force conditions were not found to differ significantly. This is in agreement with both the previous experiment reported in this chapter and Colwell et al (1998). Thus, the finding that the rate of change in perceived roughness as a function of changes in the groove width does not differ between sighted and blind individuals appears to be reliable. The magnitude estimates of perceived roughness obtained from the three force conditions were also not found to significantly differ between blind and sighted individuals, this is also

consistent with the results of the previous experiment. The fact that there were no significant main effects of visual status in this experiment is also in line with the findings of Heller (1989), who found no significant differences between sighted and blind individuals ability to discern the smoother of pairs of real textured surfaces.

This experiment yielded an interesting interaction between the variables of visual status and groove width: the blind participants perceived the virtual textures featuring the two narrowest groove widths as nominally rougher than the sighted participants, but from that point onwards the sighted participants perceived the virtual textures as nominally rougher than the blind participants. Curiously, an interaction of a different nature was found in the previous experiment reported in this chapter. On that occasion, the blind participants perceived all the virtual textures as nominally rougher than the sighted participants. However, the difference between the magnitude estimates returned by the sighted and blind individuals increased with groove width. The reason for this discrepancy is not clear at this time.

In summary, the amount of contact force participants applied to the virtual textures was found to be a significant determinant of perceived roughness, in that the virtual textures were judged as being roughest in the experimental condition that involved the imposition of the highest degree of contact force. This is consistent with the real world based literature on the effect of contact force on perceived roughness (e.g. Lederman, 1972; Lederman, 1974; Lederman, 1981). Nevertheless, when left to their own volition, participants were consistent in the amount of contact force that they chose to apply across the respective virtual textures. This indicates that contact force is redundant as an influence on perceived roughness when the participants are left to control its application. Furthermore, contact force was not found to exert a significant effect on the exponent relating the groove widths of the virtual textures to perceived roughness.

The fact that the amount of contact force the participants chose to apply to the virtual textures did not differ reliably as a function of the factor of Groove Width conflicts with real world based studies, insofar as the amount of contact force that participants apply to real textures has been found to increase with increasing groove width (Lederman, 1974).

The amount of contact force used by the participants of their own volition when exploring each of the virtual textures did not differ significantly between the thimble and stylus endpoints. This undermines the notion that the significant difference in the exponents obtained between the stylus and thimble endpoints could be explained in terms of the amount of contact force the participants applied to the virtual textures with the two endpoints.

Visual status was found to have a negligible effect on the amount of contact force the sighted and blind participants chose to apply to the virtual textures. The effect of contact force on the perception of the roughness of the virtual textures was also consistent between sighted and blind individuals i.e. the virtual textures were deemed to be roughest in the high force condition for both groups of participants.

Having considered both physical and interaction related determinants of the perception of a material object attribute in HVR, the thesis now moves on to investigate the perception of two geometric object attributes in HVR, namely: size and angular extent.



### **3. Chapter 3: The perception of the size and angle of shear of 3-D objects in HVR and the real world**

This chapter presents two experiments (experiments 3 and 4) in which the perception of the object attributes of size and angle of shear are examined in sighted and blind individuals. In the first experiment, the perception of these attributes was studied in HVR, with the PHANTOM™ device. In the second experiment, the perception of these attributes was examined in the real world with real counterparts to the virtual stimuli.

The general aim of these experiments was to determine how 3-D object size and angle of shear is perceived for both virtual objects and their real counterparts. The objects used were simple 3-D geometric objects, (cubes, spheres and sheared cubes). In both HVR and the real world, participants explored the cubes and spheres from both the inside (internally) and from the outside (externally). The sheared cubes were examined from the inside only in both HVR and the real world.

In HVR, participants were asked to explore the cubes, spheres and sheared cubes via the thimble and stylus endpoints of the PHANTOM™ device. The real counterparts to the virtual objects were examined via the deactivated PHANTOM™ device, the detached PHANTOM's stylus endpoint, a bare index finger and under a free exploration condition in which participants were allowed to examine the real objects in any manner they wished.

### **3.1 Experiment 3: The perception of the size and angle of shear of 3-D virtual objects with the PHANTOM™ device**

There has been little research on how attributes of object form are perceived in HVR. However, Colwell et al (1998a; 1998b) and Bruns, (1998) conducted similar studies with the IE3000 haptic device, an experimental haptic device which pre-dated the PHANTOM™ device used in the reported experimentation. The work of Colwell et al and Bruns is described here in some detail because the reported experiment addresses much the same questions and one of the aims of the reported experiment is to compare the perception of the attributes of size and angle of shear across two 3-D force feedback devices.

Colwell et al (1998) conducted the first investigation into the perception of size and angle of shear in HVR with the IE3000 haptic device. This experiment involved sighted and blind individuals feeling a series of virtual three-dimensional cubes and spheres, 2.7 cm, 3.6 cm and 4.5 cm in size and sheared cubes, (trapezoids) featuring 18, 41 and 64 of shear.

The methodology of Bruns (1998) was similar to that of Colwell et al (1998), except that he only addressed perceived size and the participants were asked to reproduce the size of the virtual objects rather than visually or tactually selecting a match from comparison objects, as had been the case in Colwell et al.

Unfortunately, neither the work of Colwell or Bruns allows a comprehensive characterisation of the haptic perception of size or angularity in HVR, since the matching procedure used by Colwell means that the participants' estimates of size and angular extent were an artefact of the response stimuli

selected. Although Bruns remedied this problem by asking participants to reproduce the perceived size of the virtual objects, he compared only the estimates of size per se, with no further description of the relationship between actual and perceived size. However, the work of Colwell and Bruns made some interesting contributions by examining the impact of a number of factors on perceived size and angular extent in HVR. These factors are outlined below.

Both Colwell and Bruns were interested in comparing the perceived size of different types of virtual objects. Thus, both experimenters examined the perceived size of virtual cubes and spheres. However, only Bruns performed a direct statistical comparison between the perceived sizes of the two types of virtual objects. He found that size estimates of objectively equally sized virtual cubes and spheres did not differ reliably.

In providing the programming for the IE3000 device, Dr. Andrew Hardwick, of BT Exact technologies, noticed that virtual objects could be presented in both an external presentation mode, in which participants could explore the virtual objects from the outside and an internal presentation mode, in which participants could explore the internal dimensions of hollow versions of the virtual objects. Both Colwell et al and Bruns were interested in the implications of these different modes of presentation for perceived size. Therefore, both experimenters presented each virtual object type/size permutation in an external and internal presentation mode. Both experimenters found that the virtual objects presented in the internal presentation mode were reliably perceived as being larger than equivalently sized objects presented in the external presentation mode. This was called the 'Tardis' effect.

Colwell et al and Bruns were also interested in the implications of visual status for the perception of size in HVR and, thus, compared perceived size

and angle of shear between sighted and blind individuals. In both instances, the results indicated that the estimates of size returned by blind and sighted individuals did not differ reliably. Colwell et al also conducted comparisons of perceived angle of shear between sighted and blind individuals, which also yielded no reliable overall difference between the estimates returned by the two groups of participants. However, the sighted participants underestimated the angular extent of all of the sheared cubes, whereas the blind participants overestimated the size of the cube featuring the least degree of shearing and underestimated the other sheared cubes.

Experiment 3 was conducted to examine the perceived size and angle of shear of 3-D virtual objects with the PHANTOM™ device. The stimuli used in experiment 3 were identical to that of Colwell et al (1998), thus, in addition to addressing the perception of size and angle of shear with the PHANTOM™ per se, experiment 3 also permits a comparison of perceived size and angular extent between the PHANTOM™ device and the IE3000 device.

In experiment 3, participants were asked to examine and reproduce the size of virtual cubes and spheres and the angular extent of virtual sheared cubes. One amendment to the procedure used by Colwell (1998) and Bruns (1998) was implemented: the sighted participants were blindfolded to ensure that vision could not be a factor in their estimates of size and angle of shear with the PHANTOM™ device. In common with Colwell and Bruns, experiment 3 investigated the impact of a number of factors on the perception of size and angle of shear in HVR, these are outlined in the following subsections.

### **3.1.1 The effect of object type on perceived size with the PHANTOM™ device**

Bruns (1998) found that there were no reliable differences between the perceived size of objectively equally sized cubes and spheres. However, the

impact of the type of 3-D object being explored on perceived size has not been examined with the PHANTOM™ device. Therefore, the participants in experiment 3 were asked to judge the size of virtual cubes and spheres in order to determine whether perceived size is consistent between these two types of virtual objects with the PHANTOM™ device.

### **3.1.2 The effect of the presentation mode of the virtual objects on perceived size with the PHANTOM™ device**

Both Bruns (1998) and Colwell (1998) found that virtual objects presented in the internal mode i.e. explored from the inside, were reliably perceived as being larger than their equivalently sized counterparts presented in the external mode, i.e. explored from the outside. To determine if this effect is specific to the IE3000 device or a perceptual distortion attributable to the mode of presentation of the virtual objects per se, participants in experiment three were asked to explore each object size and type permutation in both an internal and external mode of presentation.

### **3.1.3 The effect of the endpoint used with the PHANTOM™ device on perceived size and angular extent of 3-D objects**

The results of experiments one and two with the virtual textures, described in chapter three, indicated that the endpoint used with the PHANTOM™ exerted a significant effect on the perception of the attribute of roughness. However, the implications of the endpoint used with the PHANTOM™ device for perceived size and angular extent have not been studied. Consequently, in experiment three, participants were asked to examine the virtual objects with both the thimble and stylus endpoints of the PHANTOM™, to determine whether the perception of 3-D object size and angle of shear would differ significantly between these two endpoints.

### **3.1.4 The effect of visual status on perceived size and angular extent with the PHANTOM™ device**

Visual status was found to have a negligible effect on perceived size and angle of shear in Colwell (1998) and Bruns (1998) with the IE3000 device. However, the perception of object size and angle of shear between blind and sighted individuals with the PHANTOM™ device has not previously been studied. Therefore, a sample of blind participants was incorporated into experiment three to determine whether the perception of these attributes would be consistent between sighted and blind individuals with the PHANTOM™ device.

## **3.2 Method**

### **3.2.1 Participants**

Experiment 3 utilised 24 participants, 14 participants were sighted and the remaining 10 were blind. The sighted participant sample consisted of six males and eight females, all of who reported having no sensory-motor impairments. Their ages ranged from 19 to 36, with the mean age being 27. The sighted participants were all University students recruited from various disciplines.

The blind participant sample consisted of 8 males and 2 females, all of who reported having no other sensory-motor impairments. 5 of the blind participants were congenitally blind, the remaining 5 lost their sight between the ages of 8 and 42. The ages of the blind participants ranged from 19 to 54, with the mean age being 46. The blind participants were all volunteers recruited from a list visually impaired individuals who had expressed an interest in participating in the S.D.R.U.'s research.

Both the sighted and blind groups of participants used in this experiment had also taken part in experiment 1.

### 3.2.2 Design

- Perception of virtual object size

This part of the experiment utilised a five factor mixed design, consisting of one between subjects factor and five within subjects factors. The between subjects factor Visual Status consisted of two levels, blind and sighted participants. The within subjects factor Object Type consisted of two levels, virtual cubes and spheres. The within subjects factor Object Size consisted of three levels, 2.7 cm, 3.6 cm and 4.5 cm objects. The within subjects condition Object Orientation consisted of two levels, an external object orientation condition and an internal object orientation condition. In the external object orientation condition the virtual objects were placed within an otherwise empty virtual environment and explored from the outside. In the internal exploration condition, hollow counterparts to the external virtual objects were explored from the inside. The remaining within subjects condition of Endpoint also consisted of two levels, the thimble or stylus endpoints of the PHANTOM™.

- Perception of virtual object angle of shear

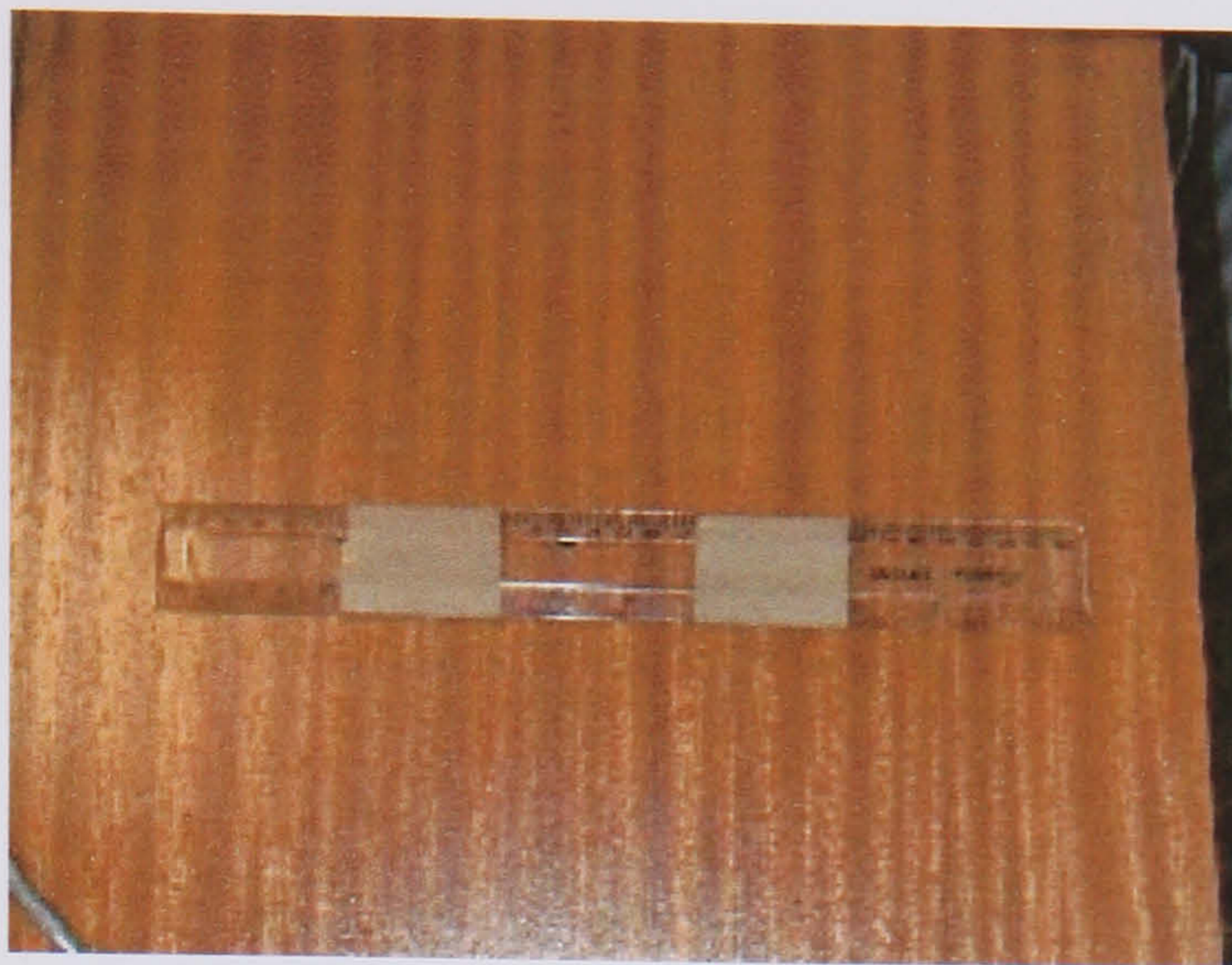
This part of the experiment consisted of a three factor mixed design, featuring one between subjects factor and two within subjects factors. The between subjects factor Visual Status consisted of two levels, blind and sighted participants. The within subjects factor Angle of Shear consisted of three levels, 18, 41 and 64 degrees. The within subjects condition Endpoint consisted of two levels, the thimble or stylus endpoints of the PHANTOM™.

The object size and object angle of shear parts of the experiment were run in the same session. The Object Type, Size and Orientation permutations yielded a total of 15 individual objects for the participants to explore, this is illustrated in table 3.1 in the stimulus section. The presentation order of the objects was always randomised. The participants underwent 2 runs of the 15 objects, one run with the thimble endpoint of the PHANTOM™ and the other run with the stylus endpoint of the PHANTOM™. The endpoint that was used first was counterbalanced between the participants. Therefore, each participant underwent a total of 30 trials in this experiment.

### **3.2.3 Apparatus**

The stimuli were presented via the PHANTOM™ haptic device connected to a Pentium II 400 Mhz computer with 64MB of RAM, running the Windows NT operating system. A Blindfold was used on sighted participants for the duration of the experiment to prevent them from obtaining visual cues as to the size/angle of shear of the virtual objects by monitoring the movement of their hand. Participants used an occluding sleeves ruler (pictured in figure 3.1) to estimate the size of the virtual cubes and spheres. The occluding sleeves ruler was a standard 60cm ruler, featuring two cardboard sleeves. One sleeve was fixed in place, the other could be slid up and down the length of the ruler. The participants gave their estimates by adjusting the spacing between the sleeves such that the distance between them corresponded to the perceived size of the virtual object. Participants used an angular ruler (depicted in figure 3.2) to estimate the angle of shear of the sheared cubes. The angular ruler consisted of two 30cm rulers attached by a hinge that permitted the two rulers to be adjusted to form any angle between 0-360 degrees. The participant had to adjust the configuration of the two rulers such that their angular relationship corresponded to perceived angle of shear of the sheared cube.





**Figure 3.1 The occluding sleeves ruler**



**Figure 3.2 The angular ruler.**

### **3.2.4 Stimuli**

The experimental stimuli consisted of fifteen virtual objects (described in table 3.1). The cubes and spheres were presented in three sizes: 2.7 cm, 3.6 cm and 4.5 cm. Each of the cubes and spheres were presented in an external and internal orientation. Three sheared cubes were used, sheared

by 18, 41 and 64 degrees respectively. The sheared cubes were presented in the internal exploration only and their size was held constant at 3.6 cm.

**Table 3.1 The object type/size/orientation permutations examined by the participants. A tick denotes that a particular permutation of object type, size and orientation was presented, a cross indicates that a permutation of object type/size and orientation was not presented.**

Object type/size/angularity	External format	Internal format
Cubes		
2.7 cm	✓	✓
3.6 cm	✓	✓
4.5 cm	✓	✓
Spheres		
2.7 cm	✓	✓
3.6 cm	✓	✓
4.5 cm	✓	✓
Sheared cubes		
18°	x	✓
41°	x	✓
64°	x	✓

### 3.2.5 Procedure

Participants were seated with the PHANTOM™ device in front of them in the horizontal plane. Participants were asked to sit at a distance whereby they could comfortably explore the device's entire workspace without needing to change their seating position. Participants were also asked not to change their seating orientation relative to the PHANTOM™ throughout the course of

the experiment. The Sighted participants were blindfolded for the duration of the experiment.

The participants were informed that the experiment would involve them making a series of judgments about the size and angle of 3-D virtual objects. They were then sequentially presented with an example of a virtual cube and sphere and simply asked to explore the objects in their entirety. They were informed that some of the virtual objects would be presented in an internal orientation. After explaining this concept, the experimenter displayed the internal counterparts of the previously presented cube and sphere for the participant to explore. Finally, the experimenter explained the concept of a sheared cube to the participants and presented them with an example, which they were asked to explore.

The participants were informed that after being presented with a virtual cube or sphere they would be asked to use the occluding sleeves ruler to estimate the edge length of the virtual cubes and the diameter of the virtual spheres, respectively. In the case of the sheared cubes, they were informed that they would be asked to use the angular ruler to estimate the angle of shear. The operation of the occluding sleeves ruler and angular ruler was then demonstrated to the participants. For estimates of size, participants adjusted the occluding sleeves ruler in the horizontal plane by gripping the fixed sleeve with one hand and adjusting the movable sleeve with the other, until they were satisfied that the distance between the sleeves corresponded to the size of the virtual object.

For estimates of angular extent, participants adjusted the angular ruler in the horizontal plane by gripping one of the arms with one hand whilst adjusting the relative orientation of the remaining arm with the other hand, until they were satisfied that the angular relationship of the two arms corresponded to angular extent of the sheared cubes

The sighted participants were informed that they would be required to remain blindfolded during the entire experiment. All participants were informed that they would be permitted as much time as they required in examining each object and in making their estimates. The only stipulation imposed on the participants was that they not interact with the virtual objects whilst making their estimates. The participants were asked to make their estimates as accurately as possible.

If the participants did not have any questions about the experimental procedure, the 15 virtual objects (randomly ordered) were then presented. When the participants indicated that they were ready to make an estimate of the size or angle of shear of the virtual object, the experimenter passed them the appropriate ruler. Upon indicating that they were satisfied with their estimate, they handed the ruler to the experimenter.

The experimenter recorded the participants' size and angular extent estimates by hand. For estimates of size, the experimenter traced the distance between the occluding sleeves of the ruler, as set by the participant, with a pencil and then recorded the extent of this mark using a conventional ruler. For the estimates of angular extent, the experimenter traced the angle of the intersection formed by the two arms of the angular ruler, as set by the participant, with a pencil and then recorded the angle with a protractor.

### **3.3 Results**

- Perception of virtual object size

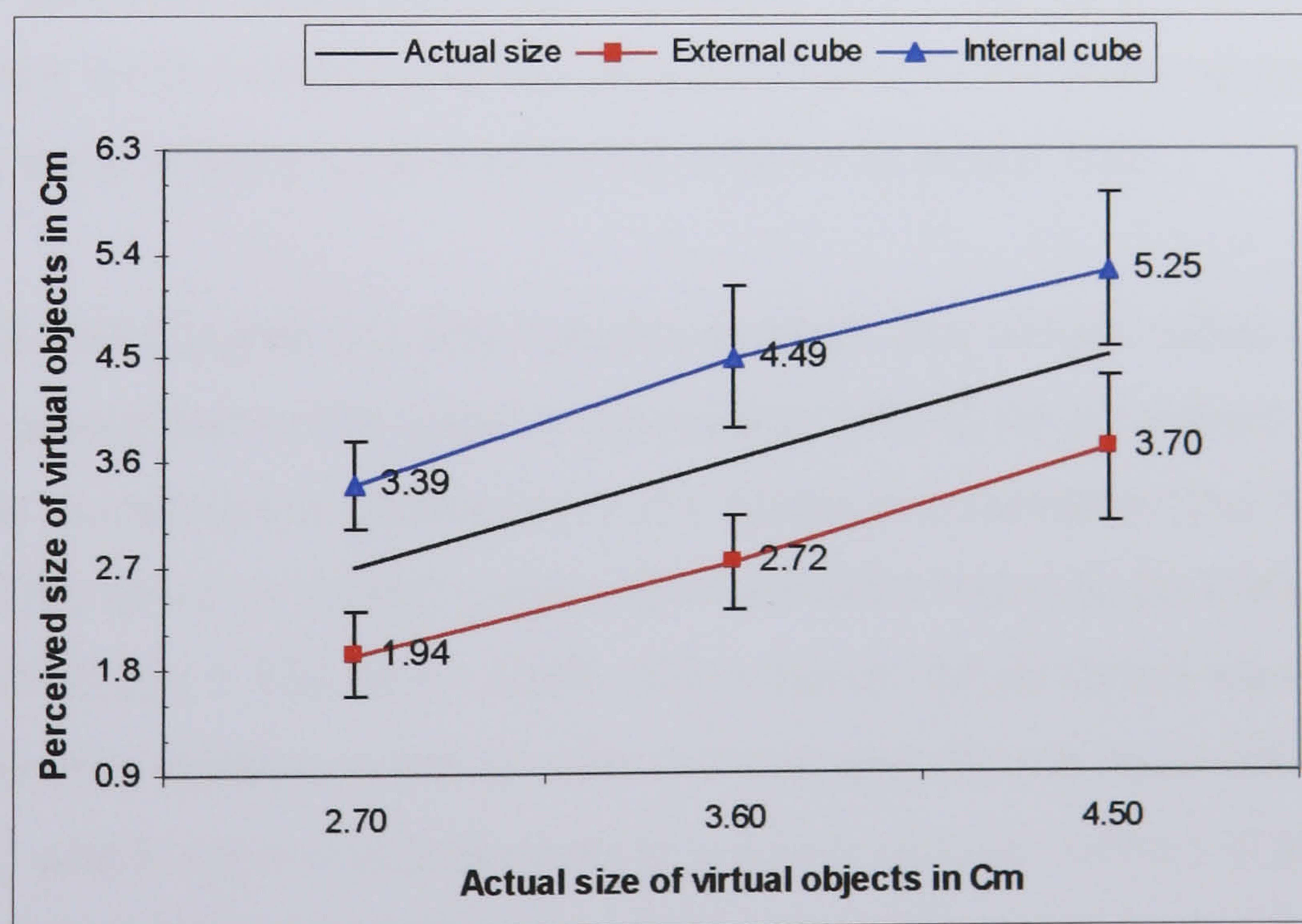
The analysis of the participants' size and angular extent estimates is multifaceted. First, analyses of variance were applied to the raw data. These alone tell us simply whether the size estimates derived from the various experimental levels are reliably different. A linear regression is then used to

determine the relationship between perceived size and actual size. A statistically reliable linear effect means that the ordering of the actual object sizes/angular extents was preserved in the participants' judgments. In addition, confidence limits for each size and angles estimate were calculated from the standard errors of the mean. These are useful in comparing perceived estimates of size and angular extent against actual stimuli values. If the high confidence limit for a particular object falls below the actual stimulus value, we can conclude that the object is reliably underestimated at the 95% confidence level. Conversely, if the low confidence limit falls above the actual stimulus value, we can conclude that the object is reliably overestimated at the 95% level. It should be noted that the confidence intervals shown in tables 3.2 and 3.3 are based on variability among individuals. They are appropriate for comparing average attribute estimates (size or angle) with physical values. They are not appropriate for comparisons between different objects or other experimental variables as these were within participant effects. The mixed design ANOVAs give the correct information as to which differences are statistically reliable.

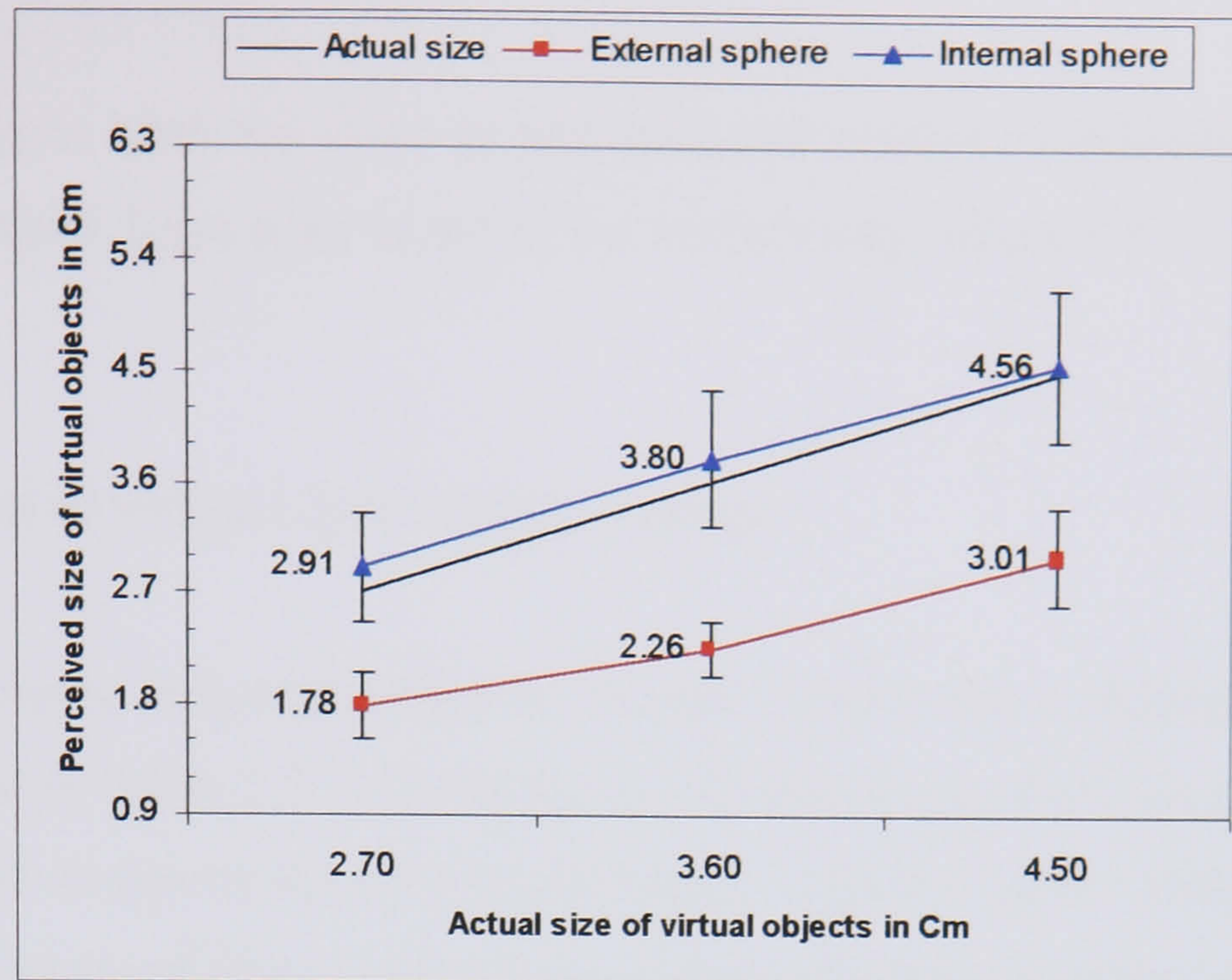
The participants' size estimates for the virtual objects are summarised in table 3.2 (on the following page). Inferential tests were all conducted to the 95% confidence limit. No statistically reliable main effects or interactions involving the factors of Visual Status or Endpoint were found. Accordingly, the data in table 3.2 has been collapsed over these factors.

**Table 3.2: Mean perceived sizes and associated confidence limits for the cubes and spheres collapsed across the factors of visual status and endpoint (all sizes in cm)**

Object type	Mean perceived size	Lower confidence limit	Upper confidence limit
External cube 2.7	1.94	1.57	2.30
External cube 3.6	2.72	2.32	3.13
External cube 4.5	3.70	3.07	4.33
Internal cube 2.7	3.39	3.01	3.77
Internal cube 3.6	4.49	3.87	5.11
Internal cube 4.5	5.25	4.58	5.91
External sphere 2.7	1.78	1.51	2.04
External sphere 3.6	2.26	2.04	2.49
External sphere 4.5	3.01	2.62	3.40
Internal sphere 2.7	2.91	2.47	3.36
Internal sphere 3.6	3.80	3.24	4.37
Internal sphere 4.5	4.56	3.95	5.17



**Figure 3.3 The perceived size of the external and internal virtual cubes**



**Figure 3.4 The perceived size of the external and internal virtual spheres**

Looking at table 3.2 and figures 3.3 and 3.4, a few trends become apparent. Firstly, the mean perceived sizes of the virtual cubes and spheres, in both the internal and external orientations, increases with the actual size of the stimuli, as would be expected. The effect of Object Size was found to be statistically reliable,  $F(2, 21) = 121.15$   $p < .0005$ . The linear contrast for the effect of size was also statistically reliable,  $F(1) = 162.28$   $p < .0005$ . The confidence limits indicate that the perceived size of the external cubes and spheres were reliably underestimated relative to actual size.

Table 3.2 and Figures 3.3 and 3.4 also indicate that virtual cubes and spheres presented in the internal orientation tend to be perceived as larger than their counterparts presented in the external orientation (the Tardis effect). This effect of Object Orientation was also found to be statistically reliable,  $F(1, 22) = 127.38$   $p < .0005$ . The internal virtual cubes were reliably overestimated relative to actual size, but this was not the case with the virtual spheres, which were overestimated to a lesser extent. Table 3.2 and comparisons of Figures 3.3 and 3.4 indicate that the perceived sizes of the virtual spheres are lower than the perceived sizes of equivalently sized

virtual cubes in both the internal and external modes of presentation. This effect of Object Type was found to be statistically reliable:  $F(1, 22) = 38.89$   $p < .0005$ .

- Perception of virtual object angle of shear

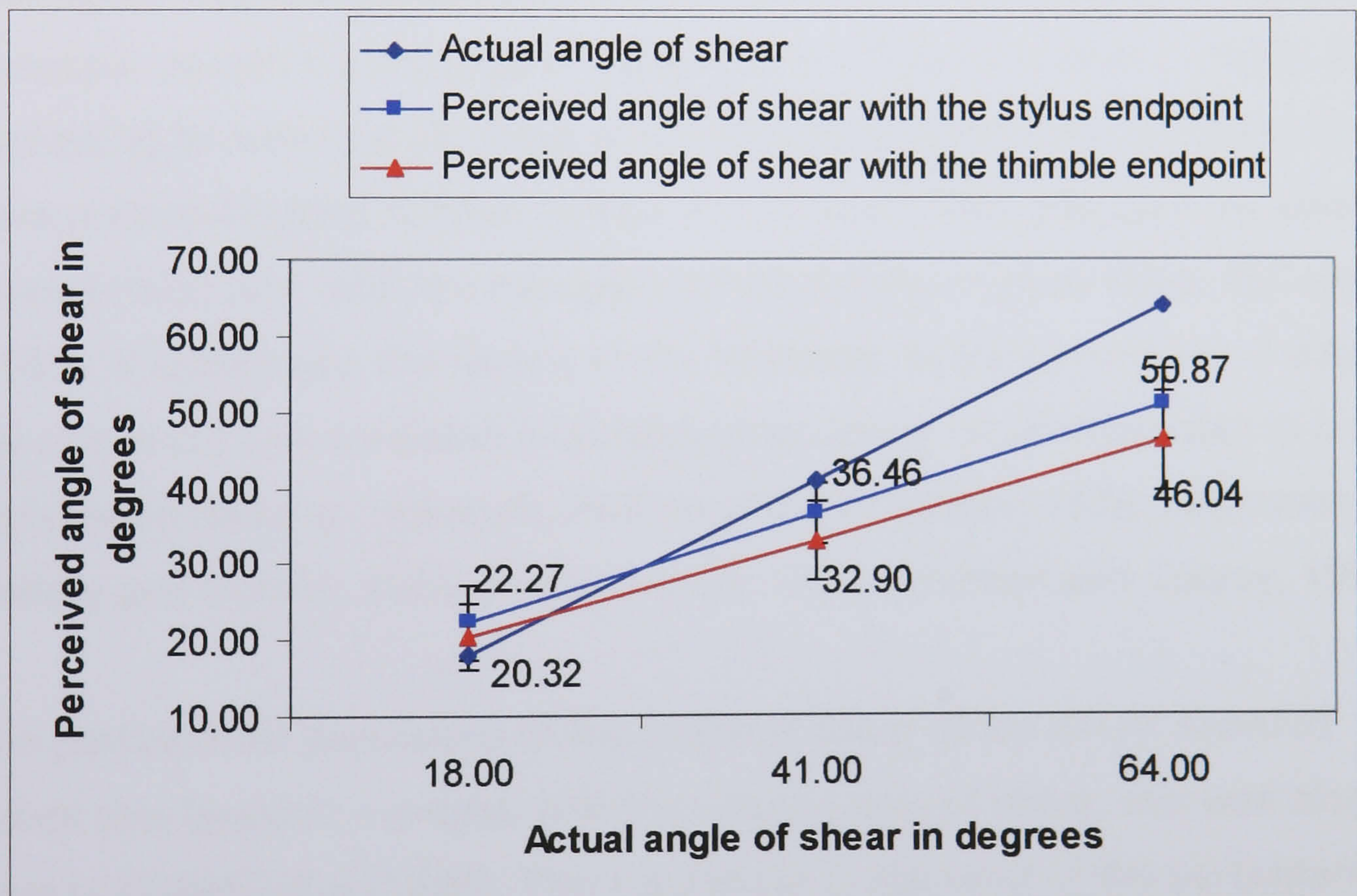
The participants' angle of shear estimates for the virtual objects are summarised in table 3.3. A three factor mixed design ANOVA consisting of one between subjects factor (Visual Status) and two within subjects factors (Endpoint, Angle of Shear) found no statistically reliable effect of Visual Status. According, the data in table 3.3 and figure 3.4 has been collapsed over sighted and blind participants.

**Table 3.3 Mean perceived angle of shear (in degrees) for the respective sheared cubes collapsed across visual status.**

Stylus endpoint		Lower confidence limit	Upper confidence limit
Actual degree of shear	Mean perceived shear (stylus)		
18	22.27	17.46	27.09
41	36.46	32.44	40.48
64	50.87	46.07	55.68
Thimble endpoint			
Actual degree of shear	Mean perceived shear (thimble)		
18	20.32	15.99	24.65
41	32.90	27.68	38.11
64	46.04	39.36	52.72



Looking at table 3.3, a number of trends become apparent. As expected, perceived angle of shear increases with actual angle of shear for both the thimble and stylus endpoints. This effect of Angle of Shear was found to be statistically reliable,  $F(2, 21) = 58.15$   $p < .0005$ . The linear contrast for the effect of angle of shear was significant,  $F(1) = 73.06$   $p < .0005$ . Figure 3.5, table 3.3 and figure 3.5 indicate that the 18 degree sheared cube was overestimated and the 41 and 64 degree sheared cubes were reliably underestimated, with both the thimble and stylus endpoints. However, it is also clear from figure 3.5 that the thimble endpoint yielded greater underestimates of shear than the stylus endpoint for all the sheared cubes. This effect of Endpoint was found to be statistically reliable,  $F(1, 22) = 6.34$   $p = .020$ .



**Figure 3.5 The mean perceived angle of shear estimates for the sheared cubes with the Stylus and thimble endpoints of the PHANTOM™**

## **3.4 Discussion**

The following discussion covers both the perception of object size and angle of shear with the PHANTOM™ device and the impact of the factors outlined in the introductory section on the perception of these attributes.

### **3.4.1 The perception of virtual object size and angular extent with the PHANTOM™ device**

The participants' perception of the size of the virtual objects was found to increase with increases in the actual sizes of the virtual objects, irrespective of whether they were presented in the internal or external orientation, this corresponds with the findings of Colwell et al (1998) and Bruns (1998). It is interesting to note that all of the externally presented cubes and spheres were underestimated relative to their actual sizes. This was also the case in Bruns (1998) and, with the exception of the smallest virtual cube, in Colwell (1998). Interestingly, the review of the literature on the perception of size in the real world also revealed a consistent tendency for stimulus size to be underestimated (eg. Hohmuth, Phillips and Van Romer, 1976; Lederman Klatzky and Barber, 1985; Seizova-Cajic, 1998; Solomon and Turvey, 1998).

The participants' perception of the angle of shear of the virtual sheared cubes was found to increase with the actual angle of shear, this was also the case in Colwell et al (1998). The magnitude of the error of the participants' angle of shear estimates increased with increasing angle of shear for both the stylus and thimble endpoints. In the real world based literature, Appelle (1971) also noted that the size of the error in judging the angle of the stimuli tended to increase with increasing stimulus size.

### **3.4.2 The effect of object type on perceived size with the PHANTOM™ device**

Interestingly, the results of this experiment indicated that the internally and externally oriented virtual spheres were judged to be smaller than equivalently sized internally and externally oriented virtual cubes. This is not an effect that either Colwell (1998) or Bruns (1998) found in their experiments. It may be the case that participants were using different strategies for perceiving the extent of the spheres between the two devices. For example, unlike the virtual cubes, the size of which can only be directly measured from tracing the edges of the cubes, there are two possible ways of determining the diameters of the virtual spheres. One way is to trace the circumference of the spheres and infer the Euclidean distance from the top of the sphere to its base. The other way is to try and memorise the spatial location of the top and bottom of the sphere and traverse the Euclidean distance between these points. Perhaps the participants using the PHANTOM™ device were more inclined to use the latter strategy than the participants using the IE3000. If the latter strategy promoted greater underestimation of the size of the spheres than the former strategy, this could account for this effect. This explanation is rather speculative at this time. Clearly the strategy that the participants use in arriving at size estimates of virtual spheres needs to be scrutinised in more detail.

### **3.4.3 The effect of the presentation mode of the virtual objects on perceived size with the PHANTOM™ device**

The participants' estimates of the virtual cubes and spheres presented in the internal orientation were significantly larger than their estimates of the corresponding cubes and spheres presented in the external orientation (The Tardis effect). This effect was evident irrespective of the size of the cubes and spheres and for both the stylus and thimble endpoints. This effect was

also evident in both Colwell et al (1998) and Bruns (1998) and is, therefore, not specific to the IE3000 device. At this stage, it is not clear what is responsible for producing the Tardis effect. Colwell (2001) noted that when feeling externally presented virtual objects, “many participants were observed to get temporarily ‘lost’ in the virtual space. This seemed to occur in three different circumstances: when feeling a new type of object; when searching for an object; and when searching for and feeling a very small object.” (p281). Many participants were observed to experience the same problems for the externally presented objects with the PHANTOM™ device. However, these problems would not occur with either the IE3000 or the PHANTOM™ device for the internally presented objects, as there is no ‘unused’ virtual space to get lost in; the object itself constitutes the virtual environment. Perhaps the explanation for the Tardis effect lies in this difference: the external objects might just seem small in relation to the large unused virtual environment, whereas the volume of unused space is not a factor in the judgments of the same sized objects presented in the internal orientation.

The accuracy of participants’ perception of the size of the cubes and spheres in the internal orientation was greater than when they were presented in their external orientations. This was also found by Bruns (1998). This is most likely due to the fact that the internally presented cubes and spheres were easier to perceive than their externally presented counterparts. This is simply because the participants’ movements could not exceed the dimensions of the internally presented cubes and spheres, whereas they could easily ‘fall off’ the externally presented cubes and spheres into empty virtual space. It is slightly perplexing that the internal objects were not perceived more accurately than the external objects in Colwell et al (1998), however this may be an artifact of the matching methodology used in that study. Indeed, it is probably not particularly useful to look at the accuracy of the participants’ estimates in Colwell et al (1998) as in that experiment the participants’

responses were dictated by the range of sizes used for the comparison stimuli rather than being representative of actual differences between the perceived and actual sizes of the stimuli.

At this time, it is also not clear whether the Tardis effect is specific to HVR or would occur in the real world should real replicas of the virtual stimuli be manufactured. Indeed, determining whether the effect occurs with real counterparts to the virtual stimuli might be useful in elucidating the mechanism of the effect.

#### **3.4.4 The effect of the endpoint used with the PHANTOM™ device on perceived size and angular extent**

It is interesting that the endpoint used with the PHANTOM™ did not reliably affect the participants' perception of the size of the virtual cubes and spheres. This stands in contrast to the results of the experiments on texture perception in HVR, reported in chapter 2 of this thesis, where perceived roughness was found to be influenced by the endpoint used. It would appear that whether the endpoint used with the PHANTOM™ exerts a significant effect on perception, depends on the object attribute in question. At this time it is not clear on what basis the two endpoints can be distinguished and how any difference between the endpoints might affect the perception of attributes other than the ones covered in this thesis. Clearly, where the perception of a virtual object attribute is affected by the endpoint used, a more in depth scrutiny of the way participants use the thimble and stylus is required to uncover the basis for the effect.

The endpoint used with the PHANTOM™ was also found to have a significant influence on the participants' estimates of angle of shear. The stylus endpoint yielded higher estimates of angle of shear than the thimble endpoint for all the sheared cubes. The participants slightly overestimated

the sheared cube featuring the lowest angle of shearing with both the stylus and thimble endpoints. This contrasts with the non-significant effect of endpoint on the participants' size estimates. At this point in time it is not clear what is responsible for this effect. Perhaps the participants used the stylus as a reference point against which to judge angle of shear. For example, the participants could have adjusted the position of the stylus in their hand, such that its angle (slope), relative to 90 degrees (upright) corresponded to that of the perceived angle of shear of the stimulus. This would not have been a particularly intuitive thing to do with the thimble endpoint, however. Clearly some more work needs to be directed at the manner in which the participants use the stylus and thimble endpoint when judging angular extent. It would also be interesting to reproduce the sheared cubes in the real world and determine whether giving participants freedom as to the EP used in arriving at their estimates affected the trends noted in this experiment.

### **3.4.5 The effect of visual status on perceived size and angular extent with the PHANTOM™ device**

The size estimates from sighted and blind individuals with the PHANTOM™ device were not found to differ significantly for the cubes or spheres, irrespective of whether they were presented in their internal or external orientations or examined with the stylus or thimble endpoints. Colwell et al (1998) and Bruns (1998) also found no significant differences between the perceived size of virtual cubes and spheres between sighted and blind individuals with the IE3000 device. It would, therefore, appear that visual status is not a significant factor in size estimation across 3-D force feedback devices.

A question that does emerge from the non-significant effect of visual status is whether the similarity between the size estimates returned by sighted and blind individuals can be attributed to the fact that both groups had to use the

same EP -that of contour following- to estimate the extent of the virtual objects with both the PHANTOM™ and IE3000 devices. Davidson (1972) found that blind individuals were superior to their sighted counterparts in making estimates of curvature. He attributed this superiority to blind individuals using a more efficient EP for judging curvature more frequently than sighted individuals. However, comparisons between blind and sighted individuals' use of EPs in arriving at size estimates in the real world has not been examined. Therefore, it would be interesting to determine whether the perceived size of real counterparts to the virtual objects differed between sighted and blind individuals under a condition in which both groups are constrained to using the same EP in arriving at their size estimates and a further condition in which both groups are permitted to use whatever EP they wished in arriving at their estimates.

In common with the data on the perceived size of the virtual cubes and spheres, the angle of shear estimates did not differ significantly between sighted and blind participants. The absence of a significant effect of visual status is consistent with Colwell et al (1998). However, Colwell et al (1998) found an interaction between the variables of visual status and angle of shear: blind participants overestimated the angle of the sheared cube featuring the least degree of shearing and underestimated the two sheared cubes featuring the intermediate and greatest degree of shearing. The sighted participants underestimated the angle of all three sheared cubes. Such an interaction was not present in the reported experiment. In fact, sighted and blind individuals overestimated the degree of shear for the cubes sheared by 18 degrees and underestimated the degree of shear for the cubes sheared by 41 and 64 degrees. At this stage it is not clear whether this difference can be attributed to the different devices used or the difference between the nature of response methods used between the two experiments.

In summary, the perceived size of virtual 3-D objects with the PHANTOM™ device was found to increase with actual object size in a linear fashion. The results showed that participants underestimated the size of the virtual objects in the external presentation mode, but overestimated the size of the virtual objects in the internal presentation mode.

The results of experiment 3 showed that virtual cubes and spheres examined in the internal exploration mode were perceived as significantly larger than their equivalently sized counterparts examined in the external exploration mode (the Tardis effect). This is consistent with earlier work in HVR with the IE3000 device e.g. (Colwell et al, 1998 and Bruns, 1998) and constitutes the first demonstration of this effect with the PHANTOM™ device.

The results of experiment 3 also indicated that the perceived size of the 3-D objects with the PHANTOM™ was not uniform between different types of virtual 3-D objects: the virtual cubes were judged as being larger than equivalently sized virtual spheres. Neither Colwell et al (1998) or Bruns (1998) found this discrepancy with the IE3000 device.

The endpoint used with the PHANTOM™ device had a negligible effect on the perceived size of the 3-D virtual objects. However, this was not the case for the perceived angular extent of the virtual sheared cubes: the stylus endpoint returned higher estimates of angular extent for the virtual sheared cubes than the thimble endpoint.

The impact of visual status on the perceived size and angular extent of 3-D objects with the PHANTOM™ device was negligible. The estimates of the size and angular extent of the 3-D virtual objects did not differ significantly between sighted and blind individuals, nor were there any interactions between the factor of Visual Status and any of the other factors investigated in experiment 3.



Having investigated the perception of the attributes of 3-D object size and angular extent in VR, the following experiment addresses the perception of the same attributes in the real world.

### **3.5 Experiment four: An investigation into the perception of object size and angle of shear in the real world.**

The previous experiment on the perception of the size and angle of shear of virtual 3-D objects in HVR begs the question, “how does the perception of these object attributes compare between HVR and the real world”.

Experiments that have directly compared the perception of an object attribute in HVR with the same object attribute in the real world are very rare. Jansson (1998) found no significant differences between the perceived roughness of real and virtual replicas of sandpaper stimuli. Buttolo, Kung and Hannaford (1995) compared the performance of participants on a series of simple manipulation tasks performed in either HVR or in the real world. The results indicated that the time taken to perform the respective tasks was comparable between HVR and the real world. More recently, Kilchenman-O'Malley, and Goldfarb (2001) examined participants' ability to identify and discriminate between different sized virtual blocks and real counterparts and found that the performance was comparable between HVR and the real world.

Therefore, experiment 4 was devised to determine if the perception of 3-D object size and angle of shear would be significantly different between HVR and the real world. In order to achieve this, the methodology used in experiment 3 was adopted with real counterparts to the virtual stimuli.

Experiment 4 aimed to determine the impact of a number of different factors on the perception of the size and angle of shear of real counterparts to the virtual objects. These are outlined below.

### **3.5.1 The effect of the conditions of exploration on the perceived size of the size and angular extent of real 3-D objects**

Just comparing the perception of the attributes of size and angular extent between HVR and naturalistic haptic perception in the real world might not be particularly informative should it indicate any differences between HVR and the real world. For example, if the Tardis effect, noted in the previous experiment with the virtual objects and in Colwell et al (1998) and Bruns (1999), was not found with the real objects, there would be little indication which aspect/s of haptic interaction with a 3-D force feedback device caused the effect.

Interaction with virtual objects via a 3-D force feedback device differs from interaction with analogous real world objects in a number of ways. Firstly, there are the physical dimensions of the device itself to consider: movement with the PHANTOM™ involves greater inertia than movement using the hand alone. Secondly, when interacting with virtual objects via the PHANTOM™, the participant is deprived of any direct cutaneous information about the objects. Thirdly, the PHANTOM™ imposes a single point of contact between the user and the virtual objects that, in turn, imposes restrictions on the type of EPs they can use when examining the virtual objects.

In order to achieve this, participants were asked to make size and angle of shear estimates under a number of different exploration conditions. In one condition, the participants used the de-activated PHANTOM™ device, with the stylus attachment, to interact with the real objects. This provides the most similar comparison of the perception of size and angle of shear of 3-D objects between HVR and the real world, as all the characteristics of haptic interaction with the PHANTOM™ are retained, except that the device is now being used to examine real, rather than virtual objects. In another condition,

participants interacted with the real objects using the PHANTOM's detached stylus. This isolates the impact of variables associated with the PHANTOM™ device itself, e.g. the friction and inertia of the device's moving parts, on the perception of the size and angle of shear of the real 3-D objects, since the lack of direct cutaneous information about the real objects and the single point interaction characteristics of haptic interaction via the PHANTOM™ were retained. Participants also examined the real objects using only their bare index finger. This was used to determine the effect of the lack of cutaneous information on a single point based method of arriving at size and angle of shear estimates of real 3-D objects. Finally, participants examined the objects freely i.e. with no constraints on the way in which they interacted with the real objects. This indicates how the real counterparts to the virtual objects are perceived via touch under naturalistic conditions. The exploration conditions used in this experiment together with their associated characteristics are summarised in table 3.4.

**Table 3.4 The exploration conditions and their associated characteristics**

Exploratory condition	Free of device Mechanism	Cutaneous information	Multiple points of contact
De-activated PHANTOM™ condition	x	x	x
Stylus condition	✓	x	x
Bare Index Finger condition	✓	✓	x
Free Exploration condition	✓	✓	✓

### **3.5.2 The effect of object type on the perceived size of the real 3-D objects**

In experiment 3, participants were asked to estimate the size of virtual cubes and spheres. The results showed that virtual cubes were perceived as being larger than equivalently sized virtual spheres. Therefore experiment 4 used real counterparts to the virtual cubes *and* spheres to determine if the same effect would be evident in the real world.

### **3.5.3 The effect of the Presentation mode of real objects on perceived size**

In experiment 3, participants were asked to estimate the size of virtual cubes and spheres presented in both an internal presentation mode, in which the participants explored them from the inside and an external presentation mode, in which the participants explored them from the outside. The results showed that cubes and spheres explored from the inside were perceived as being larger than equivalently sized cubes and spheres explored from the outside (the Tardis effect).

### **3.5.4 The effect of visual status on the perceived size and angular extent of the real objects**

In experiment 3, visual status had a negligible role in the perception of the size and angular extent of the virtual objects. However, it was not clear if this would be the case with the real counterparts to the virtual objects under naturalistic haptic exploration. Unfortunately, owing to constraints on the blind participants' time, it was not possible to test them under each of the exploration conditions. Instead, the blind participants only took part in the Free Exploration condition.

## **3.6 Method**

### **3.6.1 Participants**

This experiment utilised 20 participants, 10 participants were sighted and the remaining ten were blind. The sighted participant sample consisted of 3 males and 7 females, all of who reported having no sensory-motor impairments. Their ages ranged from 24 to 42, with the mean age being 33. The sighted participants were all University students recruited from various disciplines.

The blind participant sample consisted of 8 males and 2 females, all of who reported having no other sensory-motor impairments. Four of the blind participants were congenitally blind, the remaining six lost their sight between the ages of 1 and 30 years of age. The ages of the blind participants ranged from 33 to 55, with the mean age being 47. The blind participants were all volunteers recruited from a list visually impaired individuals who had expressed an interest in participating in the S.D.R.U.'s research. The blind participants used in this experiment had also taken part in experiment 2.

### **3.6.2 Design**

- Perception of size with real objects

There were 2 experimental designs. Three within factors were common to both designs, namely: Object size (2.7 cm, 3.6 cm, 4.5 cm; object type (cubes and spheres); and mode of presentation (external and internal object presentation modes).

The first design used only sighted participants, but featured an additional within subjects factor: Exploration type (de-activated PHANTOM™ device, bare index finger, the detached PHANTOM's stylus and free exploration).

The second design involved only the free exploration level, but featured the between subjects Factor of Visual Status (blind and sighted participants).

- Perception of angle of shear with real objects

Once again, there were 2 experimental designs. One within subjects factor was common to both designs, namely: angle of shear (18, 41 and 64 degrees of shear). The first design used only sighted participants, but featured an additional within subjects factor: Exploration type (de-activated PHANTOM™ device, bare index finger, the detached PHANTOM™ 's stylus and free exploration).

The second design involved only the free exploration level, but featured the between subjects factor of Visual Status (blind and sighted participants).

As in experiment 3, with the virtual objects, the object size and angle of shear components of the experiment were run concurrently. The Object Type, Size and Orientation permutations yielded a total of 15 individual objects for the participants to explore. For the sighted participants, the same 15 objects were presented in four separate runs, with each run corresponding to one of the exploration levels. Therefore, each sighted participant underwent a total of 60 trials (15 objects x 4 exploratory levels). The ordering of both the exploration levels and the objects within each exploration level was randomised for each participant. The blind participants interacted with the objects under just one exploration level run, thus undertook a total of 15 trials. The ordering of the presentation of the objects was, once again, randomised for each participant.

### 3.6.3 Stimuli

The stimuli for experiment 4 comprised real counterparts to the virtual objects used in the previous experiment i.e. solid and hollow cubes and spheres. The cubes and spheres were presented in three sizes: 2.7, 3.6 and 4.5cm. The sheared cubes were sheared by 18, 41 and 64 degrees respectively and were only presented in the internal orientation. The size of the sheared cubes was held constant at 3.6cm. The stimuli were fabricated from wood with a shellnar finish. The real objects are depicted in figure 3.6



**Figure 3.6 The real counterparts to the virtual objects**

Creating real counterparts to the virtual external cubes and spheres was not difficult. However, producing real counterparts to the virtual cubes and spheres in an internal orientation was more difficult. This is because the participant has to be able to access the internal dimensions of the object, which is impossible if the external geometry of the object is not compromised. Hollow cubes minus one of their component faces constituted the real world versions of the virtual cubes in the internal orientation. Half-spheres, cut out of larger cylindrical blocks constituted the real world

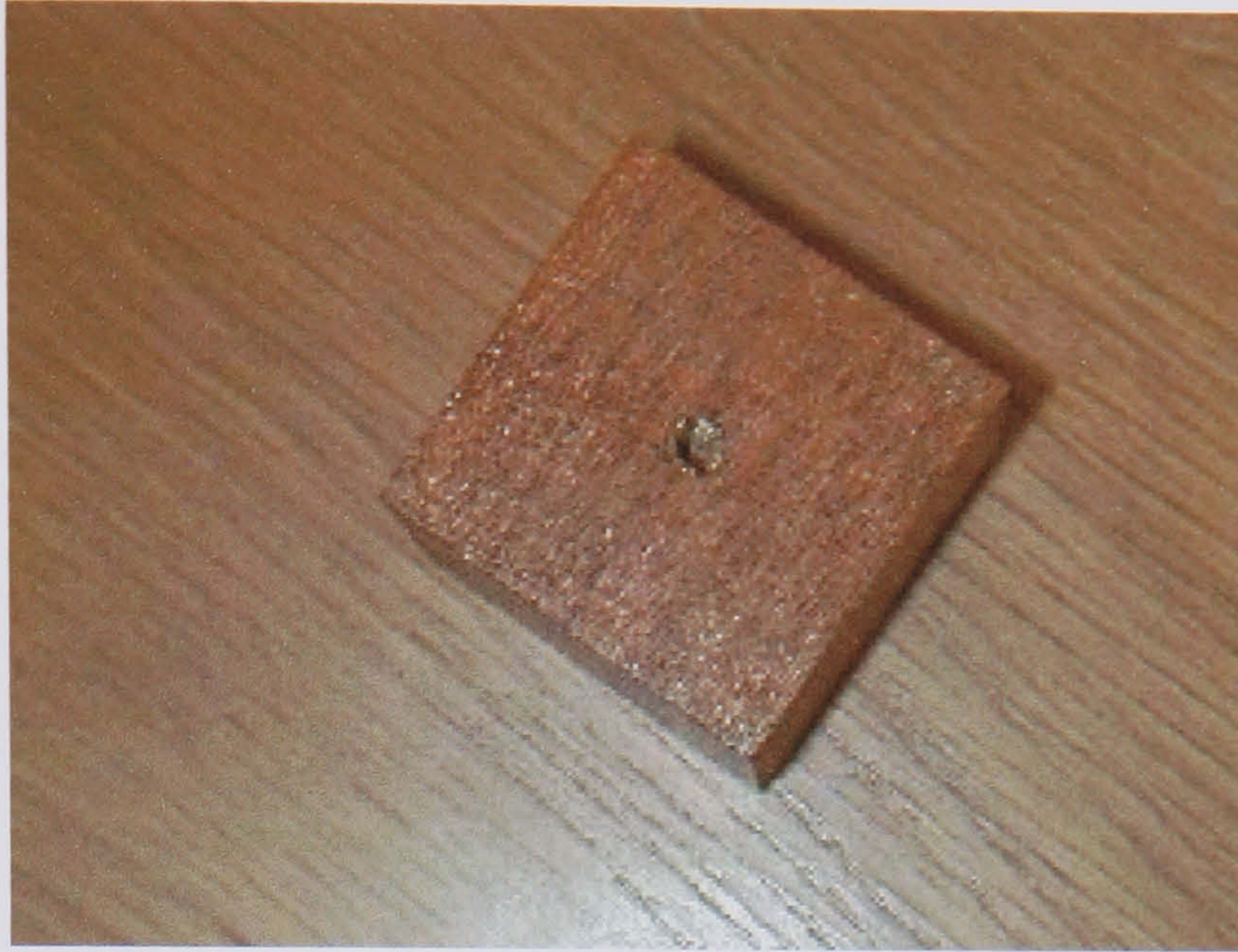


versions of the virtual spheres in the internal orientation. As with the virtual objects, the internal dimensions of the objects in the internal orientation corresponded to the external dimensions of the objects in the external orientation.

### **3.6.4 Apparatus**

In the previous experiment, the virtual objects were simply suspended in the middle of a virtual environment, with nothing attaching them to a surface of any kind. Obviously this is not possible in the real world. Therefore, in order to make interaction with the real objects under the de-activated PHANTOM™, stylus and bare index finger exploration levels feasible, it was necessary to devise a method of securing the objects in the same position that the virtual objects had occupied. This method had to fulfil three criteria. It had to be as unobtrusive as possible, such that it provided minimal cues as to the objects location and did not restrict the participants' access to objects themselves. It had to hold the objects securely in place whilst the participant explored them. Finally, it could not damage the objects or corrupt their geometry or dimensions.

The chosen method involved inserting a 5mm. expansion fitting into each object, shown in figure 3.7. The experimental apparatus was produced by Robert Luker, from the Department of Manufacturing Systems Engineering at the University of Hertfordshire.



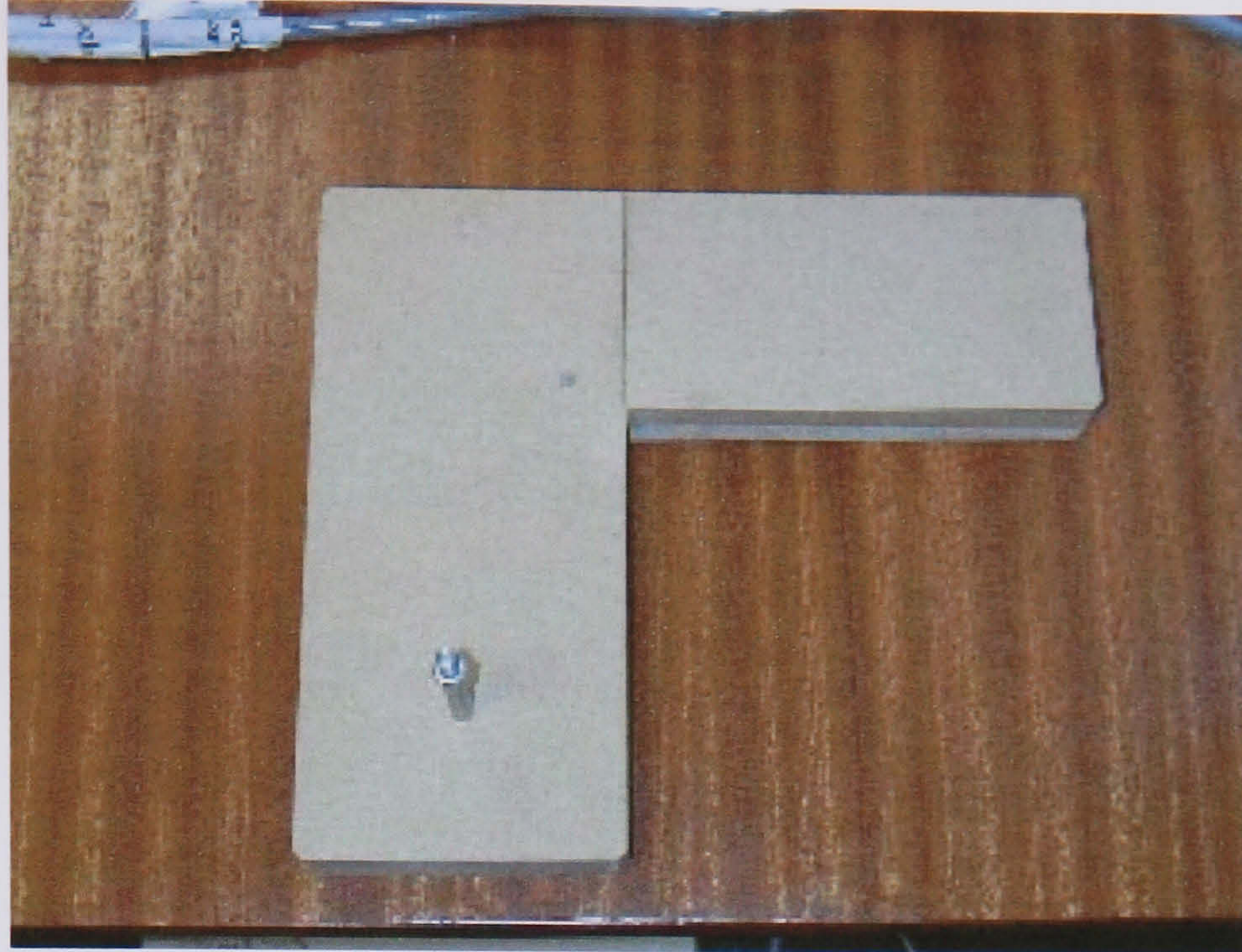
**Figure 3.7 An expansion fitting inserted into one of the real-world cubes**

This fitting allowed the experimenter to screw and unscrew the objects from a support pole measuring 4.5 cm in length and featuring a threaded end (as shown in figure 3.8).



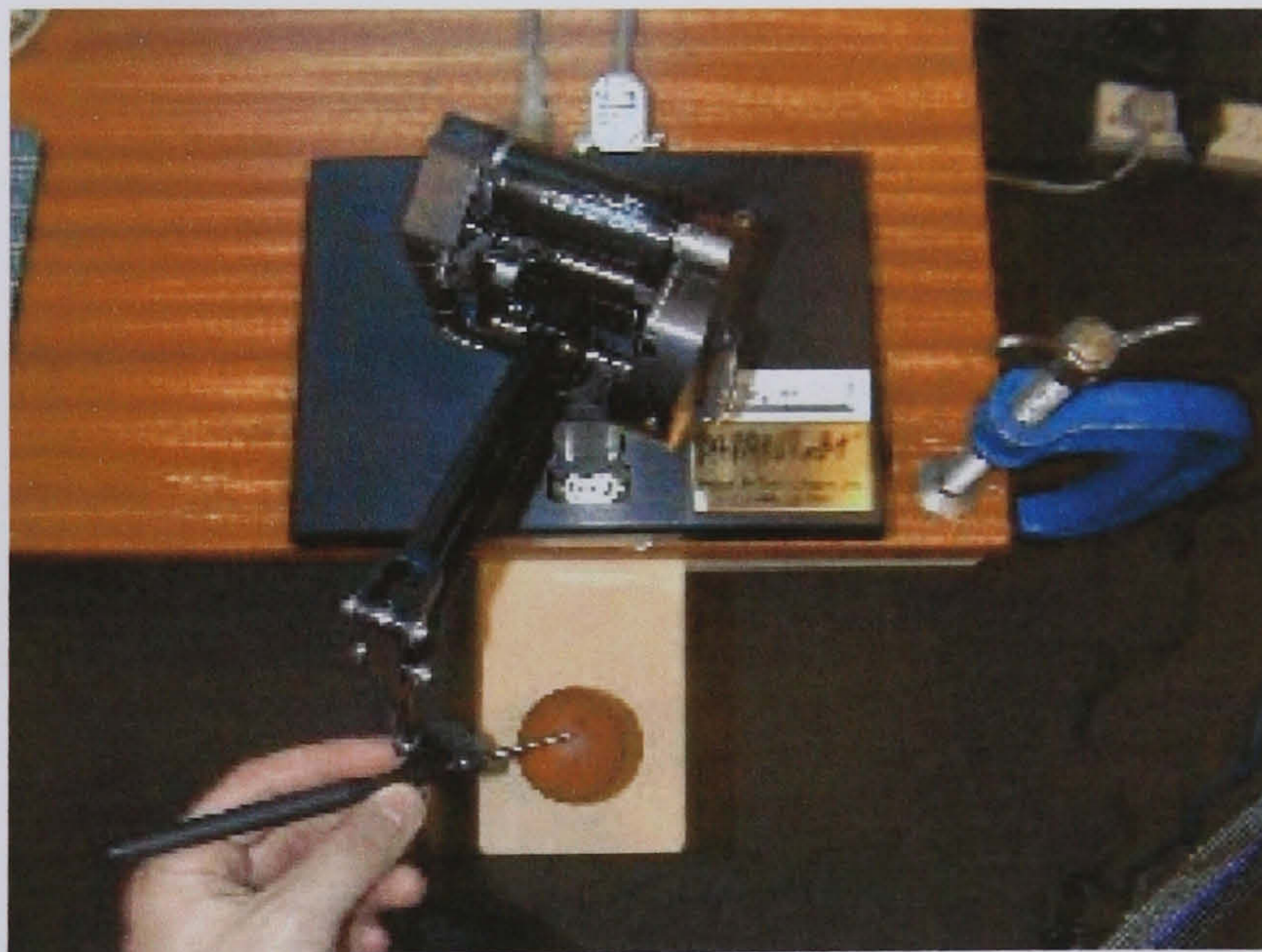
**Figure 3.8 The support pole to which the real objects were attached.**

The support pole was attached to a wooden base shown in figure 3.9.



**Figure 3.9 The wooden base.**

The wooden base was attached to the table surface via a G clamp such that the end of the pole corresponded to the position of the PHANTOM's probe in its reset position. The entire apparatus can be seen in figure 3.10.



**Figure 3.10 A plan view of the experimental apparatus set-up**

To enable the participants to interact with the objects in the deactivated PHANTOM™ exploration level, it was necessary to produce a modified version of the PHANTOM™ 's stylus. This was very similar to the original stylus, with the exception that the length of the metal probe emanating from the stylus grip protruded out of the grip by a length of 5 cm, and the end the metal probe was rounded off to a tip with a contact diameter of 1.5 mm. The stylus can be seen in figure 3.11. The participants also used this modified stylus in the stylus exploration level.



**Figure 3.11 The modified stylus endpoint.**

Participants used the same occluding sleeves ruler, to make object size estimates, and angular ruler, to make angle of shear estimates, as had been used in experiment 3.

### **3.6.5 Procedure**

The experimental procedure was very similar to that used in the previous experiment. Accordingly, only the differences will be covered here.

Participants were seated in front of the experimental apparatus them in the horizontal plane. Participants were asked to sit at a distance whereby they could comfortably explore the device's entire workspace without needing to change their seating position. Participants were also asked not to change their seating orientation relative to the PHANTOM™ throughout the course of the experiment. The Sighted participants were blindfolded for the duration of the experiment

In the de-activated PHANTOM™ level, the participants were asked to examine the real objects via the PHANTOM™ device, with the modified stylus endpoint attached. They were told not to use anything other than the PHANTOM™ in examining the real objects.

In the stylus level, the participants were asked to examine the real objects via the detached PHANTOM's stylus. They were asked not to use anything other than the stylus when examining the real objects.

In the bare index finger level, the participants were asked to examine the real objects using only their extended index finger. The participants were also asked to only use a contour following method of exploration when examining the objects. This was then demonstrated to the participant. This request was made in order that any effect of the availability of cutaneous information for single point interaction would not be confounded by use of different EPs, for example, it would have been possible for participants in this level to use the enclosure EP.

In the free exploration level, the participants were asked to examine the objects using whatever exploration method they felt would yield the most accurate estimate. They were told that they could use as many fingers as they wished, on one or both hands. They were also told that they may use different strategies for different objects, but were not obliged to do so. After providing a judgment for each object, the participant was asked to demonstrate the strategy they used to arrive at that estimate, this was noted by the experimenter.

It is important in order to determine whether that participants were taking advantage of the freedom afforded by the free exploration level and not simply using the same EP of contour following that they would have had to use in the single point interaction levels. Participants were observed to use 3 EPs in arriving in their size and angle estimates: Contour following; Enclosure and an EP that will be referred to as 'anatomical referencing'. This involved the participant using part the hand as a fixed reference point against which to judge object size or angular extent. A preliminary examination of the incidence of these EPs indicates that participants were indeed using EPs other than just contour following in arriving at their estimates of size and angular extent in the free exploration level. Of the three EPs observed, contour following was least frequently identified by participants as being the EP they relied on in their estimates.

The sighted participants underwent all four exploration levels. The order in which they were undertaken was randomised for each participant. The blind participants only undertook the Free Exploration level.

In all exploration levels, the participants were informed that after being presented with a cube or sphere they would be asked to use the occluding sleeves ruler to estimate the edge length of the virtual cubes and the diameter of the virtual spheres, respectively. In the case of the sheared

cubes, they were informed that they would be asked to use the angular ruler to estimate the angle of shear. The operation of the occluding sleeves ruler and angular ruler was then demonstrated to the participants. For estimates of size, participants adjusted the occluding sleeves ruler in the horizontal plane by gripping the fixed sleeve with one hand and adjusting the movable sleeve with the other, until they were satisfied that the distance between the sleeves corresponded to the size of the object.

For estimates of angular extent, participants adjusted the angular ruler in the horizontal plane by gripping one of the arms with one hand whilst adjusting the relative orientation of the remaining arm with the other hand, until they were satisfied that the angular relationship of the two arms corresponded to angular extent of the sheared cubes.

In all of the exploration levels the experimenter recorded the participants' size and angular extent estimates by hand. For estimates of size, the experimenter traced the distance between the occluding sleeves of the ruler, as set by the participant, with a pencil and then recorded the extent of this mark using a conventional ruler. For the estimates of angular extent, the experimenter traced the angle of the intersection formed by the two arms of the angular ruler, as set by the participant, with a pencil and recorded the angle with a protractor.

## **3.7 Results**

- **Perception of the size of the real objects**

The approach taken in examining the data on the real objects was the same as that taken with the virtual objects, outlined in section 3.3. The participants' size estimates for the real objects are summarised in table 3.5. The main effect of the exploration type factor was not statistically reliable. Accordingly,

the data has been collapsed across the exploration conditions. There were interactions between the exploration type factor and other factors, which are discussed later.

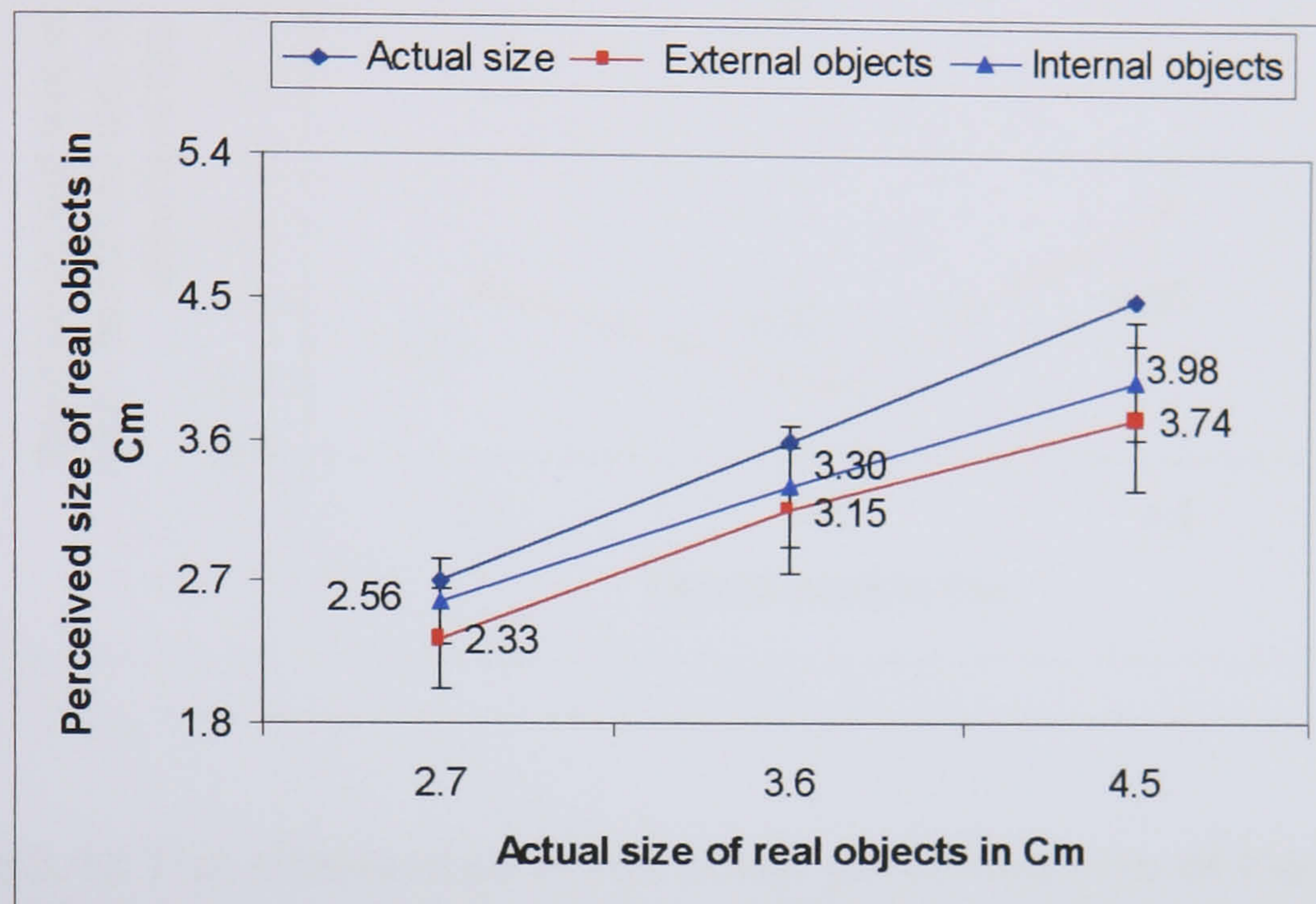
**Table 3.5 Mean perceived sizes and associated confidence limits and for the real cubes and spheres**

Object type	Mean perceived size	Lower confidence limit	Upper confidence limit
External cube 2.7	2.31	2.03	2.59
External cube 3.6	3.08	2.64	3.52
External cube 4.5	3.91	3.50	4.31
Internal cube 2.7	2.54	2.16	2.92
Internal cube 3.6	3.36	2.89	3.83
Internal cube 4.5	3.88	3.46	4.30
External sphere 2.7	2.36	1.81	2.90
External sphere 3.6	3.23	2.59	3.87
External sphere 4.5	3.58	2.94	4.22
Internal sphere 2.7	2.59	2.28	2.89
Internal sphere 3.6	3.24	2.84	3.65
Internal sphere 4.5	4.08	3.65	4.51

Table 3.5 and Figure 3.12 (on the following page) show that the sizes of all of the real cubes and spheres, irrespective of whether they were presented in the internal or external orientation, were underestimated. The mean perceived sizes of the cubes and spheres increases with the actual size of the stimuli, for both the internal and external orientations. This effect was found to be statistically reliable,  $F(2, 8) = 162.55$   $p < .0005$ . The linear contrast for the effect of size was also statistically reliable,  $F(1) p < .0005$



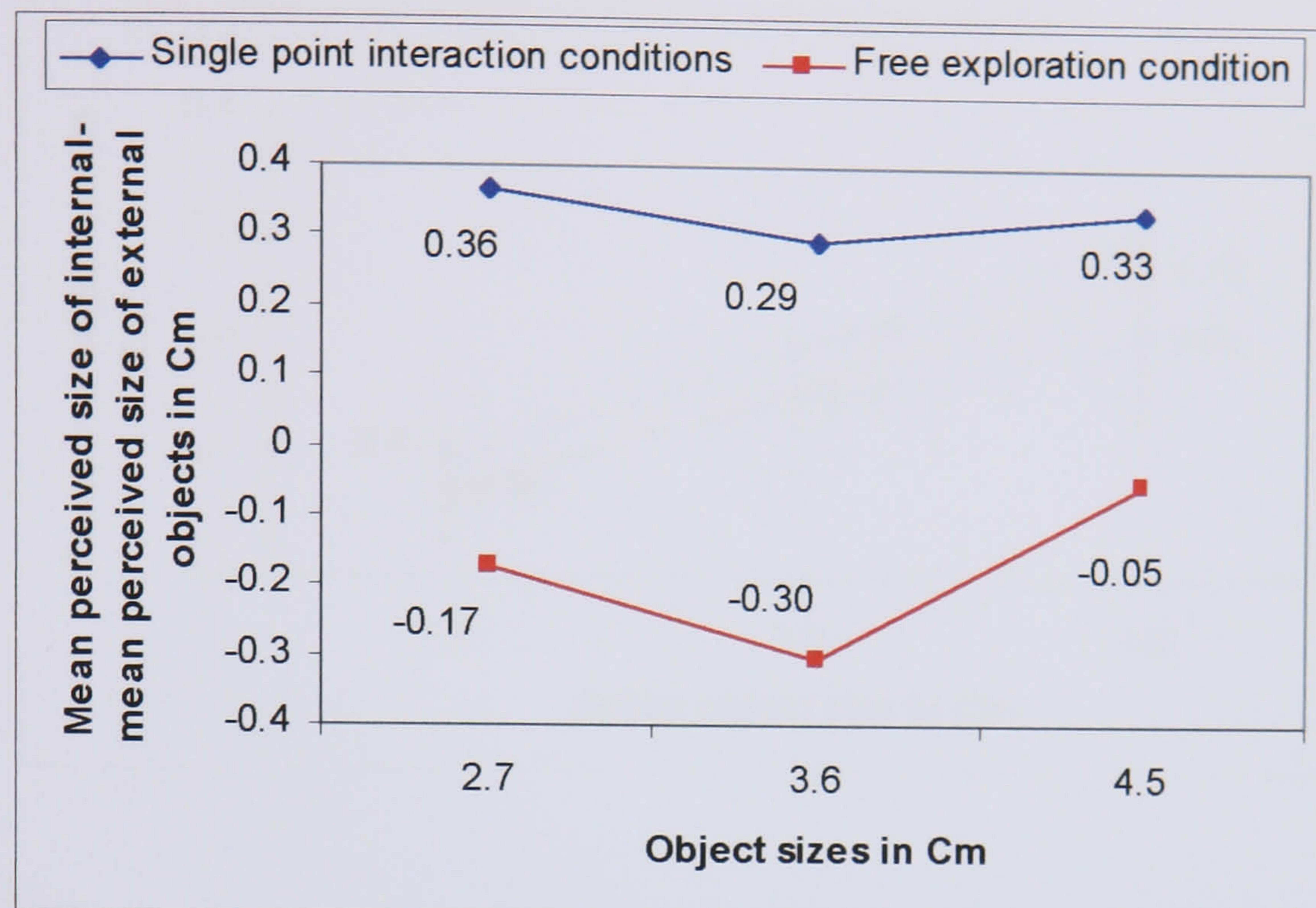
Table 3.5 and figure 3.12 also indicate that cubes and spheres presented in the internal orientation were underestimated to a lesser extent, thus were perceived as larger than the same sized objects in the external orientation (i.e. the Tardis effect). This effect was found to be statistically reliable,  $F(1, 9) = 6.64$   $p = .030$ .



**Figure 3.12 The mean perceived size estimates, collapsed over Object Type for the internal and external orientation conditions**

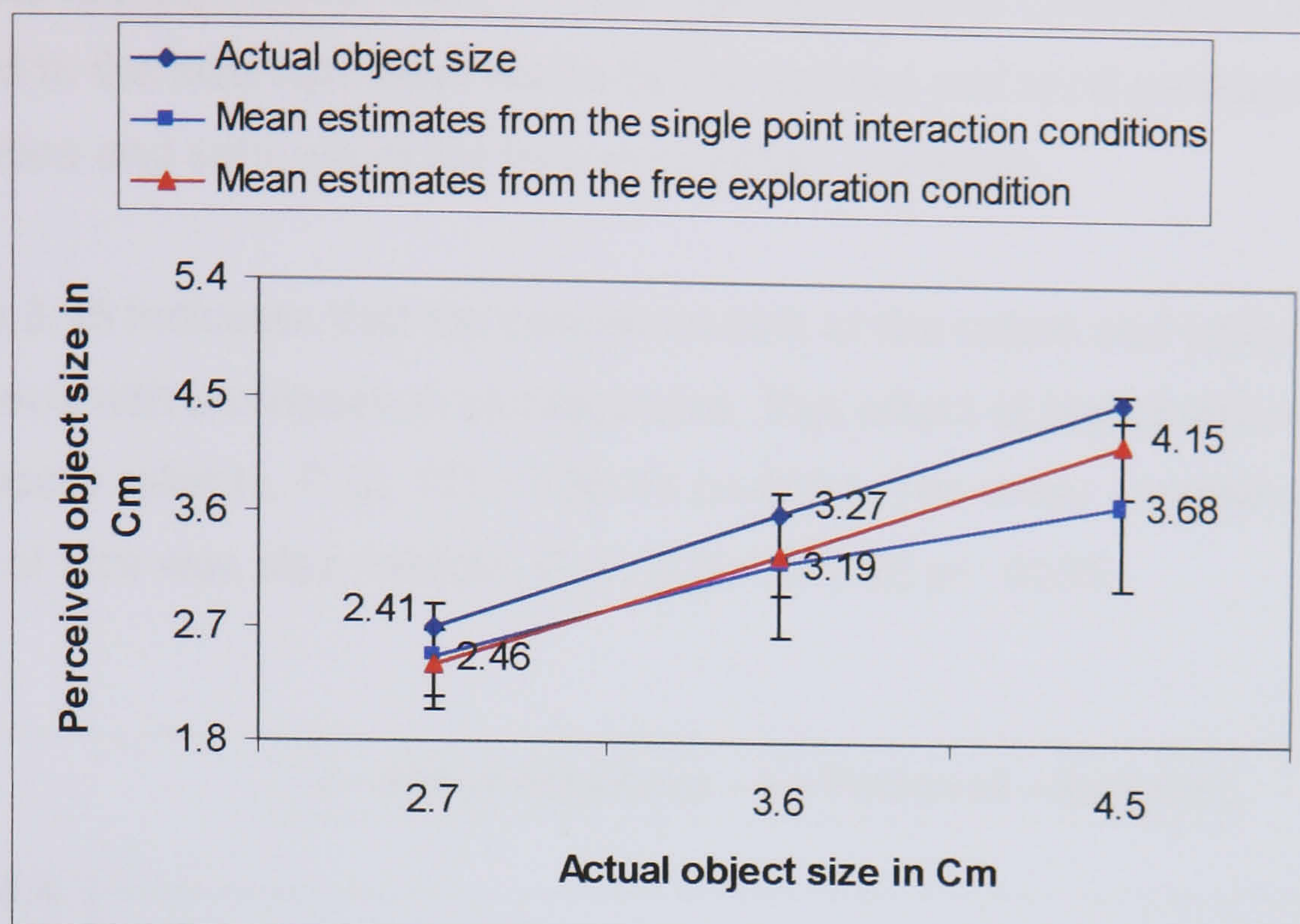
Figure 3.13 (on the following page) indicates that the mean sizes of the cubes and spheres presented in the internal orientation were judged as larger than their externally presented counterparts in all the exploratory conditions except the free exploration condition. This interaction between the factors of Exploration Type and Object Orientation was confirmed as statistically reliable,  $F(3,7) = 6.70$   $p = .002$ , furthermore a within subjects contrast on the interaction between the factors of Exploration Type and Object Orientation showed a reliable difference between the free exploration

condition and the mean of the other exploration conditions  $F(1) = 12.26$   $p = .007$ .



**Figure 3.13** The differences in the mean perceived size of the internal and external modes of presentation, collapsed over object type, for the single point interaction conditions and the free exploration condition

Figure 3.14 (on the following page) indicates that the difference in the mean size estimates between the exploratory conditions is similar for the real objects measuring 2.7 and 3.6 cm. However, the free exploration condition returns a higher estimate for the 4.5 cm real objects than the De-activated PHANTOM™, Stylus and Bare Finger conditions. This interaction between the factors of Exploration Type and Object Size was also found to be statistically reliable,  $F(6,4) = 4.76$   $p = .001$ . Furthermore, a within subjects contrast on the interaction between the factors of Exploration Type and Object Size showed a reliable difference between the free exploration condition and the mean of the other exploration conditions for the estimates of the largest objects relative to the mean of the other size conditions,  $F(1) = 16.02$   $p = .003$



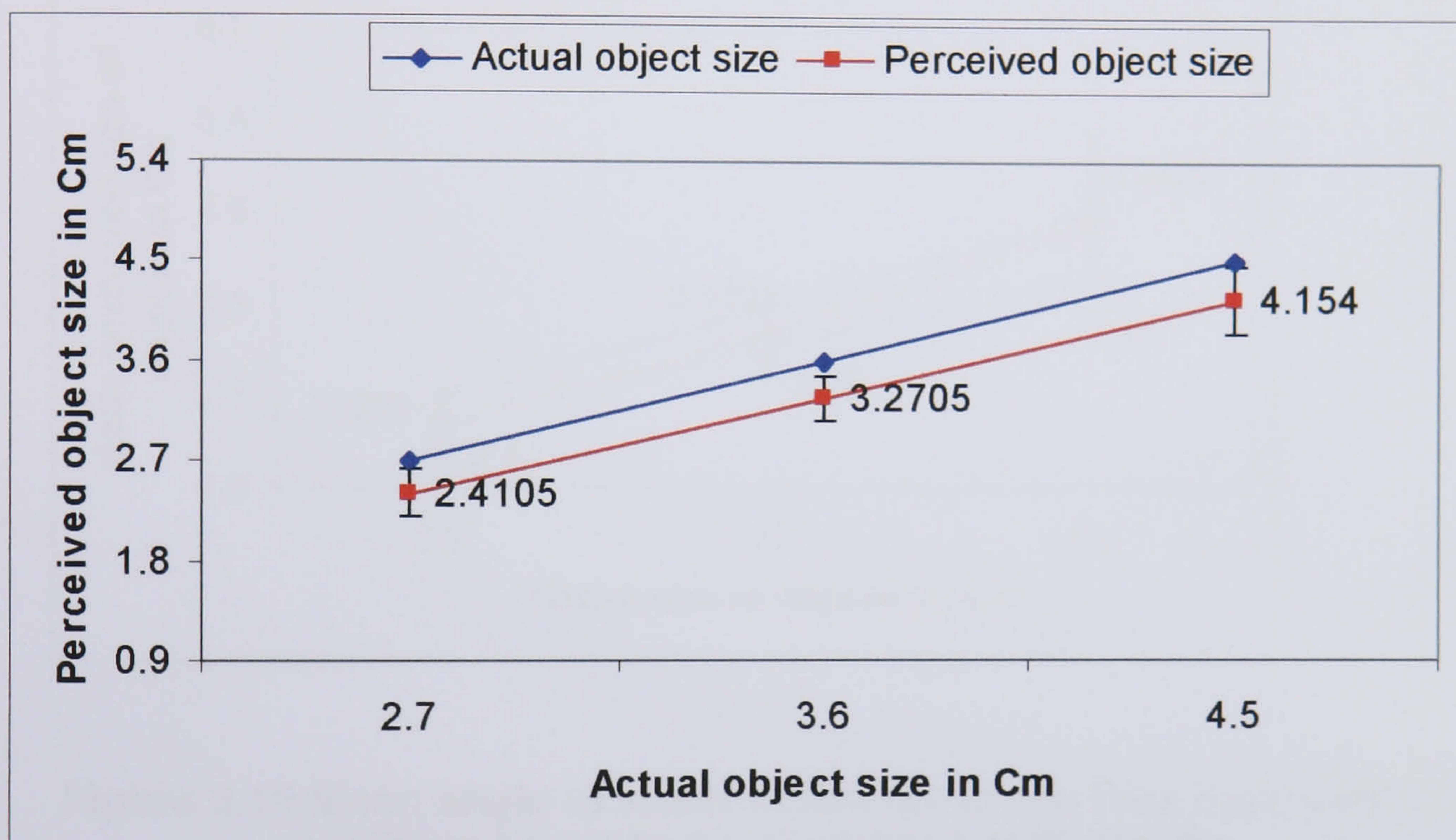
**Figure 3.14 Mean size estimates, collapsed over Object Type, for the exploratory conditions**

The significant interaction between the factors of Exploration Type and Object Orientation appears to have been caused by the lack of the Tardis effect in the free exploration condition. Similarly, the interaction between the factors of Exploration Type and Object Size seemed to be attributable to the influence of the free exploration condition. Thus, if one were to exclude the data from the free exploration condition from the analysis, one would expect the interactions noted above to disappear. Accordingly, the analysis was re-run without the data from the free exploration condition and the interactions were no longer present.

The data from the second experimental design involving a comparison of the perceived size for the real objects in the free exploration between blind and sighted participants was then undertaken. A mixed design ANOVA, consisting of one between subjects factor (Visual Status) and three within

subjects factors (Object Size, Object Type and Object Orientation) was then applied to the size estimates made by the sighted and blind participants for the cubes and spheres in the free exploration condition.

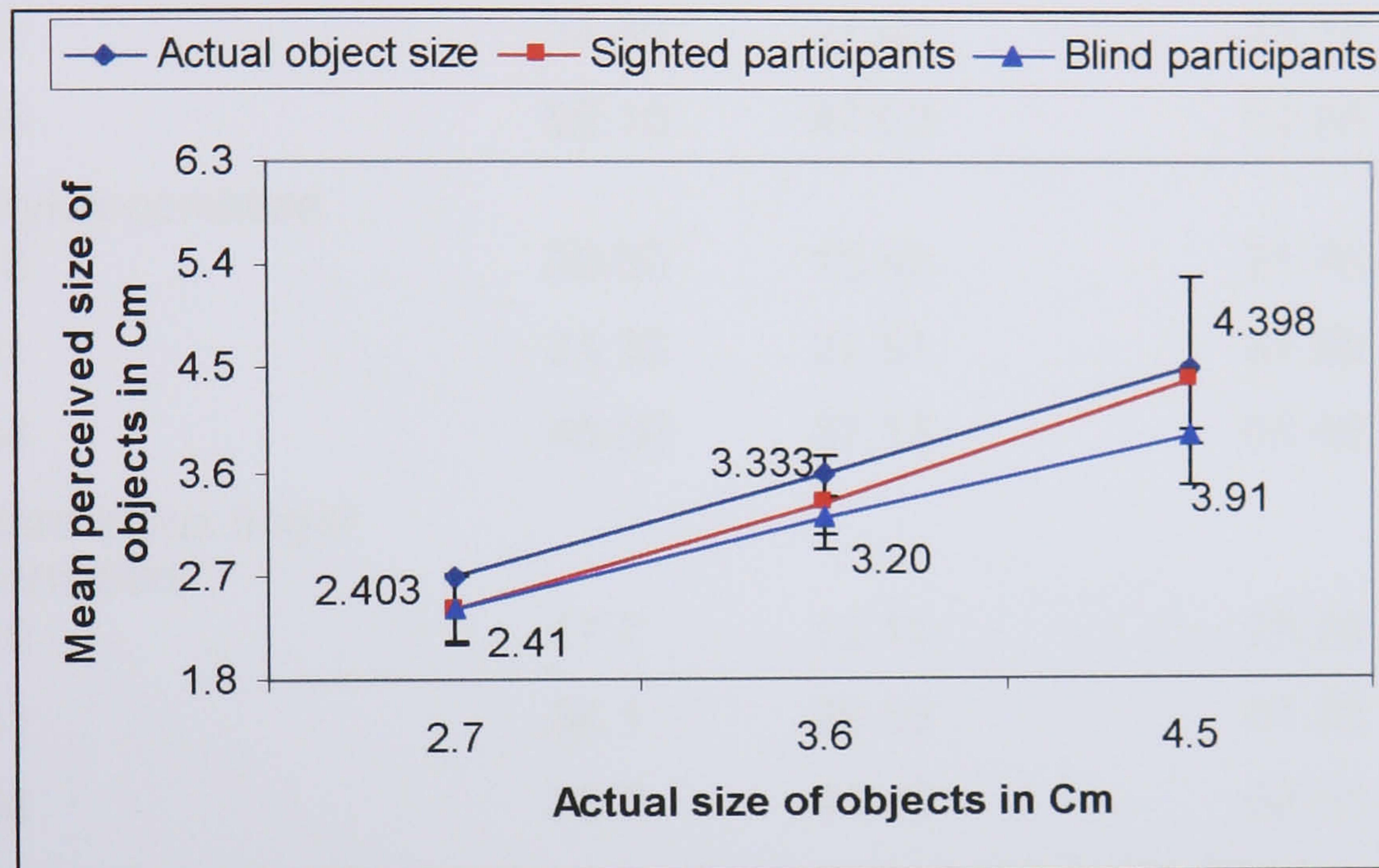
Figure 3.15 indicates that the perceived size of the cubes and spheres increases with increases in stimulus size. This effect of object size was statistically reliable,  $F(2, 17) = 158.14$   $p < .0005$ . The linear contrast for the effect of size was also reliable,  $F(1, 22) = 243.06$   $p < .0005$ .



**Figure 3.15 Mean sizes for the real objects in the free exploration condition collapsed over object orientation, object type and visual status.**

There was no statistically reliable main effect of visual status. However, Figure 3.16 (on the following page) indicates that the mean estimates of size from the blind and sighted participants were very similar for the objects measuring 2.7 and 3.6cm. However, the difference between the two groups

is somewhat greater for the virtual objects measuring 4.5cm, with the sighted participants returning higher estimates than the blind participants. A reliable interaction between the factors of Object Size and Visual Status,  $F(2, 17) = 3.49$   $p < .041$  and a within subjects contrast on the interaction between Object Size and visual status found the perceived size of the largest objects to be significantly greater than the mean sizes of the two smaller objects,  $F(1) = 4.81$   $p < .042$



**Figure 3.16 Mean angle of shear estimates in the Free Exploration condition from blind and sighted participants**

● Perception of Real object angle of shear

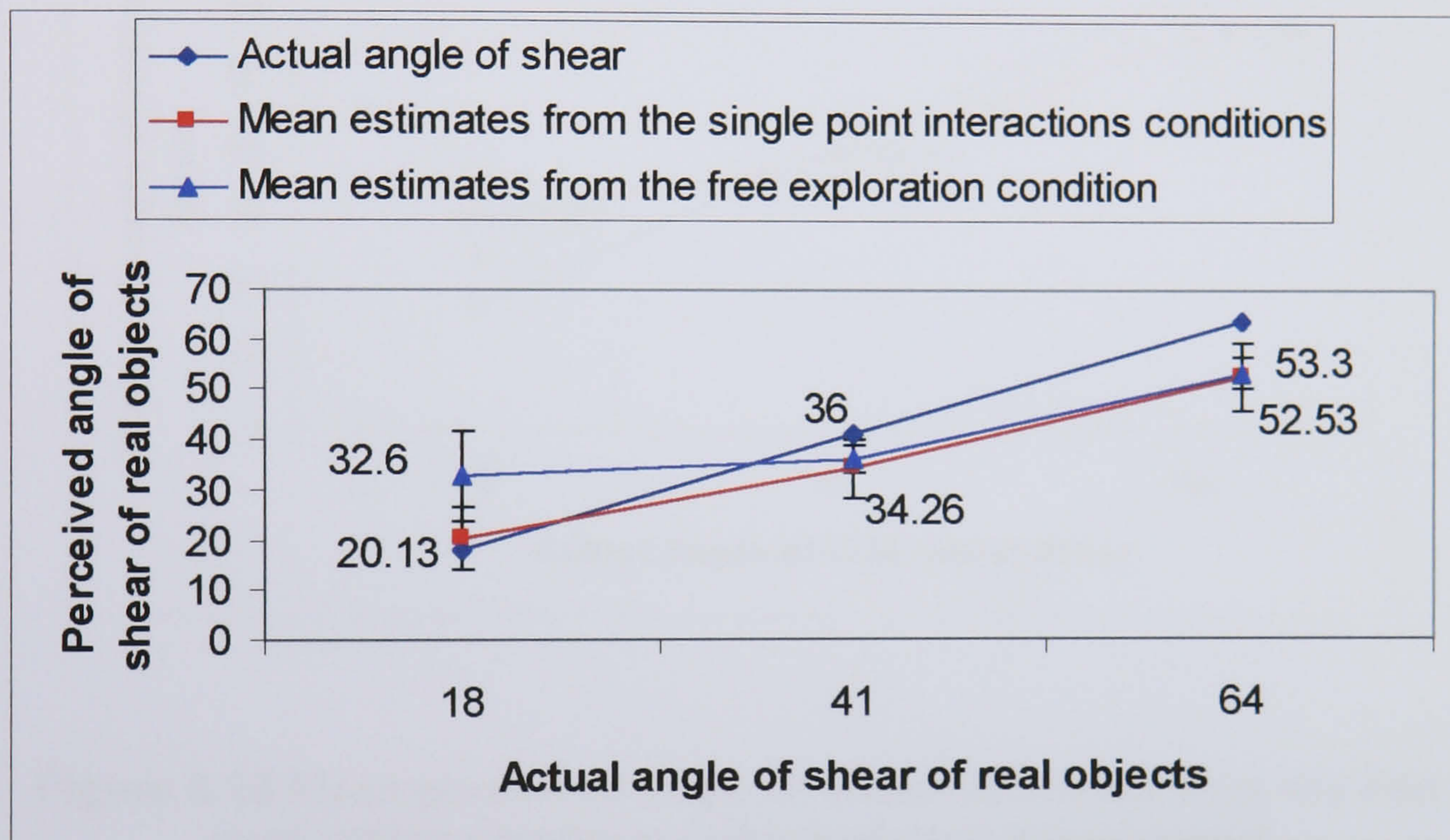
Angle of shear estimates for the real sheared cubes in the first experimental design involving the de-activated PHANTOM™, stylus and bare index finger condition are summarised in table 3.6

**Table 3.6 Participants mean angle of shear estimates for the sheared cubes**

Actual degree of shear	Perceived angle of shear	Lower confidence limit	Upper confidence limit
De-activated PHANTOM™ condition			
18	22.10	15.58	28.61
41	34.40	27.67	41.12
64	55.10	47.63	62.56
Stylus condition			
18	20.60	15.45	25.75
41	34.30	27.51	41.08
64	48.80	37.13	60.46
Bare index finger condition			
18	17.7	12.11	23.28
41	34.1	26.83	41.36
64	53.7	44.46	62.93
Free exploration condition			
18	32.60	23.51	41.68
41	36.00	29.11	42.88
64	53.30	44.31	62.28

Table 3.6 and figure 3.17 (on the following page) suggest that perceived angle of shear increased with actual angle of shear in all of the exploration conditions. A two factor within subjects design ANOVA (Exploration Condition, Angle of Shear) found the effect of Angle of shear to be statistically reliable,  $F(2, 8) = 128.05$   $p < .0005$ . The linear contrast for the effect of angle of shear was also highly significant,  $F(1) = 145.72$   $p < .0005$ .

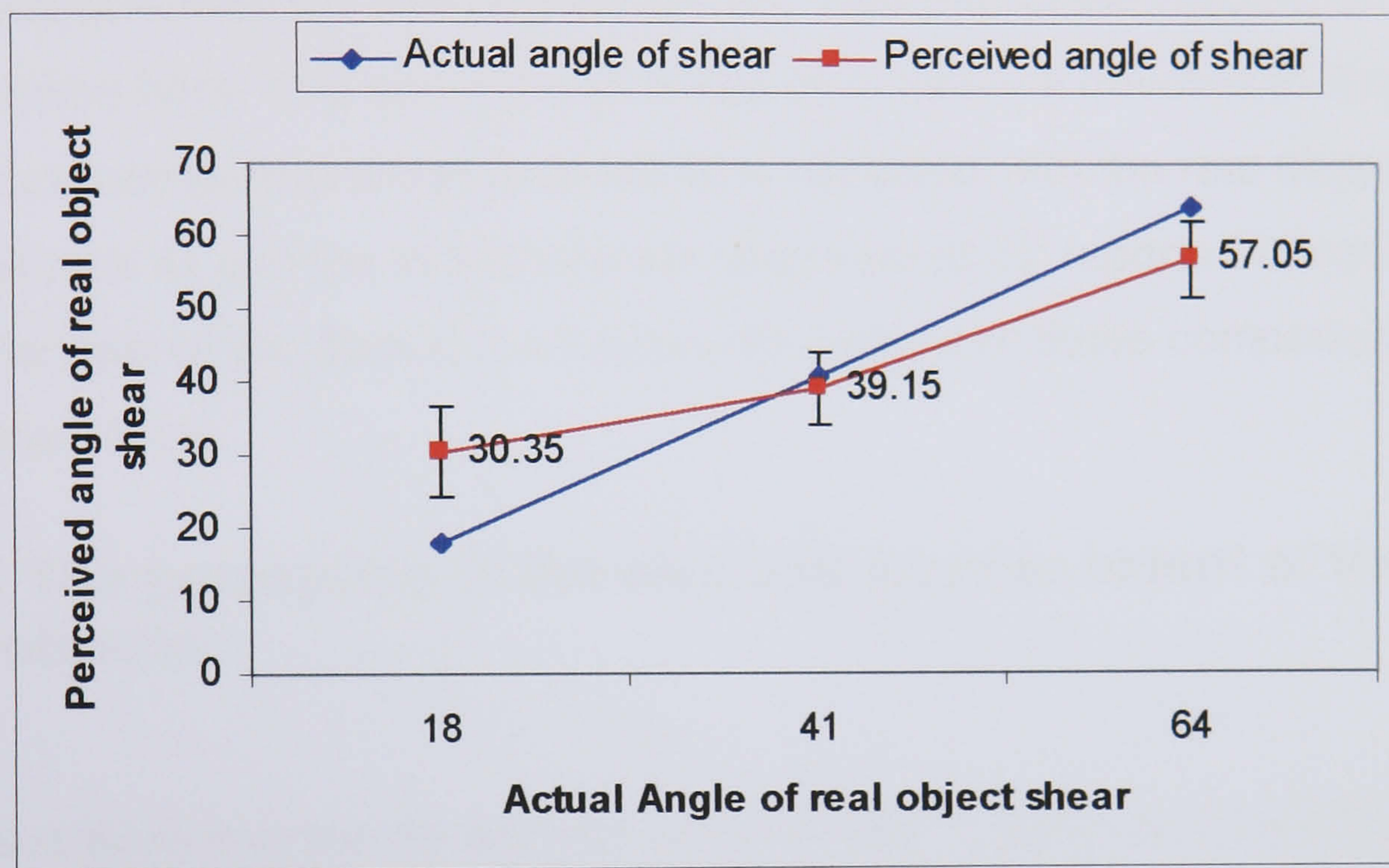
The effect of Exploration Condition was found to be statistically reliable,  $F(3, 7) = 3.04$   $p = .046$ . Within subjects contrasts for the factor of Exploration Condition found a significant difference in perceived angle of shear between the Free Exploration condition and the means of the Deactivated PHANTOM™, Stylus and Bare Index Finger conditions,  $F(1) = 5.60$   $p = 0.042$ . Figure 3.17 indicates that the free exploration condition yielded higher estimates of shear than the mean estimates from the single point interaction conditions particularly for the cube sheared by 18 degrees.



**Figure 3.17 Mean perceived angle of shear estimates from the single point interaction conditions and the free exploration condition**

The data from the second experimental design involving a comparison of the perceived angular extent for the real objects in the free exploration between blind and sighted participants was then undertaken. A two factor mixed design ANOVA, consisting of one between subjects factor (Visual Status) and one within subjects factor (Angle of Shear), found no statistically reliable

effect of visual status. Accordingly, the participants' of angle of shear estimates have been collapsed over the factor of Visual status in figure 3.18. Figure 3.18 indicates that the perceived angle of shear increased with the actual angle of shear. This effect of angle of shear was found to be statistically reliable,  $F(2,17) = 34.38$   $p < .0005$ . The linear contrast for the effect of angle of shear was statistically reliable,  $F(1) = 47.33$   $p < .0005$ .



**Figure 3.18 Mean perceived angle of shear estimates from the free exploration condition collapsed over visual status**



## **3.8 Discussion on the perception of the size and angular extent of the real objects**

The data obtained in experiment 4 is quite extensive; therefore the discussion is divided into two parts. The first part deals with the perception of object size and angular extent based on the results of experiment 4, with the real objects per se. This part of the discussion is undertaken here. The second part of the discussion is devoted to the statistical comparisons between the data obtained with the real objects (experiment 4) and the virtual objects (experiment 3), reported in section 3.9. Part two of the discussion follows the reports of those comparisons in section 3.10.

### **3.8.1 The perception of the size and angular extent of the real objects**

It was striking that the de-activated PHANTOM™, stylus and bare finger conditions were statistically indistinguishable. These conditions are henceforth referred to as the 'single point of interaction' conditions, since this characteristic is common to them all and distinguishes them all from the free exploration condition.

The free exploration condition was found to be statistically distinct from the single point of interaction conditions. However, the forms the differences took were quite subtle, i.e. it was not the case that the free exploration condition yielded higher or lower estimates of perceived size per se, but rather it qualified the effects of the factors of Object Size and Object Presentation Mode.

The free exploration condition also differed from the single point of interaction conditions with regard to the impact of the factor of Object Size. The difference in size estimates between the exploration conditions is similar for the real objects measuring 2.7 and 3.6 cm. However, the

extent of the underestimation of the 4.5cm cubes and spheres was smaller in the free exploration condition than in the single point of interaction conditions. It may be the case that the participants in the free exploration condition were using different EPs to judge the size of the 4.5 cm objects than the 2.7 and 3.6 cm objects. This would not have been an option in the single point of interaction conditions, as these conditions constrained the participants to using the EP of contour following. Lederman and Klatzky (1987) indicated that participants tend to use the optimal EP for the perception of an attribute without instruction. The EP of enclosure has been identified as 'optimal' for the perception of size (Lederman and Klatzky, 1987; Lederman and Klatzky, 1993 and O'Modhain, 1999). In the light of these assertions, one would assume that the participants in the free exploration condition were predominantly using enclosure in judging the size of the objects. However, the participants' choice of EPs in the free exploration condition needs to be scrutinised to determine if participants were, indeed, using the 'optimal' EP of enclosure, alone, or in conjunction with other EPs for the 4.5cm objects.

It should be noted that the methodology of the studies that have rated the efficacy of EPs for judging size (e.g. Lederman and Klatzky, 1987; Lederman and Klatzky 1993; and O'Modhain, 1999) was different to that used in this experiment. In the above studies, participants sorted stimuli according to their size, as opposed to reproducing their size. The accuracy of different EPs in reproducing the size of an object has not been examined. An experiment investigating this issue is clearly warranted. It would also be interesting to replicate the sorting task used by the above authors with the stimulus and the exploratory conditions of experiment 4, to determine if the similarity between the exploratory conditions would still be evident when participants were asked to discriminate between, as opposed to reproduce, various sized cubes and spheres.

The participants' estimates of angle of shear in the free exploration condition were significantly different from those obtained in the single point of interaction conditions, but the nature of the difference is not entirely straightforward. The participants' estimates of angle of shear were higher in the free exploration condition for the 18 degree sheared cube than in the single point of interaction conditions. The free exploration condition also yielded the highest estimates for the 41 degree sheared cube, but curiously, not for the 64 degree sheared cube.

The ordering of the exploratory conditions in term of highest to lowest estimates of angle of shear is consistent for the 18 and 41 degree sheared cubes: the free exploration condition returns the highest estimates, followed by the Deactivated PHANTOM™ condition, then the Stylus condition and finally the Bare Index Finger condition. However, the ordering of the exploratory conditions undergoes a change for the 64 degree sheared cube. Here, the de-activated PHANTOM™ condition returns the highest estimates of angle of shear, followed by the bare index finger condition, then the free exploration condition and finally the stylus condition.

Quite why the data from the exploration conditions should be so inconsistent is not clear at this time. With respect to the data from the free exploration condition, one might speculate that perhaps participants were using a different EP to judge the 64 degree sheared cube than had been used for the 18 and 41 degree sheared cubes. However, it is hard to see how the same explanation can be used for the single point of interaction conditions, as the participants would have been restricted to the EP of contour following. Clearly, further investigation in which the participants' examination of the sheared cubes is scrutinised in more detail is warranted.

### **3.8.2 The effect of object type on the perceived size of the real 3-D objects**

The participants' size estimates were found to be consistent between the real cubes and spheres in all of the exploration conditions. This is a difficult finding to put into context as the author is aware of only one real world based study that examined the perceived size of different types of 3-D objects (i.e. Roeckelein, 1968). Roeckelein found similar exponents relating actual size to perceived size for both cubes and spheres, so it could be argued that the findings of experiment 4 are in broad agreement with this finding i.e. that perceived size is consistent between cubes and spheres.

### **3.8.3 The effect of the Presentation mode of real objects on their perceived size**

In the single point of interaction conditions, the participants' estimates of internally presented cubes and spheres were significantly larger than their estimates of the corresponding externally presented cubes and spheres (The Tardis effect). However, this effect was absent in the free exploration condition. This finding provides some insight as to a possible cause of the effect. In the discussion section for experiment 3, it was hypothesised that the Tardis effect was possibly due to difficulties associated with not losing contact with the externally presented virtual objects. When the participants lost contact with a virtual object and had to re-locate it, the size of the virtual object may have seemed relatively small in relation to the size of the empty virtual environment. This could not occur with the internally presented virtual objects, as there was no external environment to judge the objects in relation to. The same principles would have applied to the real external and internal objects in all of the exploratory conditions used in experiment 4, except the free exploration condition. This is because in the free exploration condition, the participants were allowed to handle the internal and external objects. Being able to hold the externally presented objects meant that the participants were very unlikely to lose contact with the real objects. This

makes the size of the unused space surrounding the objects in the external presentation mode redundant; participants would have judged both the internal and external objects on the basis of the object dimensions per se.

One cannot conclude that the above explanation of the Tardis effect is accurate solely from the results of experiment 4. Its presence in every exploration condition bar the free exploration condition has served “narrow down” the potential causes of the effect and identify this explanation as a possibility. One way of establishing if the above reasoning is sound would be to compare the perceived size of virtual external and internal cubes and spheres under conditions in which the participants cannot lose contact with the virtual objects during the process of exploration. This could be easily achieved in HVR by reducing the size of the entire virtual environment, such that it is only nominally bigger than the size of the external object being presented.

#### **3.8.4 The effect of visual status on the perceived size and angular extent of the real objects**

There were no statistically reliable differences between the size estimates returned by the blind and sighted individuals in the free exploration condition, which was also the case with the virtual objects in experiment 3. However, an interaction between the factors of Visual Status and Object Size was noted: the estimates of object size from the blind and sighted participants were very similar for the objects measuring 2.7 and 3.6cm, however, the sighted participants returned higher estimates than the blind participants for the virtual objects measuring 4.5cm. This interaction was not noted in the experiment 3 with the virtual objects. There is the possibility that this interaction might be due to the use of different EPs by sighted and blind participants in judging the 4.5 cm cube and sphere. It would be interesting to see if this interaction was present under conditions in which the use of EPs were equated between the two groups of participants.

There were no statistically reliable differences between the angle of shear estimates returned by the blind and sighted individuals in the free exploration condition. Sighted and blind Participants' estimates of angle of shear were also found to be consistent with the virtual objects in experiment 3.

### **3.9 Results for comparisons between the perception of the size and angular extent of virtual and real objects**

- Comparisons of object size between HVR and the real world

The size estimates of the real cubes and spheres by the participants in experiment 4 were compared to the size estimates of their virtual counterparts in experiment three. Two sets of comparisons were made, as the results of experiment four indicated that the statistically reliable interactions associated with the factor of exploration type were due solely to the Free Exploration condition. Therefore, the first comparison involved the mean size estimates from the single point of interaction conditions and the size estimates obtained in HVR. The second comparison involved the data from the Free Exploration condition and the size estimates obtained in HVR.

The data for the virtual objects in experiment 3 was collapsed over the factors of visual status and endpoint, since neither factor exerted a statistically reliable effect on the size estimates. With these provisos, Table 3.7 (on the following page) displays the mean perceived size of the real objects in experiment 4, collapsed over the de-activated PHANTOM™, stylus and bare index finger exploration conditions compared to the perceived size of the virtual objects in experiment three, collapsed over the non-significant factors of visual status and endpoint.

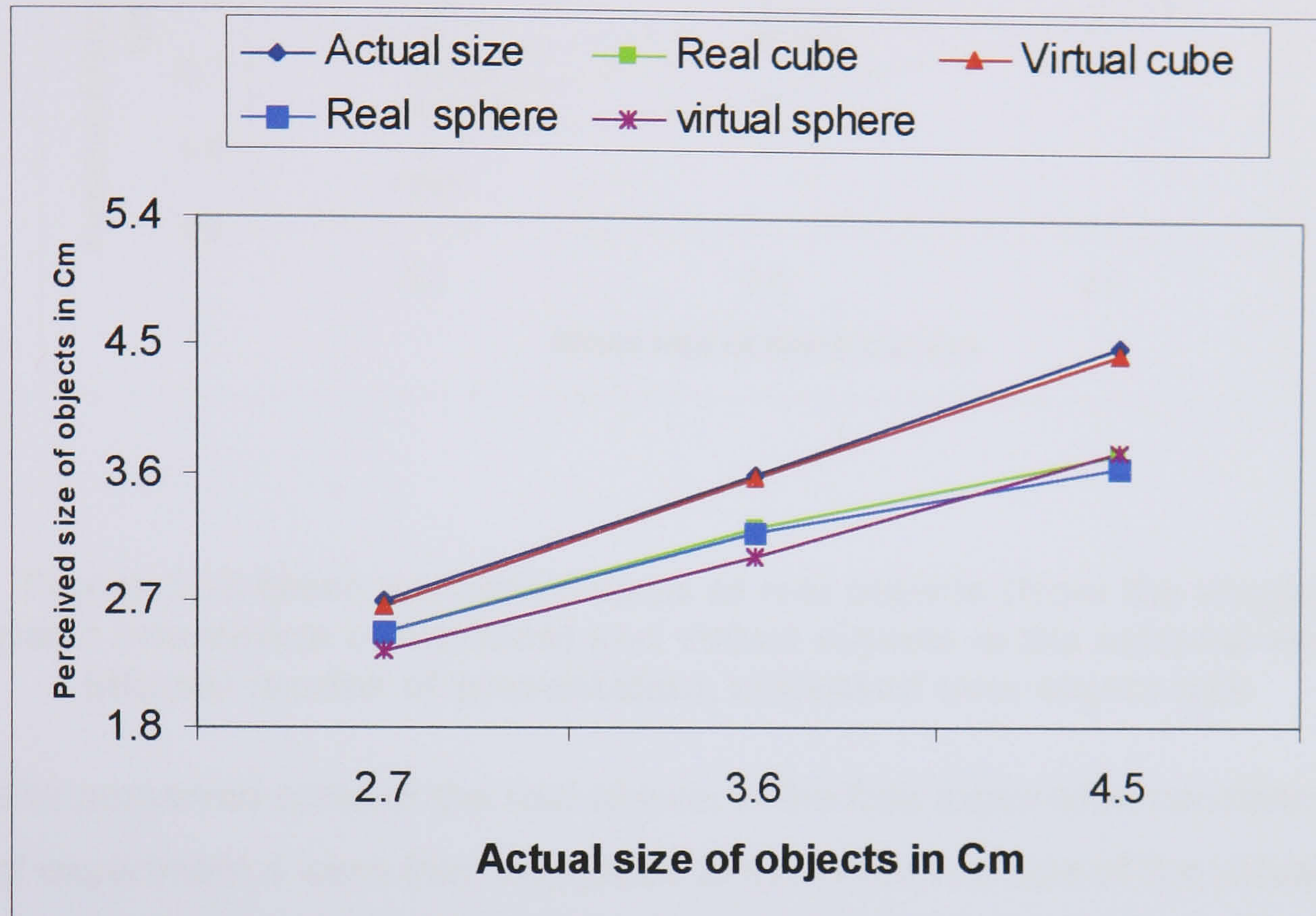
**Table 3.7 The mean perceived sizes of the virtual cubes and spheres and their real counterparts explored in the Deactivated PHANTOM™, Stylus and Bare finger exploration conditions**

Object type & actual size	Mean Perceived size, virtual objects	Confidence limits, lower (L) and upper (U)	Mean Perceived size, real objects	Confidence limits, lower (L) and upper (U)
External cube 2.7	1.94	(L) 1.57 (U) 2.30	2.31	(L) 1.83 (U) 2.79
External cube 3.6	2.72	(L) 2.32 (U) 3.13	3.03	(L) 2.45 (U) 3.60
External cube 4.5	3.70	(L) 3.07 (U) 4.33	3.70	(L) 2.89 (U) 4.52
Internal cube 2.7	3.39	(L) 3.01 (U) 3.77	2.61	(L) 2.07 (U) 3.15
Internal cube 3.6	4.49	(L) 3.87 (U) 5.11	3.38	(L) 2.55 (U) 4.22
Internal cube 4.5	5.25	(L) 4.58 (U) 5.91	3.77	(L) 2.90 (U) 4.63
External sphere 2.7	1.78	(L) 1.51 (U) 2.04	2.25	(L) 1.85 (U) 2.64
External sphere 3.6	2.26	(L) 2.04 (U) 2.49	3.06	(L) 2.63 (U) 3.49
External sphere 4.5	3.01	(L) 2.62 (U) 3.40	3.33	(L) 2.78 (U) 3.89
Internal sphere 2.7	2.91	(L) 2.47 (U) 3.36	2.68	(L) 2.10 (U) 3.26
Internal sphere 3.6	3.80	(L) 3.24 (U) 4.37	3.30	(L) 2.56 (U) 4.04
Internal sphere 4.5	4.56	(L) 3.95 (U) 5.17	3.94	(L) 3.13 (U) 4.75

Table 3.7 and figure 3.19 (on the following page) suggest that the size estimates of the virtual and real cubes and spheres are in broad agreement. This was confirmed by a four factor mixed design ANOVA consisting of one between subjects factor (Reality i.e. real world and HVR) and three within subjects factors (Object Type, Object Orientation and Object Size). This analysis did not find a statistically reliable effect of Reality, but did uncover several interactions involving the factor of Reality, discussed subsequently. Table 3.7 indicates that all of the externally and internally presented virtual cubes are judged to be larger

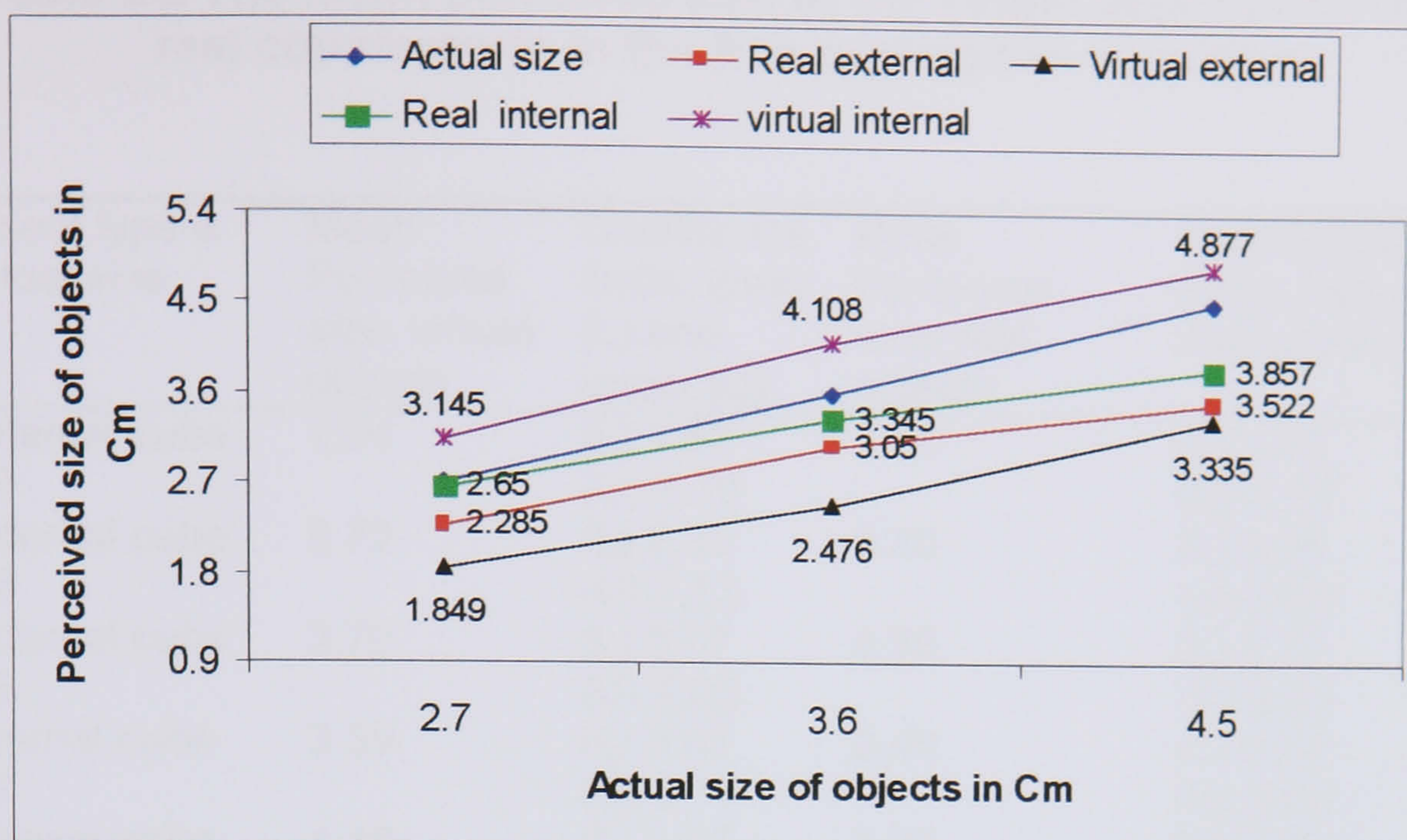


than their equivalent sized virtual sphere counterparts. However, this trend is not evident with the real cubes and spheres. This interaction between the factors of Reality and Object Type was found to be statistically reliable,  $F(1,18) 8.648 p=.006$



**Figure 3.19 Mean perceived size of real and virtual cubes and spheres**

Table 3.7 and figure 3.20 (on the following page) also clearly indicate that the virtual cubes and spheres in the internal orientation were perceived as being larger than their counterparts presented in the external orientation (the Tardis effect). However, the magnitude of the Tardis effect is notably lower with the real counterparts to the virtual objects. This interaction between the factors of Reality and Object Orientation was also statistically reliable,  $F(1,18) 31.75 p< .0005$ .



**Figure 3.20 Mean perceived sizes of real objects (from the single point interaction conditions) and virtual objects in the external and internal modes of presentation, collapsed over object type**

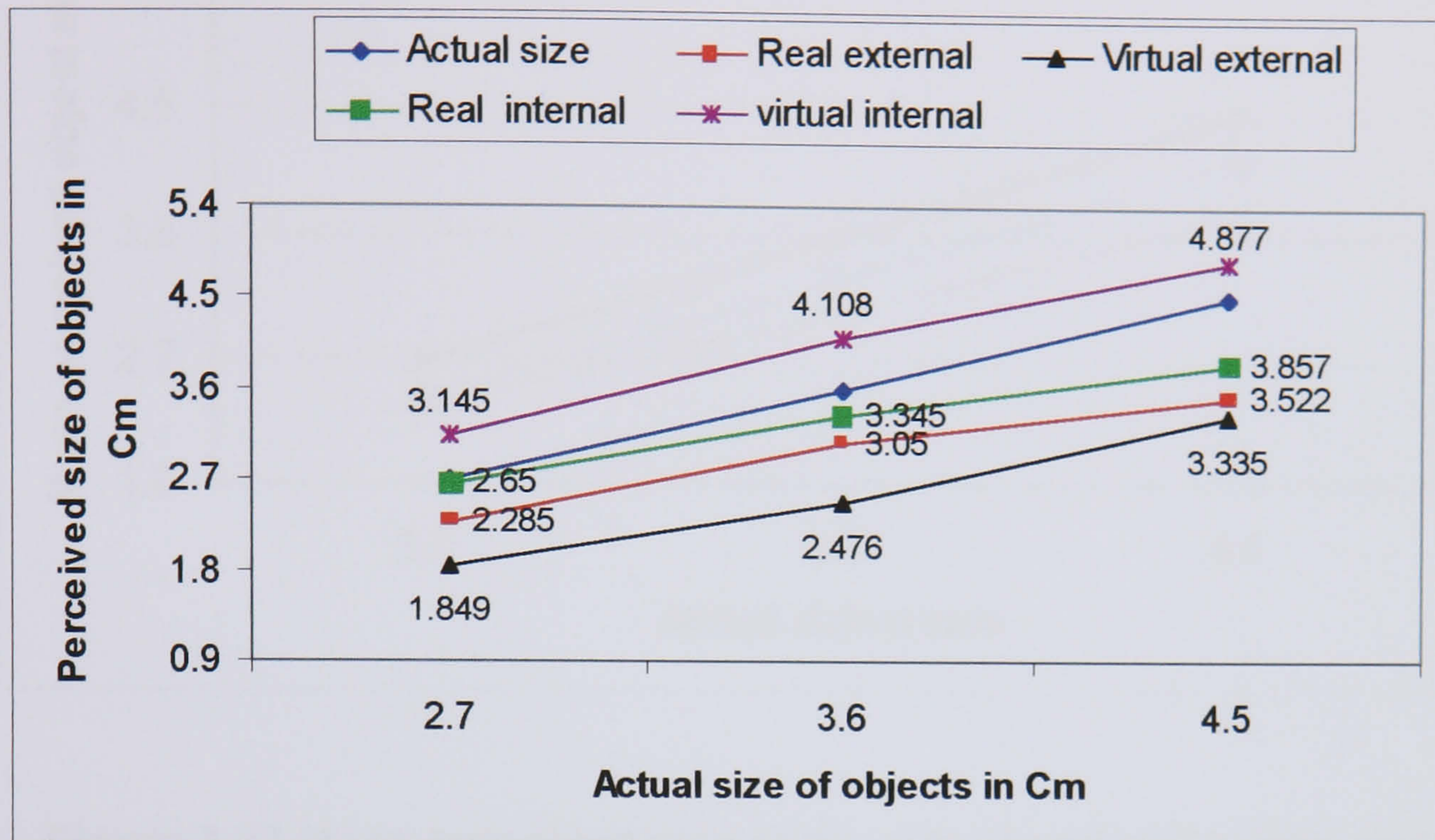
The perceived sizes of the real objects in the free exploration condition of experiment 4 were then compared to the perceived size of the virtual objects in experiment 3. Table 3.8 (on the following page) displays the perceived size of the real objects in the free exploration condition collapsed over the non-significant factor of visual status, compared to the perceived size of the virtual objects in experiment 3, collapsed over the non-significant factors of visual status and endpoint.

**Table 3.8 The mean perceived size of the virtual objects and their real counterparts in the free exploration condition**

Object type & actual size	Mean Perceived size, virtual objects	Confidence limits, lower (L) and upper (U)	Mean Perceived size, real objects	Confidence limits, lower (L) and upper (U)
External cube 2.7	1.94	(L) 1.57 (U) 2.30	2.43	(L) 2.13 (U) 2.72
External cube 3.6	2.72	(L) 2.32 (U) 3.13	3.30	(L) 2.96 (U) 3.65
External cube 4.5	3.70	(L) 3.07 (U) 4.33	4.26	(L) 3.77 (U) 4.75
Internal cube 2.7	3.39	(L) 3.01 (U) 3.77	2.40	(L) 2.10 (U) 2.69
Internal cube 3.6	4.49	(L) 3.87 (U) 5.11	3.23	(L) 2.76 (U) 3.69
Internal cube 4.5	5.25	(L) 4.58 (U) 5.91	4.03	(L) 3.52 (U) 4.54
External sphere 2.7	1.78	(L) 1.51 (U) 2.04	2.52	(L) 2.18 (U) 2.87
External sphere 3.6	2.26	(L) 2.04 (U) 2.49	3.49	(L) 3.18 (U) 3.80
External sphere 4.5	3.01	(L) 2.62 (U) 3.40	4.10	(L) 3.64 (U) 4.56
Internal sphere 2.7	2.91	(L) 2.47 (U) 3.36	2.28	(L) 1.91 (U) 2.65
Internal sphere 3.6	3.80	(L) 3.24 (U) 4.37	3.05	(L) 2.61 (U) 3.48
Internal sphere 4.5	4.56	(L) 3.95 (U) 5.17	4.21	(L) 3.73 (U) 4.68

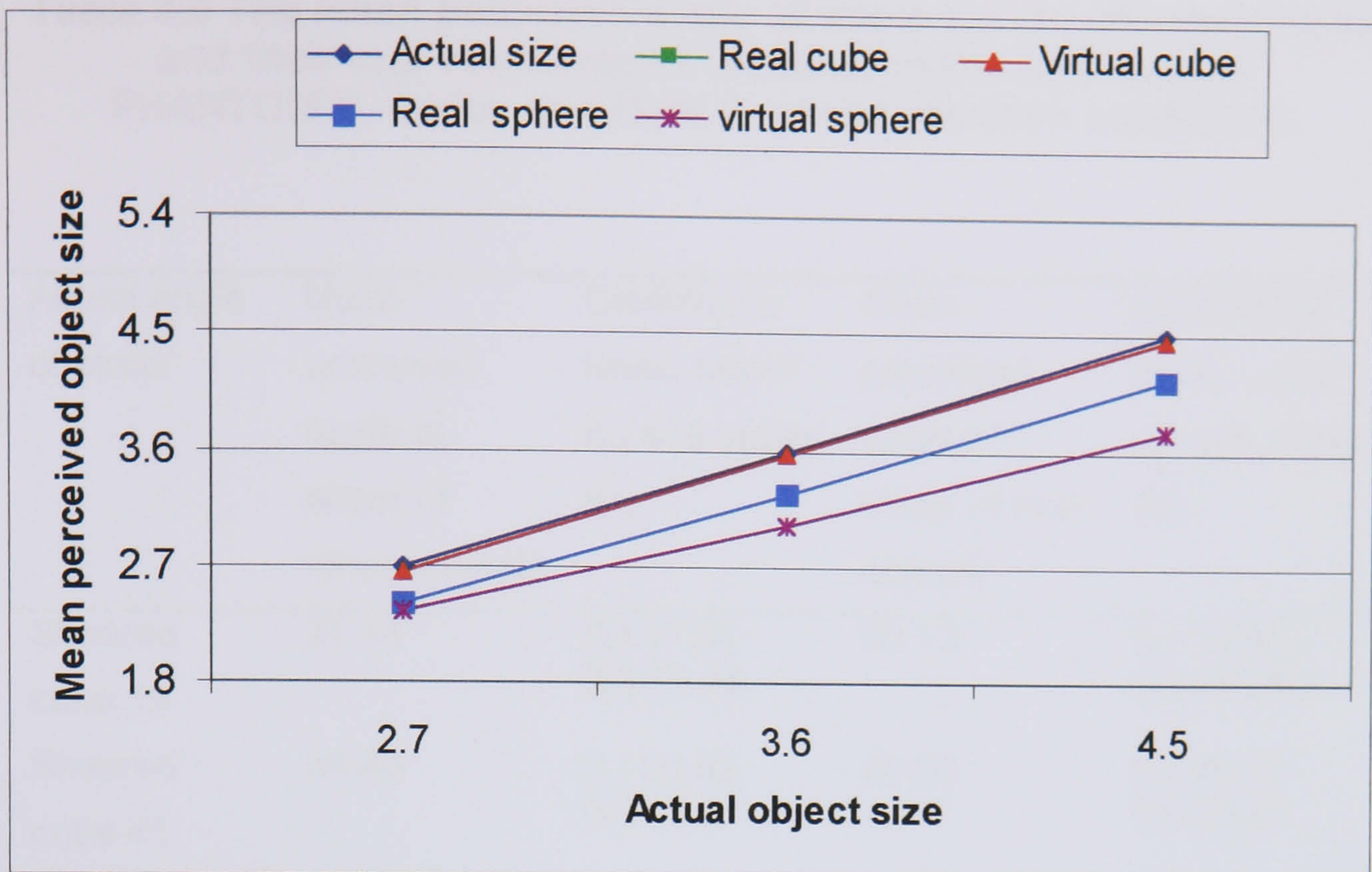
Table 3.8 and figure 3.21 (on the following page) indicate that the external virtual objects tend to be judged as smaller than their real counterparts. However, the reverse is true for the internal objects; the virtual internal objects are judged as larger than their real counterparts. A four factor mixed design Anova consisting of one between subjects factor (Reality) and three within subjects factors (Object Type, Object Orientation and Object Size), did not find a statistically reliable effect of reality. However, as the data from table 3.8 and figure 3.21 suggests, the Tardis effect is completely absent in the free exploration condition. The internal orientations of the cubes and spheres are, without exception, judged to be smaller than their external counterparts. This is the direct opposite of what occurs with the virtual objects. This interaction between

the factors of Reality and Object Orientation was also found to be statistically reliable,  $F(1,18) 109.67 p < .0005$ .



**Figure 3.21 Mean perceived size of the virtual and real objects in the internal and external presentation modes in the free exploration condition**

Table 3.8 and figure 3.22 (on the following page) also indicate that the virtual cubes are invariably judged to be larger than equivalent sized spheres. However, this is not the case with the real cubes and spheres in the free exploration condition. In this instance, only the external 4.5 cm cube and the internal 2.7 and 3.6 internal cubes were judged to be larger than their spherical counterparts. This interaction between the factors of Reality and Object Type was found to be statistically reliable,  $F(1,18) 17.61 p < .0005$ .



**Figure 3.22 Mean perceived size of the virtual and real cubes and spheres collapsed over the internal and external presentation modes in the free exploration condition**

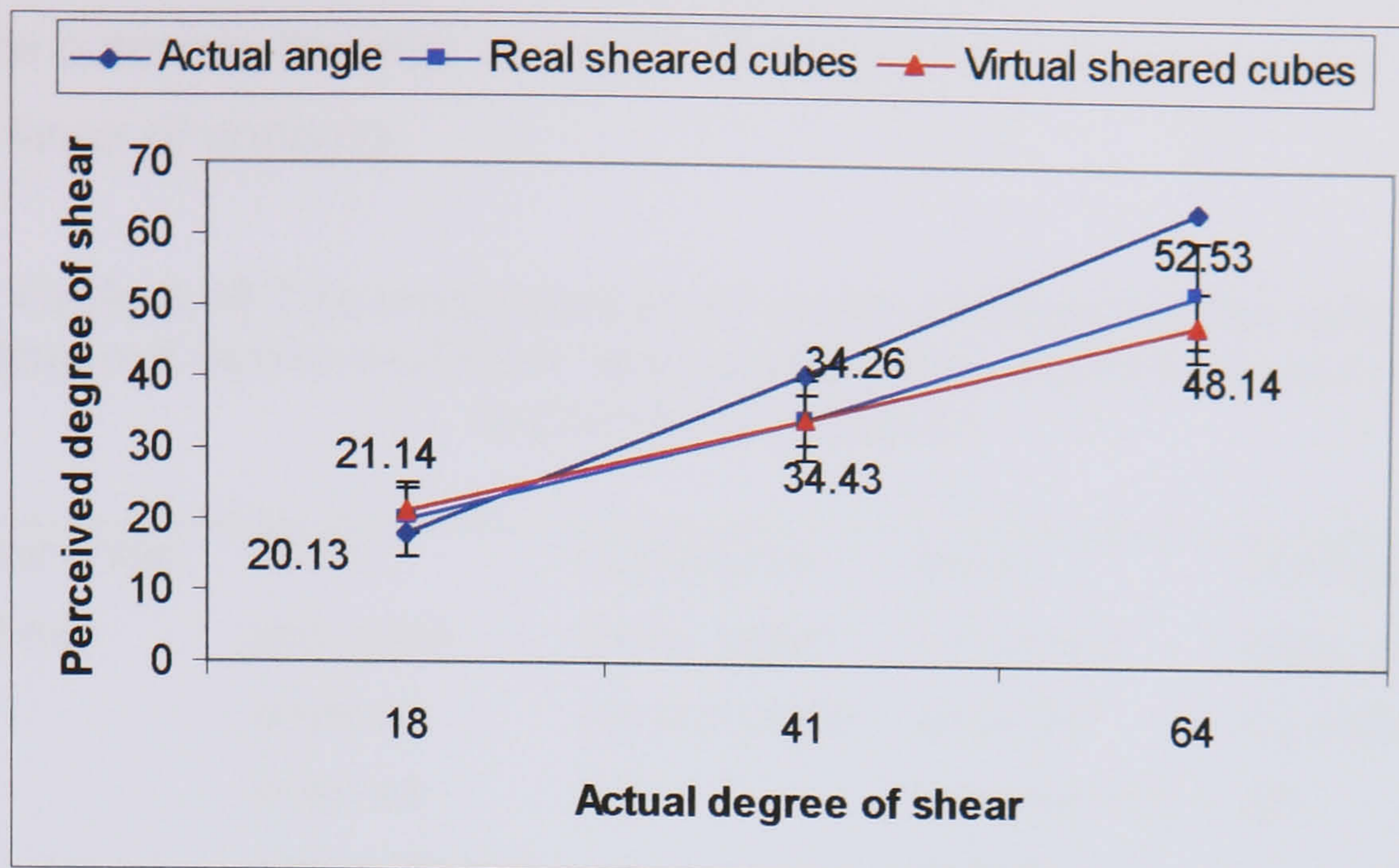
- Comparison of angle of shear between HVR and the real world

The angle of shear estimates of the virtual sheared cubes by the participants in experiment three were then compared to the estimates of the real sheared cubes by the participants in this experiment. Table 3.9 (on the following page) displays the perceived size of the real objects collapsed over all the exploration conditions except the free exploration condition and the perceived size of the virtual objects, collapsed over visual status and endpoint.

**Table 3.9 The mean perceived angle of shear for the sheared cubes and their real counterparts explored in the Deactivated PHANTOM™, Stylus and Bare finger exploration conditions**

Actual angle of shear	Mean perceived angle of shear of virtual objects	Confidence limits, Lower (L) and upper (U)	Mean perceived angle of shear of real objects	Confidence limits, Lower (L) and upper (U)
Sheared cube 18	21.14	(L) 17.81 (U) 24.48	20.13	(L) 14.96 (U) 25.29
Sheared cube 41	34.43	(L) 30.85 (U) 38.01	34.26	(L) 28.72 (U) 39.81
Sheared cube 64	48.14	(L) 43.33 (U) 52.96	52.53	(L) 45.07 (U) 59.99

Table 3.9 indicates that the estimates of angle of shear for the virtual sheared cubes and their real counterparts were similar. Since a significant effect of endpoint was discovered for the virtual sheared cubes, two mixed design, two factor Anovas were used. The first compared the data obtained for the virtual sheared cubes with the stylus endpoint to the data obtained with the real sheared cubes. The second compared the data obtained for the virtual sheared cubes with the thimble endpoint to the data obtained with the real sheared cubes. Both Anovas consisted of one between subjects factor (reality) and one within subjects factor (angle of shear). Neither Anova found a statistically reliable main effect of reality or an interaction with this factor and the Factor of angle of shear. Therefore the data in table 3.9 and figure 3.23 (on the following page) has been collapsed across the PHANTOM's endpoints.



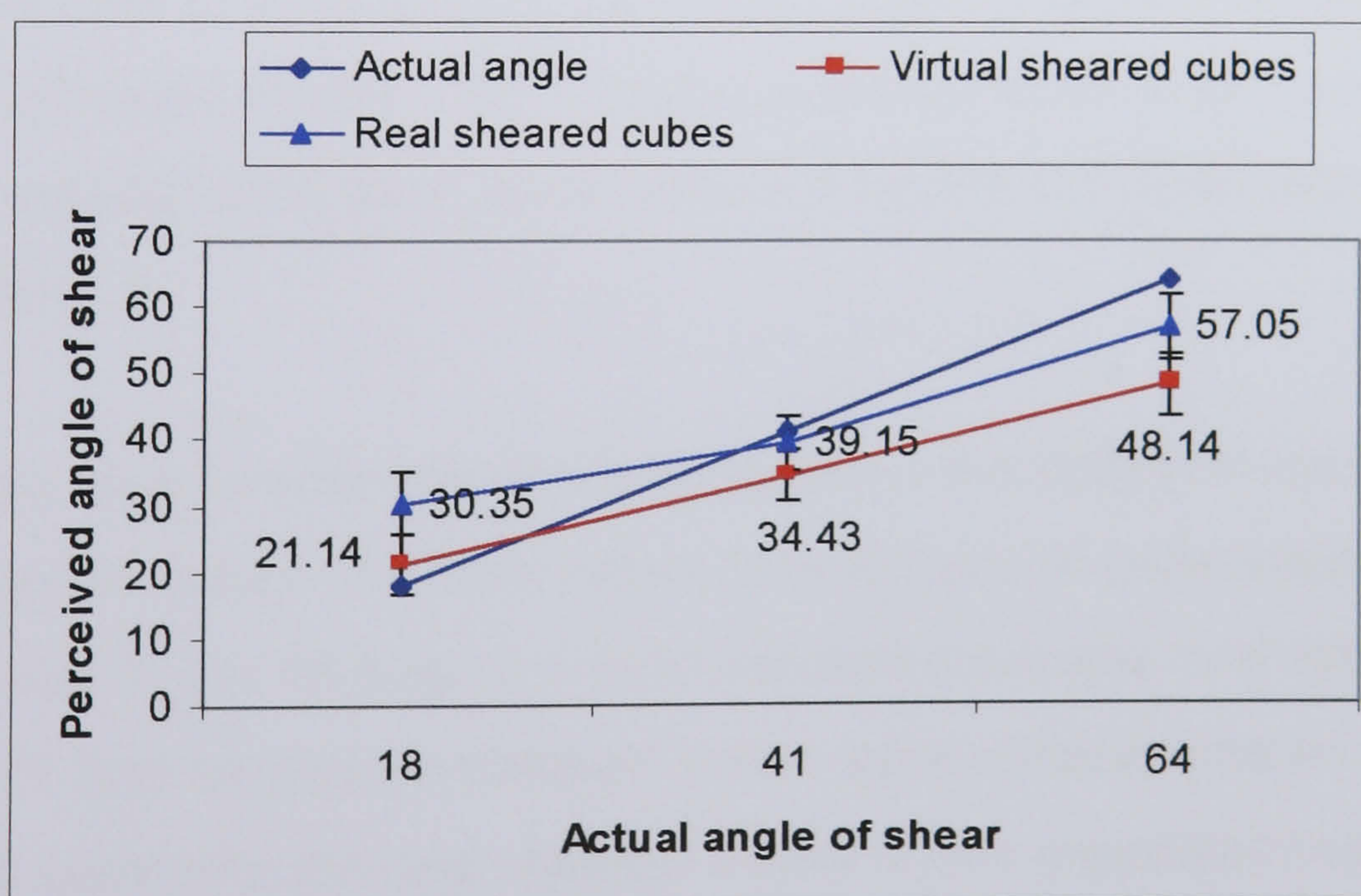
**Figure 3.23 Mean angle of shear estimates from VR (collapsed over endpoint) and the real world (mean of the three single point interaction conditions)**

The perceived angles of shear of the real sheared cubes in the free exploration condition in experiment 4 were then compared to the perceived angle of shear of the virtual sheared cubes in experiment 3. Once again, owing to the significant effect of endpoint with the virtual sheared cubes, two mixed design, two factor Anovas were used. The first compared the data obtained for the virtual sheared cubes with the stylus endpoint to the data obtained with the real sheared cubes. The second compared the data obtained for the virtual sheared cubes with the thimble endpoint to the data obtained with the real sheared cubes. Both Anovas consisted of one between subjects factor (reality) and one within subjects factor (angle of shear). Both Anovas found a statistically reliable main effect of reality, in that the perceived angles of shear for the virtual sheared cubes were lower than the real counterparts explored in the free exploration condition:  $F(1,32) 5.00 p = .032$  for the stylus endpoint and  $F(1,32) 10.41 p = .003$  for the thimble endpoint. Since the comparisons between the perceived angle of shear of the virtual objects taken from both of the PHANTOM's endpoints and perceived angle of

shear of the real objects in the free exploration condition yielded the same outcome, the data in table 3.10 and figure 3.24 is collapsed over the factor of endpoint.

**Table 3.10 The mean perceived angle of shear for the virtual sheared cubes and their real counterparts explored in the free exploration condition**

Actual angle of shear	Mean perceived angle of shear of virtual objects	Confidence limits, Lower (L) and upper (U)	Mean perceived angle of shear of real objects	Confidence limits, Lower (L) and upper (U)
Sheared cube 18	21.14	(L) 17.81 (U) 25.61	30.35	(L) 25.68 (U) 35.01
Sheared cube 41	34.43	(L) 30.85 (U) 38.37	39.15	(L) 35.03 (U) 43.26
Sheared cube 64	48.14	(L) 43.33 (U) 52.94	57.05	(L) 52.04 (U) 62.05



**Figure 3.24 Mean angle of shear estimates from VR (collapsed over endpoint) and the real world in the free exploration condition**



### **3.10 Discussion on the comparisons between the perceived size and angular extent of virtual and real 3-D objects**

The participants' perception of the size of the real cubes and spheres increased with the actual sizes of the stimuli in both the internal and external orientations, as was the case with the virtual cubes and spheres presented via the PHANTOM™ in experiment 3. This also corresponds with the findings obtained with the IE3000 in Colwell et al (1998) and Bruns (1998). It is also in agreement with the real world based literature on size perception (eg. Teghtsoonian and Teghtsoonian, 1965; Teghtsoonian and Teghtsoonian, 1980; Lanca and Bryant, 1995b).

The results of this experiment indicated that perceived angle of shear increased with the actual angle of shear in all of the exploration conditions. This is consistent with the results of the experiment 3 with the virtual objects presented via the PHANTOM™ device and in Colwell et al (1998) via the IE3000 device. The mean angle of shear estimates from the de-activated PHANTOM™, stylus and bare index finger conditions did not reliably differ from those obtained for the virtual sheared cubes in experiment 3.

It is interesting to note the similarity between the data obtained for the real sheared cubes and their virtual counterparts in experiment 3. In experiment 3, the 18 degree virtual sheared cube was overestimated, but the 41 and 64 degree sheared cubes were underestimated. This was also the case with the real sheared cubes in this experiment under all the exploration conditions except the Bare Index Finger condition. In the Bare Index Finger Condition, the angle of shear of the 18 degree sheared cube was slightly underestimated. The 41 and 64 degree sheared cubes were also underestimated, as had been the case in the other exploration conditions.

The mean angle of shear estimates from the free exploration condition did reliably differ from those obtained for the virtual sheared cubes in experiment 3, in that the perceived angles of shear for the virtual sheared cubes were lower than the real counterparts explored in the free exploration condition. It would seem, therefore, that differences between perceived angle of shear in HVR and the real world can be attributed to the single point of interaction between the user and the sheared cube. This is because a reliable difference between HVR and the real world was found only when the real objects were explored in the Free Exploration condition, in which participants were allowed to use multiple points of contact sheared cubes.

There did not appear to be any consistent trends relating the accuracy of participants' estimates of angle of shear with the real sheared cubes to the actual degree of shear. With the virtual sheared cubes, the extent of the participants' underestimation of the sheared cubes increased with increasing angle of shear, however this was only the case for the real sheared cubes explored in the Stylus and the Free exploration. It is not clear at this stage why this should be the case.

### **3.10.1 The effect of object type on the perceived size compared between virtual and real objects**

When the size estimates obtained from the de-activated PHANTOM™, stylus and bare index finger conditions were compared to the size estimates obtained with the virtual objects in experiment 3, an interaction between whether the objects were real or virtual and the factor of Object Type was noted. The externally and internally presented virtual cubes in experiment 3 were, without exception, judged to be larger than equivalent sized virtual spheres. However, this trend was not evident with the real cubes and spheres examined in the de-activated PHANTOM™, stylus and bare index finger conditions. The same interaction was noted when the when perceived size of the virtual objects in experiment 3 were compared to the perceived size of the real

objects explored in the free exploration condition. In the discussion for experiment 3, it was suggested that the significant effect of the type of object on perceived size with the PHANTOM™ device, and the non-occurrence of the same effect with the IE3000 device might reflect the use of different strategies for measuring the spheres between the devices. However, there was no effect of object type in the data from the three single point exploratory conditions, which incorporated the data from the Deactivated PHANTOM™ condition. There was also no effect of object type, or any interaction between object type and exploration conditions when the participants' data from all the exploration conditions was compared. Therefore, it may simply be the case that predominance of one method of judging a sphere over another differs between different populations of participants, rather than between different devices. This is an important distinction and warrants further investigation. A study in which the same population of participants made estimates of the real spheres and their virtual counterparts with the PHANTOM™ and the IE3000 device would provide some answers to this issue.

### **3.10.2 The effect of the Presentation mode on perceived size compared between virtual and real objects**

When the size estimates obtained from the de-activated PHANTOM™, stylus and the bare index finger conditions were compared to the size estimates obtained with the virtual objects in experiment 3, an interaction between whether the objects were real or virtual and the factor of Object Orientation was noted. The size of internally presented virtual cubes and spheres in experiment 3 were overestimated relative to equivalently sized externally presented virtual cubes and spheres (the Tardis effect). However, though present, the magnitude of the Tardis effect was lower with the real counterparts to the virtual objects examined in the de-activated PHANTOM™, stylus and bare index finger conditions. An interaction between whether the objects were real or virtual and the factor of Object Orientation was also found when the size estimates obtained from the free exploration condition were compared to the size

estimates obtained with the virtual objects in experiment 3. However, in this instance, the Tardis effect was completely absent rather than present in a diminished form. In fact, the internal orientations of the real cubes and spheres were, without exception, judged to be nominally smaller than their external counterparts.

If the Tardis effect can be attributed to the amount of empty space surrounding externally presented objects influencing the participants' judgment of size, as has been previously suggested, then these results are not surprising. The single point of contact with the real objects in the de-activated PHANTOM™, stylus and bare index finger conditions made it just as likely that the participants would lose contact with the real external objects as the virtual external objects. Upon losing contact with a real object, the participants would then have had to explore the unused space surrounding it in order to relocate it. These are the conditions thought to be responsible for the Tardis effect. However, owing to the fact that the real objects could not just be suspended in mid air, as had been the case with the virtual objects, it would have been easier to re-locate the real external objects by using the apparatus used to support them as a guide to their position. Thus the extent of explored unused space involved in the process of re-locating the external objects is likely to have been greater in HVR than in the real world. This would have had the effect of making the contrast between the size of the internal and external real objects smaller than the contrast between the internal and external virtual objects. i.e. a diminished Tardis effect. The reason for the absence of the Tardis effect in the free exploration condition has already been discussed in section 3.4.3.

It is worthy of note that with the virtual objects in experiment 3, the Tardis effect resulted from the overestimation of internal objects relative to both their perceived size in the external orientation and their actual sizes. However, with the real objects in the de-activated PHANTOM™, stylus and bare index finger conditions, the Tardis effect resulted from greater underestimation of the external cubes and spheres relative to

their internal counterparts; all of the objects were underestimated. Thus, it can be said that the Tardis effect occurs irrespective of whether the externally presented objects are overestimated relative to their actual sizes. It can also be asserted that the Tardis effect is not an artefact of HVR per se. It would seem that single point interaction, irrespective of whether it occurs in HVR or the real world, is a necessary condition for the Tardis effect to occur, since this was the single common characteristic that distinguished the de-activated PHANTOM™, stylus condition and bare index finger conditions from the free exploration condition.

The sizes of the real internal and external cubes and spheres were underestimated, irrespective of the exploration condition in which they were examined. This does contrast slightly with the results obtained in experiment 3 with the virtual objects. In that instance, although cubes and spheres presented in the external orientation were underestimated relative to their actual size, cubes and spheres presented in the internal orientation were overestimated relative to their actual size. At present the author cannot think of a reason for this discrepancy. However, it is interesting to note the consistency between the tendency for participants to underestimate of the size of virtual objects and their real counterparts in the external orientation. This is in agreement with other real world based studies which indicate the tendency for stimulus size to be underestimated (Hohmuth, Phillips and Van Romer, 1976; Lederman Klatzky and Barber, 1985; Lanca and Bryant, 1995b Seizova-Cajic, 1998; Solomon and Turvey, 1998).

Since the Tardis effect with the real objects resulted from a lesser degree of underestimation for the internal cubes and spheres than their external counterparts, it can be said that the accuracy of participants' perception of the size of the real cubes and spheres was greater in the internal orientations than in the external orientation. This was also the case in the previous experiment with the virtual objects, presented with the PHANTOM™ device and in Bruns (1998) with the IE3000 device.

The reason for the presence of this trend with real objects seem likely to be due to the same reason for its presence in the experiment 3 with the virtual objects i.e. the boundaries of the objects are more clearly defined in the internally presented orientation than the external orientation.

### **3.10.3 The effect of Visual status on perceived size compared between virtual and real objects**

There were no statistically reliable differences between the size estimates returned by the blind and sighted individuals in the free exploration condition, which was also the case with the virtual objects in experiment 3. However, an interaction between the factors of Visual Status and Object Size was noted with the real objects: the estimates of object size from the blind and sighted participants were very similar for the objects measuring 2.7 and 3.6cm. However, blind participants returned higher estimates than the sighted participants for the virtual objects measuring 4.5cm. This interaction was not noted in the experiment 3 with the virtual objects. There is the possibility that this interaction might be due to the use of different EPs by sighted and blind participants in judging the 4.5 cm cube and sphere. It would be interesting to see if this interaction was present when under conditions in which the use of EPs were equated between the two groups of participants.

In summary, the perceived size of both the virtual objects, used in experiment 3, and their real counterparts, used in this experiment, increased with actual object size in a linear fashion. This was true of the real objects, irrespective of the exploration condition under which they were examined. Indeed, the exploration conditions characterised by a single point of interaction with the real objects (i.e. the de-activated PHANTOM™, stylus and bare index finger conditions) were statistically indistinguishable. However, the participants' estimates of the size of the largest of the real objects were greater in the free exploration condition than in the single point of contact conditions.

The perceived size of the real objects was consistent between the cubes and spheres, irrespective of the exploration condition under which they were examined. Put another way: real cubes and spheres of equivalent size were perceived as being of equivalent size. However, this was not true of the virtual objects explored with the PHANTOM™: virtual cubes were judged larger than equivalent sized virtual spheres.

Virtual objects explored in the internal presentation mode were perceived as being larger than their equivalently sized counterparts presented in the external presentation mode (the Tardis effect). This also applied to the real objects in all of the single point of interaction exploration conditions. However, the Tardis effect was absent for the real objects in the free exploration condition.

In experiments 3 and 4, participants were allowed to arrive at their size estimates via the use of movements in any of the 3-D axes. The next chapter reports two experiments in which the consistency of perceived extent over the 3-D axes is examined in HVR with the PHANTOM™ device.

## **4. Chapter 4: The isotropy of perceived extent in 3-D space with the PHANTOM™ device**

This chapter encompasses experiments five and six, which investigate the perception of extent in 3-D space with the PHANTOM™ device. Specifically, this chapter addresses the question of whether objectively equal extents are subjectively equal when presented in the various 3-D axes (x, y and z). Both experiments examined the impact of visual status and the nature of the exploratory movement (active vs passive) on the perception of extent across the x,y and z axes. In experiment five, participants explored the experimental stimuli via bi-directional exploration. In experiment six, participants used uni-directional movements to examine the stimuli.

### **4.1 Experiments 5 and 6: The isotropy of haptic space via active and passive uni and bi directional movements with the PHANTOM™ device.**

#### **4.1.1 The isotropy of perceived extent over the 3-D axis**

A review of the literature on the perception of extent in the real world reveals an important issue that has yet to be investigated in HVR, that of the ‘isotropy’ of perceptual space in HVR. Isotropy refers to the question of: “how uniform is perceptual space over its several possible axes?” (Armstrong and Marks, 1999, p.1211). This issue is also important for HVR, where the perceptual space in question is the workspace of the device, which corresponds to what Lederman, Klatzky and Wardell (1987) refer to as ‘manipulatory’ space or, “small scale layouts explored via the arm system” (p606).



Manipulatory, or haptic, space can be specified in relation to the 3-D axes: x (horizontal), y (vertical) and z (depth). Each of these axes has two possible directions of movement: left and right on the x-axis, up and down on the y-axis and forwards and backwards on the z-axis.

Manipulatory space can also be specified in relation to an individual's body, " Consider a cylinder, the axis of which coincides with that of the upper torso of a person's body. Radial lines are lines orthogonal to the axis while tangential lines are lines that are tangent to the cylindrical surface" (Loomis and Lederman, 1989, 31-25). Under this definition, for a stimulus placed in front of an individual, a motion in the x (horizontal) or the y (vertical) axes involves tangential movement and a motion in the z (depth) axis involves radial movement.

Day and Wong (1971) asked participants to adjust the horizontal and vertical components of an L figure to subjective equality under two conditions. In one condition, the L figure was placed in the fronto-parallel plane (i.e. stood upright on its base). In this plane, movement along the vertical and horizontal aspects of the figure was tangential. In the other condition, the L figure was placed in the horizontal plane (i.e. laid flat on the table surface). In this plane, movement along the horizontal aspect of the L figure was tangential and movement along the vertical aspect of the figure was now radial).

When the L figure was presented in the fronto-parallel plane, there was no significant difference between the participants' perception of equality between the vertical and horizontal components and objective equality of these two components. However, when the L figure was laid flat, the participants perceived the vertical component of the L figure as being equal to the horizontal component only when they had adjusted the vertical component such that it was, on average, 4.42% greater than the horizontal component. Thus, an extent explored by a radial movement was perceived as being larger than an equivalent extent explored via a tangential movement. This effect is known as the Radial Tangential Effect (RTE) and has been obtained in numerous real world based

experimentation (Davidon and Cheng, 1964; Cheng, 1968; Wong, 1977; Marchetti and Lederman, 1983; Armstrong and Marks, 1999).

Experiment five was conducted as a preliminary investigation into the isotropy of manipulatory space in HVR. In order to achieve this, participants were asked to explore a series of extents in the horizontal (x) vertical (y) and depth (z) axes.

#### **4.1.2 The effect of the direction of movement on perceived extent**

Armstrong and Marks (1999) conducted an investigation into the RTE. In this experiment participants were asked to make magnitude estimations of the extent of a series of lines and blocks. The experimenters manipulated the nature of the arm movements required to traverse the stimuli (radial vs tangential) and the direction of the movement within radial movements (i.e. toward-away, away-toward movements) and tangential movements (i.e. left-right and right-left, up-down, down-up movements). Additionally, the position of the stimuli relative to the participant was also manipulated (to the left or right of the participants midline). Neither the position of the stimuli nor the direction of the radial and tangential movements had a statistically significant effect on judgments of extent. The extents examined via radial movements were perceived as significantly greater than objectively equal extents examined via tangential movements.

Experiment six further extended the methodology of experiment five by examining the isotropy of manipulatory space in HVR over the horizontal, vertical and depth axes, in addition to the direction of exploratory movement within each of these dimensions. In order to achieve this, participants were asked to explore a series of virtual lines extending up, down, left, right, towards and away from a common origin point and reproduce their extent.

If the effect of the direction of movement were found to be significant in the experiment six, then comparing the results to those obtained in the experiment five would provide some insight into how the participants reach an overall estimate of extent for a particular 3-D axis. For example, do participants' judgments reflect a compromise between discrepant estimates of extent gained from different directions of movement within a given dimension, or do they favour an estimate obtained via one direction of movement over another? Should experiment six reveal a non-significant effect of the direction of movement within each axis, one would expect the results from that experiment not to differ significantly from those of experiment five.

#### **4.1.3 The effect of active vs passive movements on perceived extent**

Surprisingly, the impact of active vs. passive exploratory movements on the perception of extent has received very little attention from researchers. Stanley (1966) found that participants' estimates of the extent of wooden dowels were greater when their index fingers were separated at distances describing the extents of the stimuli by the experimenter relative to when they provided the movement themselves. However, as was noted in section 1.5 of chapter one, this experiment confounded the availability of cutaneous and kinaesthetic information with active and passive movement.

To the best of this experimenter's knowledge, there have been no investigations of the impact of active and passive movement on perceived extent in HVR. Therefore, experiments 5 and 6 were designed to investigate the role of active vs. passive exploratory movements on perceived extent in HVR. This was achieved by asking the participants to examine virtual extents under an active movement condition, in which the participants explored the stimuli at a speed of their choosing, and a passive movement condition, under which the participants were guided across the virtual lines at a constant speed by the PHANTOM™ device.

There is particular impetus to study the effect of active vs passive movements on perceived extent in the context of the issue of the isotropy of haptic space. This is due to the fact that it provides a way of testing the validity of an explanation of the RTE, provided by Wong (1977). Wong posited that the RTE could be attributed to the fact that, unbeknownst to the participants, radial movements are executed more slowly than tangential movements of equivalent extent. Therefore, “because subjects rely on time estimates to determine a fixed distance and because they are unable to perceive that they are moving more slowly in the radial than the tangential direction, they overestimate radial lengths relative to tangential lengths” (Marchetti and Lederman, 1983, p43). The notion that the RTE might be due to differences in the velocity with which radial and tangential movements are performed has also been expressed by Reid (1954), Marchetti and Lederman (1983) and Armstrong and Marks (1999).

The inclusion of the active and passive movement conditions into experiments 5 and 6 permits the assessment of whether the RTE can be attributed to unnoticed differences in the speed at which radial and tangential movements are executed for both bi-directional and uni-directional movements. If so, one would expect the RTE to disappear under the passive movement condition, since the speed of radial and tangential movements was equal and the participants were explicitly aware of this.

#### **4.1.4 The effect of visual status on the isotropy of perceived extent**

The effect of visual status on the incidence of the RTE was obviously another crucial question. With the exception of the work of Heller and Joyner (1993) this subject has received little attention. Heller and Joyner indirectly compared the results of two experiments into the RTE, one involving sighted participants, the other involving blind participants. The

pattern of results obtained from sighted and late blind participants were similar in that neither group exhibited the RTE for an L figure, but both groups exhibited the illusion for an inverted T figure<sup>17</sup>.

Experiments five and six both involve direct comparisons between sighted and blind participants in order to ascertain whether the illusion is present for both groups of participants and, should the RTE be present, whether the magnitude of the illusion differs between sighted and blind individuals.

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<sup>17</sup> As will be noted in the discussion section for this chapter (section 4.4) subsequently, the inverted T stimulus configuration confounds the RTE with the HVI and the absence of the RTE with the L stimulus configuration may be due to a procedural anomaly.

## **4.2 Method**

The methods used for experiments 5 and 6 are very similar, so they are described together.

### **4.2.1 Participants**

Experiment five utilised a total of 20 participants, ten participants were sighted and the remaining ten were blind. The sighted participant sample consisted of four males and six females, all of who reported having no sensory-motor impairments. Their ages ranged from 24 to 42, with the mean age being 33. The sighted participants were all University students/staff recruited from various disciplines. The sighted participants used in this experiment had also participated in experiment 2.

The blind participant sample consisted of 8 males and 2 females, all of who reported having no other sensory-motor impairments. They were all volunteers recruited from a list visually impaired individuals who had expressed an interest in participating in the S.D.R.U.'s research. Four of the blind participants were congenitally blind, the remaining six lost their sight between the ages of 1 and 30 years of age. The ages of the blind participants ranged from 33 to 55, with the mean age being 47.

Experiment six utilised a total of 20 participants, ten participants were sighted and the remaining ten were blind. The sighted participant sample consisted of five males and five females, all of who reported having no sensory-motor impairments and were employees of BT Exact research laboratories. Their ages ranged from 19 to 48, the mean age being 26. The blind participant sample was identical to that used in experiment five. These blind individuals had also served as participants in experiment 2 and the free exploration condition of experiment 4.

## 4.2.2 Design

Experiment five utilised a four factor mixed design consisting of one between subjects factor and three within subjects factors. The between Subjects factor Visual Status featured two levels, blind and sighted participants. The within subjects factor Line Dimension featured three levels, lines extending along the x, y and z axes. The within subjects factor Line Extent featured three levels, 2.7, 3.6, 4.5cm lines. Finally, the within subjects factor Exploration Movement featured two levels, active movement and passive movement. The Line Dimension, Extent and Exploration Movement factors yielded a total of 9 stimuli for the participants to examine. The ordering of the presentation of the stimuli was randomised for each participant. The participants explored the stimuli in two consecutive runs, one run for the active movement level, the other for the passive movement level. The ordering of these levels was counterbalanced between participants. Therefore, each participant underwent a total of 18 trials (3 dimensions x 3 extents x 2 exploration movement levels).

Experiment six utilised a five factor mixed design, consisting of one between subjects factor and four within subjects factors. The between subjects factor Visual Status featured two levels, blind and sighted participants. The within subjects factor Exploration Movement featured two levels, active movement and passive movement. The within subjects factor Line Dimension featured three levels, lines along the x, y and z axes. The within subjects factor line direction consisted of two levels, corresponding to the two possible directions of movement within each of the x, y and z dimensions. The within subjects factor Line Extent featured three levels, 2.7, 3.6, 4.5cm virtual lines. The Line Dimension, Line Direction and Line Extent factors yielded a total of 18 stimuli for the participants to examine. The presentation order of the stimuli was randomised for each participant. The participants examined the stimuli in two consecutive runs, one run for the active movement level, the other for the passive movement level. The ordering of these levels was

counterbalanced between participants. Each participant underwent a total of 36 trials (3 dimensions x 2 directions x 3 extents x 2 exploration movement levels).

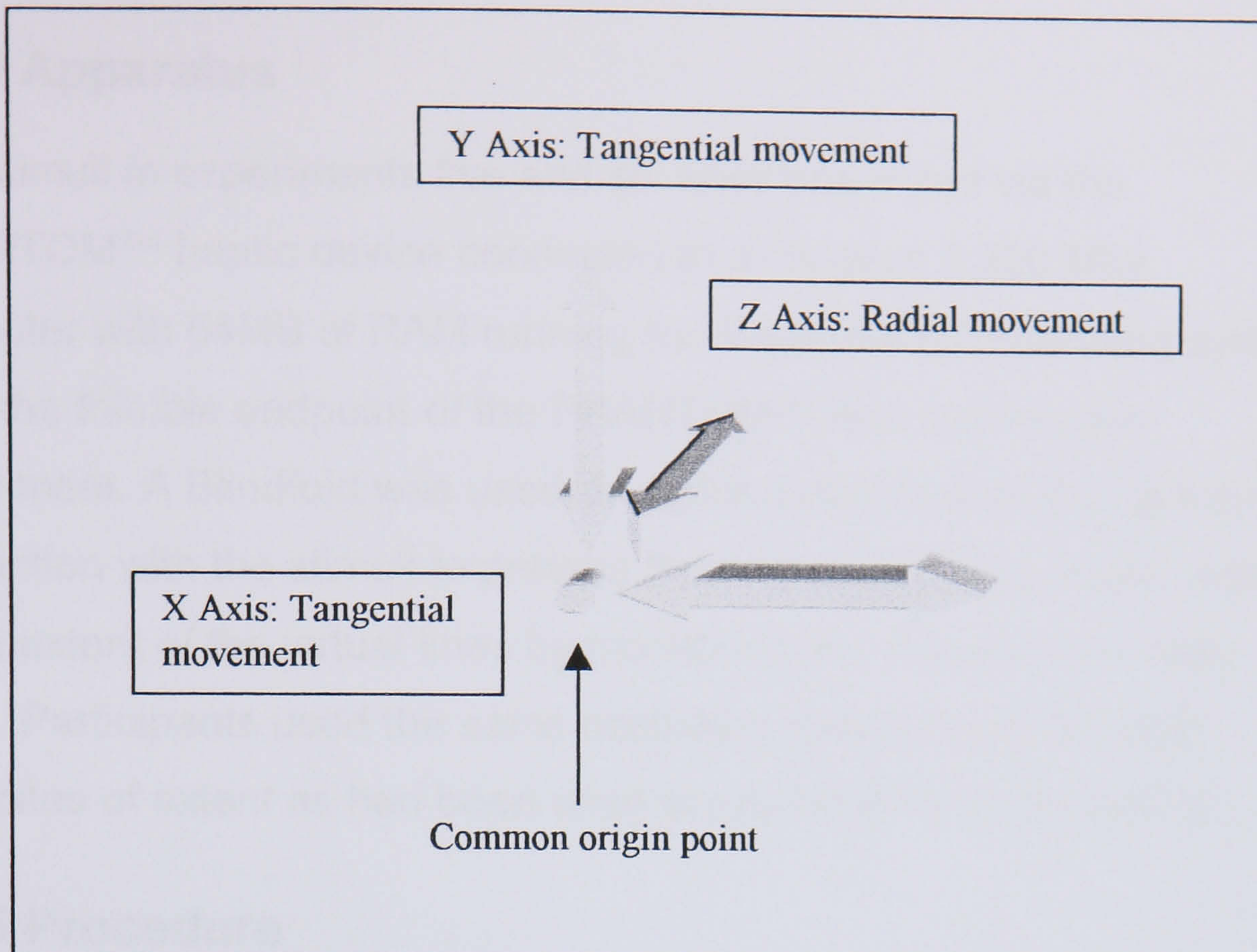
### **4.2.3 Stimuli**

The stimulus for experiment five consisted of three virtual lines (2.7, 3.6 and 4.5cms in extent). Each of these extents were presented in the x, y and z axes relative to a common point of origin, which corresponded to the PHANTOM's reset position (see figure 4.1). Each line extent, dimension and direction permutation was presented in two exploration movement levels: a passive movement exploration level, under which the PHANTOM™ guided the participant along the length of the lines at a constant speed of 1.5 cm/sec and a free exploration mode, under which the participants traversed the lines at their own pace.

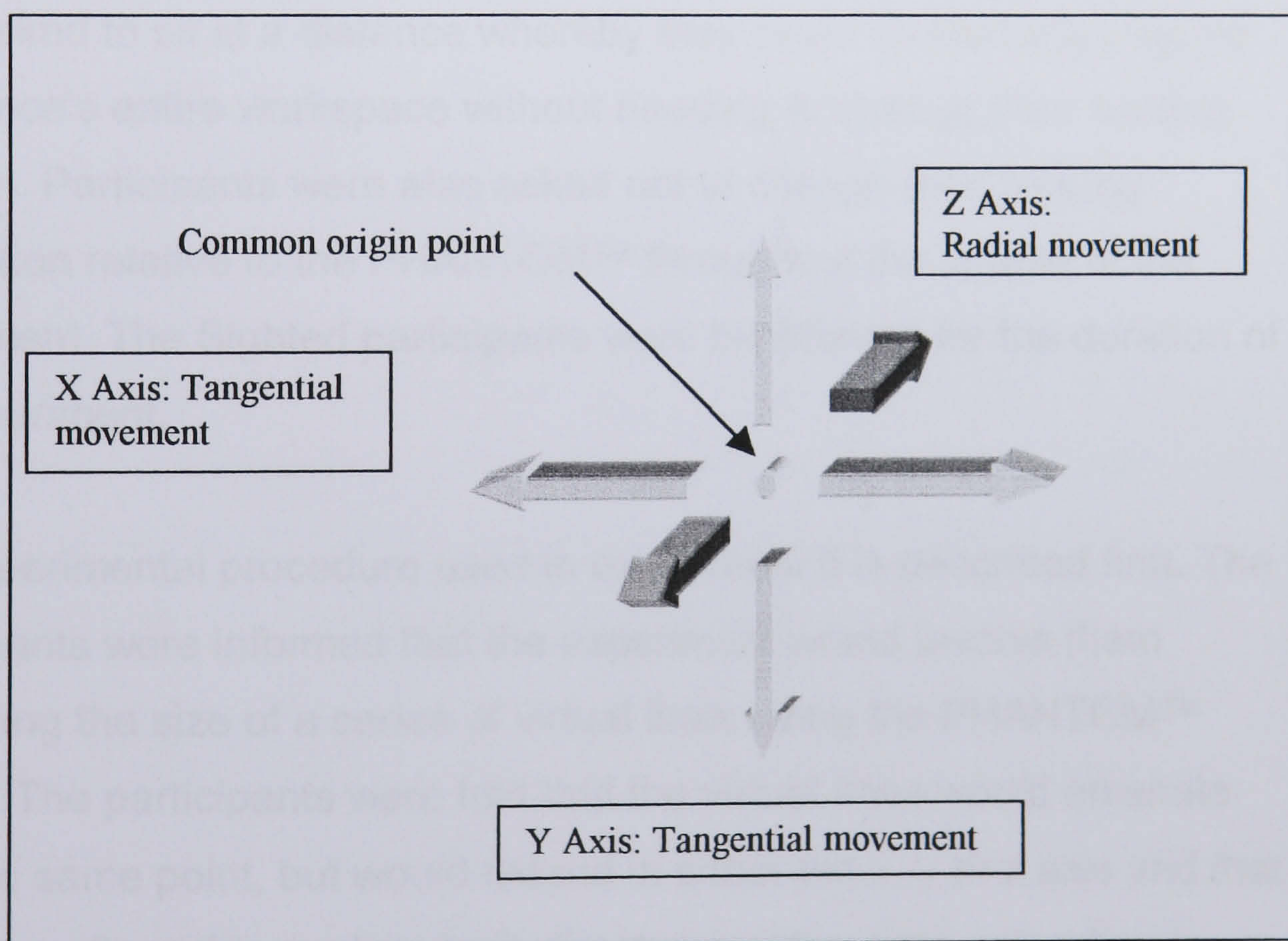
The stimuli for experiment six consisted of a series of 6 virtual lines, emanating from a common origin point, which corresponded the PHANTOM's reset point. Each of the six virtual lines extended in a different direction relative to the common origin point: up, down, left and right, backwards and forwards (see figure 4.2). The participants' movements were constrained to the virtual lines at all times; the PHANTOM™ would not permit any deviation from the lines. Three virtual line extents were used: 2.7, 3.6 and 4.5cms. The stimuli were presented in the same active and passive movement levels used in experiment 5.

The stimulus appeared in front of the participants in experiments five and six. Thus, for both experiments, lines in the x (horizontal) and the y (vertical) axes involve tangential movement and a motion in the z (depth) axis involves radial movement. This is illustrated in figures 4.1 and 4.2 respectively.





**Figure 4.1 An Illustration of the virtual line orientations, relative to a common origin point, used in experiment five**



**Figure 4.2 An Illustration of the virtual line orientations, relative to a common origin point, used in experiment six**

#### **4.2.4 Apparatus**

The stimuli in experiments five and six were presented via the PHANTOM™ haptic device connected to a Pentium II 400 Mhz computer with 64MB of RAM running the Windows NT operating system. Only the thimble endpoint of the PHANTOM™ was used in this experiment. A Blindfold was used on sighted participants during their interaction with the stimuli to prevent them from obtaining visual cues as to the extent of the virtual lines by monitoring the movement of their hand. Participants used the same occluding sleeves ruler to make estimates of extent as had been used in experiments three and four.

#### **4.2.5 Procedure**

For both experiments five and six, participants were seated with the PHANTOM™ device in front of them in the horizontal plane. Participants were asked to sit at a distance whereby they could comfortably explore the device's entire workspace without needing to change their seating position. Participants were also asked not to change their seating orientation relative to the PHANTOM™ throughout the course of the experiment. The Sighted participants were blindfolded for the duration of the experiment.

The experimental procedure used in experiment 5 is described first. The participants were informed that the experiment would involve them estimating the size of a series of virtual lines using the PHANTOM™ device. The participants were told that the virtual lines would emanate from the same point, but would extend in either the x, y or z axis and that they were allowed to explore both directions of the lines extending in each axis. The participants were told that, prior to each line being presented, the experimenter would inform them in what axis relative to the origin point the line extended.

The participants were also informed that during the course of the experiment they would be interacting with the stimuli using two different modes of exploration: one in which they were required to manually traverse the lengths of the virtual lines and another under which the PHANTOM™ would guide them along the lengths of the virtual lines at a constant speed. In both the active and passive movement levels, the participants were permitted to examine each line as many times as they desired.

The experimenter then showed the participants the occluding sleeves ruler, which they were to use in making their estimates of the extent of the virtual lines. The operation of the occluding sleeves ruler was then demonstrated to the participants.

To estimate the extent of the virtual lines, participants adjusted the occluding sleeves ruler in the horizontal plane by gripping the fixed sleeve with one hand and adjusting the movable sleeve with the other, until they were satisfied that the distance between the sleeves corresponded to the size of the virtual line.

Participants were informed that they would be permitted as much time as they required in interacting with each line and in making their estimates. However, they were informed that they were not permitted to examine the virtual lines whilst making their estimates.

Upon indicating that they were satisfied with their estimates, the participants handed the occluding sleeves ruler to the experimenter. The experimenter recorded the participants' estimates by hand. This was achieved by tracing the distance between the occluding sleeves of the ruler, as set by the participant, with a pencil and then recorded the extent of this mark using a conventional ruler.

The sighted participants were asked to wear a blindfold for the duration of the experiment. The participants were given an opportunity to practice

the experimental procedure for the exploration movement level that they would be encountering first. If the participants did not have any questions about the experimental procedure, the experimenter sequentially presented them with the 18 virtual lines, randomly ordered, under one of the two exploration movement levels. The procedure was then repeated for the second exploration movement level. The ordering of the exploration movement levels was counterbalanced between participants.

The procedure for experiment six was identical to that of experiment five, except that the participants were informed that the virtual lines would extend either up, down, left, right backwards or forwards from the same point of origin. The participants were told that, in examining a line in a specified direction, they were not allowed to retrace their progress back along the line in the opposite direction. If the participants needed to examine the line again, they were asked to remove their finger from the PHANTOM's thimble whilst the experimenter returned the probe to the origin point. They were permitted to examine each line as many times as they desired in this fashion. The lines were explored under the same active and passive levels as had been used in experiment five.

## **4.3 Results**

The approach taken in examining the data from both experiments five and six was the same as that taken for the virtual and real 3-D objects (see section 3.3)

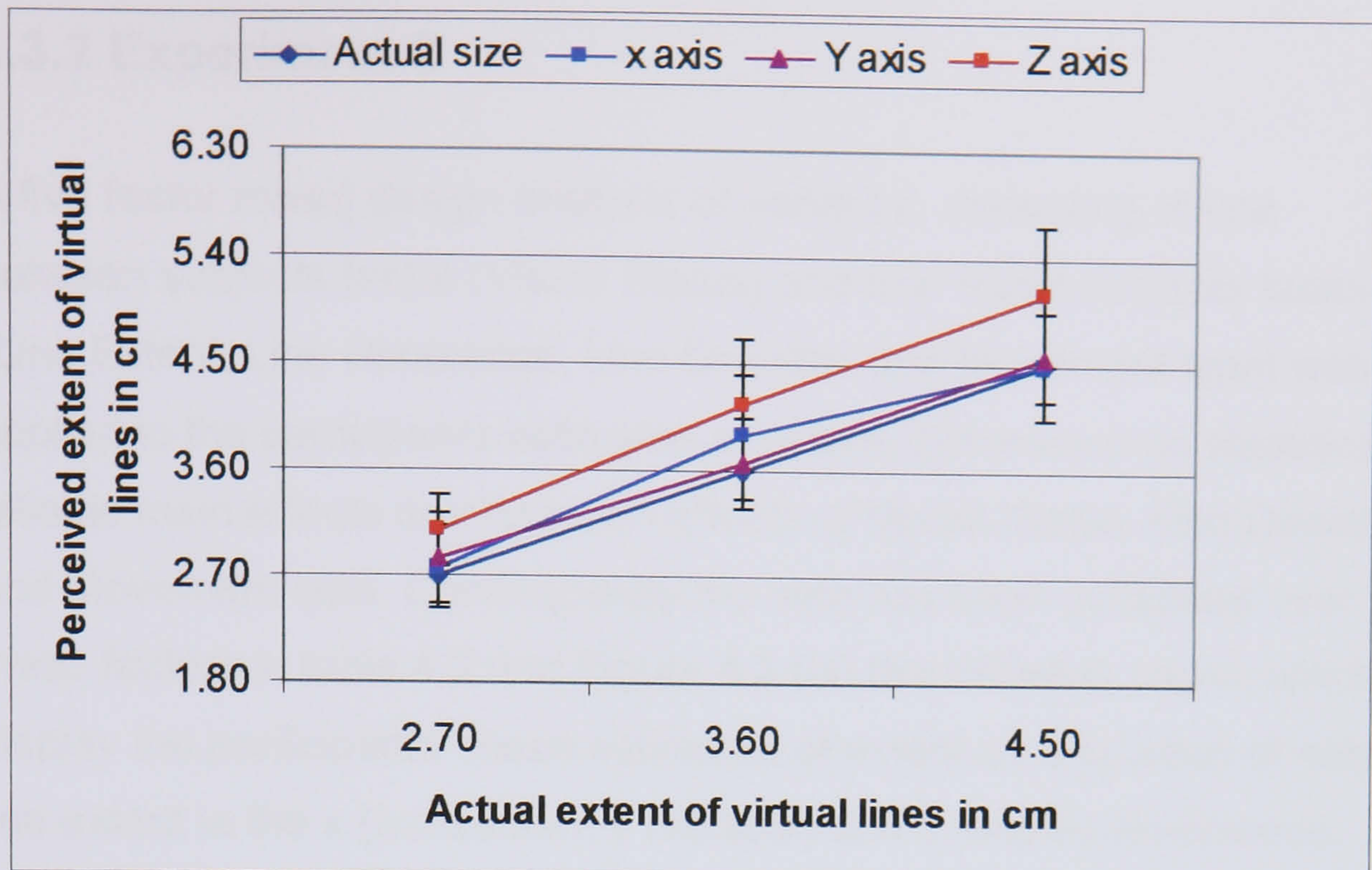
### **4.3.1 Experiment 5**

A four factor mixed design analysis of variance, consisting of one between subjects factor (Visual Status) and three within subjects factors (Line Extent, Line Dimension, and Movement type) was applied to the participants' estimates of extent. All inferential tests were conducted to the 95% confidence level. There were no statistically reliable main

effects or interaction effects of Visual Status, or Movement Type. Consequently, the data has been collapsed over these factors in table 4.1 and figure 4.3 (on the following page), which display the participants' mean estimates of extent as a function of actual line extent in the x (horizontal), y (vertical) and z (depth) dimensions. Table 4.1 also shows 95% upper and lower confidence limits for the mean estimates.

**Table 4.1 Mean size estimates, with confidence limits, of participants' estimates of line extent collapsed over visual status and active/passive movement**

Actual Line size	Perceived size X Axis	Confidence limits, lower (L) and upper (U)	Perceived size Y Axis	Confidence limits, lower (L) and upper (U)	Perceived size Z Axis	Confidence limits, lower (L) and upper (U)
2.7	2.77	(L) 2.42 (U) 3.12	2.85	(L) 2.46 (U) 3.23	3.09	(L) 2.79 (U) 3.39
3.6	3.89	(L) 3.37 (U) 4.41	3.66	(L) 3.27 (U) 4.05	4.16	(L) 3.60 (U) 4.71
4.5	4.50	(L) 4.05 (U) 4.96	4.57	(L) 4.19 (U) 4.95	5.09	(L) 4.50 (U) 5.67



**Figure 4.3 Mean estimates of extent for the x, y and z collapsed over visual status, line direction and active and passive movement plotted against actual line extents**

Table 4.1 and figure 4.3 indicate that the perceived extent of the virtual lines increased with actual line extent in all of the line dimension conditions. A four factor mixed design analysis of variance found the effect of extent to be significant,  $F(2, 17) = 69.72$   $p < .0005$ . The linear contrast for the effect of extent was also significant,  $F(1) = 102.39$   $p < .0005$ .

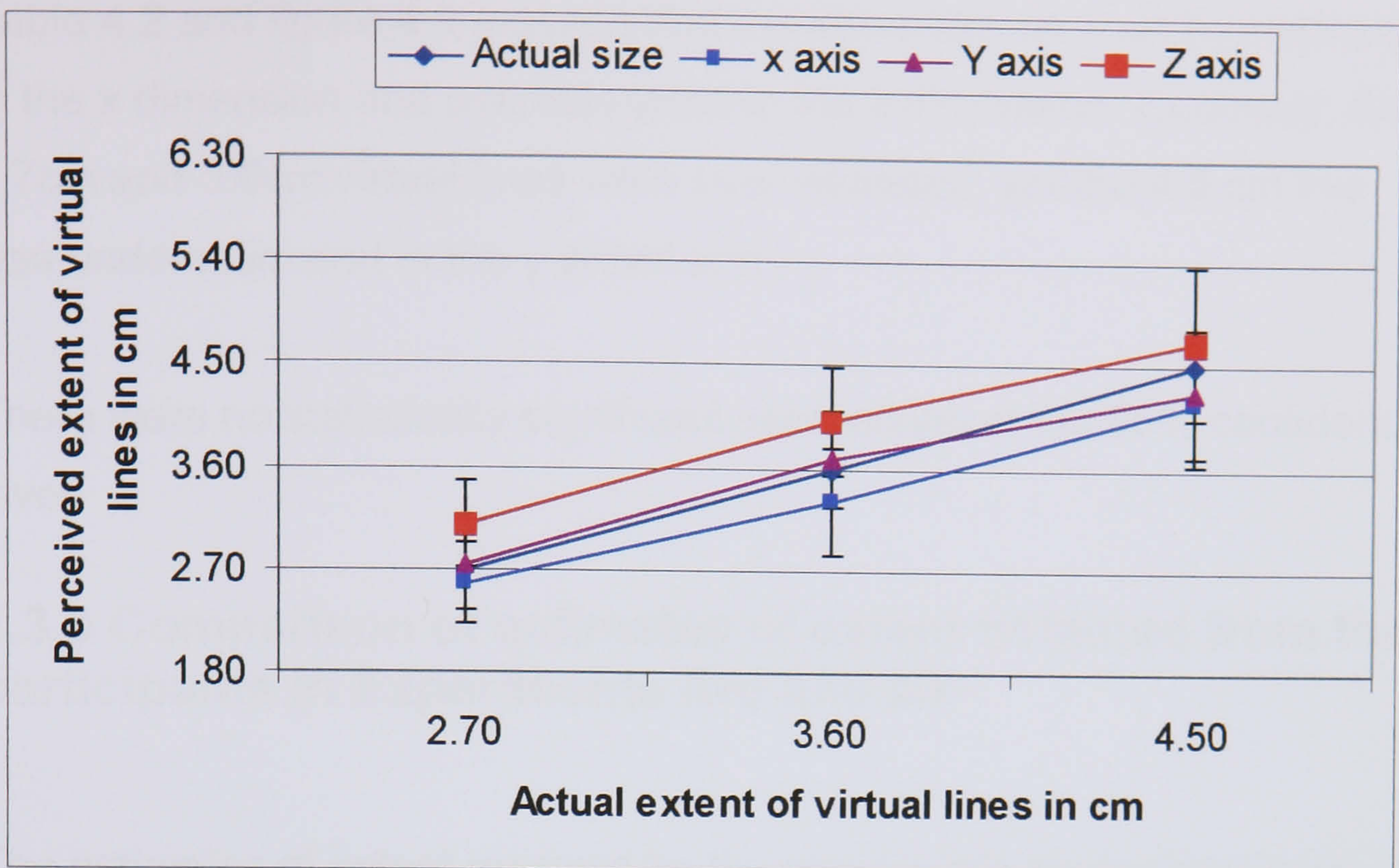
Table 4.1 and figure 4.3 also indicate that the z dimension yields the highest estimates of extent for all of the line extents. The y dimension yields higher estimates of extent for the 2.7 and 4.5 cm lines than the x dimension. However, the x dimension yields higher estimates of extent for the 3.6 cm line than the y dimension. The effect of line dimension was found to be significant,  $F(2, 17) = 5.68$   $p = .007$ . Within subject contrasts for the line dimension conditions found significant differences between the estimates of extent in the z dimension and the average values of the x and y dimensions,  $F(1) = 10.60$   $p = .004$ .

### 4.3.2 Experiment 6

A five factor mixed design analysis of variance, consisting of one between subjects factor (Visual Status) and four within subjects factors (Line Extent, Line Dimension, Line Direction and Movement type) was applied to the participants estimates of extent. There were no statistically reliable main effects or interaction effects of Visual Status, Line Direction and Movement type. Consequently the data has been collapsed over these factors in table 4.2 and Figure 4.3 (on the following page), which display the participants' mean estimates of extent as a function of actual line extent in the x (horizontal), y (vertical) and z (depth) dimensions. Table 4.2 also shows 95% upper and lower confidence limits mean for the mean estimates.

**Table 4.2 Mean size estimates, with confidence limits, of participants' estimates of line extent collapsed over visual status, line direction and active/passive movement**

Line size	X Axis	Confidence limits, lower (L) and upper (U)	Y Axis	Confidence limits, lower (L) and upper (U)	Z Axis	Confidence limits, lower (L) and upper (U)
2.7	2.58	(L) 2.22 (U) 2.95	2.75	(L) 2.35 (U) 3.15	3.09	(L) 2.71 (U) 3.47
3.6	3.31	(L) 2.84 (U) 3.78	3.68	(L) 3.25 (U) 4.12	4.01	(L) 3.54 (U) 4.48
4.5	4.19	(L) 3.63 (U) 4.75	4.27	(L) 3.71 (U) 4.83	4.71	(L) 4.04 (U) 5.38



**Figure 4.4 Mean estimates of extent for the x, y and z collapsed over visual status, line direction and active and passive movement plotted against actual line extents**

Table 4.2 and figure 4.4 indicate that the perceived size of the virtual lines increased with actual line size in all of the line dimension conditions. The five factor mixed design analysis of variance described above found the effect of extent to be significant,  $F(2, 17) = 107.25$ ,  $p < .0005$ . The linear contrast for the effect of extent was also significant,  $F(1) = 138.44$ ,  $p < .0005$ .

Table 4.2 and figure 4.4 suggest that the z dimension yields the highest estimates of line extent, followed by the y dimension and then the x dimension, for all of the line extents. The ANOVA supports these suggestions, as it showed the effect of line dimension was significant,  $F(2, 17) = 15.05$ ,  $p < .0005$ . Within subject contrasts for the line dimension conditions showed significant differences in estimates of extent between the x dimension and the y dimension  $F(1, 17) = 4.60$ ,  $p < .04$  and between the z dimension and the average values of the x and y dimensions,  $F(1) = 22.18$ ,  $p < .0005$ .



Table 4.2 and figure 4.4 indicate that the line sizes were underestimated in the x dimension and overestimated in the z dimension. Curiously, the 2.7cm and 3.6cm virtual lines were overestimated, yet the 4.5 cm line was underestimated in the y dimension.

There were no statistically significant interactions at the 95% confidence level.

### **4.3.3 Comparison of estimates of extent obtained from the participants in Experiments five and six**

The estimates of extent returned by the participants via bi directional estimates in experiment five were then compared to the estimates of extent returned by participants via unidirectional estimates in experiment six.

Since the same sample of blind participants, but two different samples of sighted participants were used between experiments 5 and 6, two different analyses of variance were performed: one for the sighted samples of participants and one for the blind sample of participants.

The analysis of variance applied to the data from the sighted participants in experiments 5 and 6 comprised a mixed design featuring one between subjects factor (Nature of Exploration, bi vs uni directional exploration) and two within subjects factors (Line Dimension, and Line Extent). The sighted participants' data from experiment five was collapsed over the factor of Movement type as it was not found to exert a statistically reliable effect..The data from experiment 6 was collapsed over the factors of Line Direction and Movement Type for the same reason.

The estimates returned by the sighted participants via bi-directional, movements in experiment five and uni-directional movements in experiment six were not found to differ reliably,  $F(1,18) = .13$   $p = .719$

The analysis of variance applied to the data from the blind participants in experiments 5 and 6 comprised a within subjects design featuring three factors (Nature of Exploration, Line Dimension and Line Extent). The blind participants' data from experiment five was collapsed over the same factors as the sighted participants' data.

The estimates returned by the blind participants via bi-directional, movements in experiment five and uni-directional movements in experiment six were also not found to differ reliably,  $F(1,9) 2.55 p=.144$

## **4.4 Discussion**

### **4.4.1 The isotropy of perceived extent over the 3-D axis with the PHANTOM™ device**

The RTE was evident in this experiment; the data indicates that the virtual lines explored via radial movement (i.e. lines in the z axis) were overestimated relative to objectively equal virtual lines explored via tangential movements (i.e. lines in the x and y axis), irrespective of the extent of the lines used, or whether the participant explored the lines via active or passive movement. Loomis and Lederman (1986) noted that the average size of the RTE found by the studies to that date was 10%. The overall size of the RTE found in this experiment is in broad agreement with this figure; the overall RTE in experiment five was 9.67% and the overall RTE in experiment six was 12.22 %. The results of this experiment are consistent with real world based studies that have found the RTE (e.g. Davidon and Cheng 1964; Cheng, 1968; Day and Avery, 1970; Wong, 1971 Wong, 1977; Marchetti and Lederman 1983 and Armstrong and Marks, 1999). The RTE is, therefore, not confined to manipulatory space in the real world, but also occurs in manipulatory space in HVR.

#### **4.4.2 The effect of active/passive movement on perceived extent with the PHANTOM™ device**

In both experiments five and six, the participants' estimates from the active movement condition, in which they traversed the virtual lines at their own pace and the passive movement condition, in which the PHANTOM™ guided them across the virtual lines at a constant speed, did not differ reliably. This is a very important finding as it undermines the notion that the RTE can be attributed to differences in the speed of exploration of radial and tangential extents. Recall that Wong (1977) observed that participants performed radial movements at a slower speed than tangential movements of equivalent extent. Furthermore, he noted that although participants were not aware of this discrepancy in exploration speed. Several other researches have also maintained that the RTE is likely to be attributable to radial movements being performed at a slower speed than tangential movements (Reid, 1954; Marchetti and Lederman, 1983; Armstrong and Marks, 1999). However, the results of experiments 5 and 6 undermine this position, since in the passive condition, the speed of exploration was equated between radial and tangential movements and the participants were made explicitly aware of this. Therefore the temporal cues between radial and tangential movements of equal extent were equal, yet the RTE still occurred.

It should be noted that the speed of the participants' radial and tangential movements in the active movement conditions of experiments five and six was not monitored, so it cannot be confirmed that participants were performing radial movements at a slower speed than equivalent tangential movements. However, a compelling reason why this tendency would not be evident HVR is not immediately apparent. Either way, the conclusion that the RTE cannot be accounted for by undetected differences in the speed at which radial and tangential extents are traversed remains.

If a difference in the speed of exploration between radial and tangential movements is not the cause of the RTE, what is? Perhaps the illusion might be attributable to another variable associated with radial and tangential movements. In fact, the RTE may be a bi-product of another haptic illusion. Consider that research has shown that an objectively straight stimulus feels curved (Crewdson and Zangill, 1940; Hunter, 1954; Davidson, 1972b) and that a curved pathway connecting two points marking off a given Euclidean distance is longer than the Euclidean distance itself. Research has also shown that the perception of the Euclidean distance between two points increases as the length of the pathway connecting those two points increases (Lederman Klatzky and Barber, 1985; Lederman, Klatzky and Wardell, 1987). These findings alone would not explain the RTE, since radial and tangential motions would both be subject to the illusion of curvature and would cancel each other out. However, if it could be shown that radial movements give rise to a stronger illusion of curvature than equivalent tangential movements and thus produce a greater pathway distance for an Euclidean extent, this would constitute a potential explanation for the RTE. Such evidence is provided when one considers the relationship between the work of Davidson (1972) and Wong (1977). Davidson (1972) noted that the curvature illusion is greater when the forearm rotates around the elbow than when the entire outstretched arm rotates about the shoulder. Wong (1977) notes that, "a purely radial motion involves greater motion at the elbow joint compared with that of the shoulder. In contrast, a purely tangential movement mainly involves abduction and adduction at the shoulder joint with the elbow joint relatively immobile" (p162). So, radial motions give rise to a stronger illusion of curvature than tangential movements of equivalent extent owing to the fact that radial motions involve greater movement of the elbow joint than tangential motions. The stronger illusion of curvature associated with radial movements means that the pathway distance connecting two points is greater with radial movements than equivalent tangential movements. This leads to the systematic overestimation of

extents explored via radial motions relative to extents examined via tangential motions.

At this point it should be noted that the RTE is not only manifest when radial movements are primarily elbow based and tangential movements are predominantly shoulder based. Wong (1971) also found the RTE when the stimulus was located to the side and slightly below the participants such that both radial and tangential movements were performed via motions about the shoulder. However, the curvature of the arc formed by the arm during radial movement of a given extent, performed about the shoulder, is greater than a tangential movement of equivalent extent, so mechanism for the RTE remains the same.

If the curvature illusion explanation of the RTE is sound, then if one were to ask participants to examine extents via radial and tangential motions under conditions that would negate the curvature illusion, one would expect the RTE to disappear or at least diminish in size. The basis for the curvature illusion is said to be the confusion between the stimulus and the natural concave path formed by a sweep of the arm (Hunter, 1954; Davidson, 1972; Davidson, 1986). If stimuli that required radial and tangential movements were to be examined using an EP, such as an enclosure, which would avoid the curved sweep of the arm being a confounding factor on participant's judgements of extent, the RTE should disappear. This line of thought has a number of converging findings to support it. Davidson (1972) found that blind individuals were more accurate in their categorization of curved stimuli than sighted individuals. He suggested that this might be attributable to the higher incidence of a more efficient 'gripping' strategy among blind individuals than the 'top sweeping' strategy used most frequently by the sighted participants. The gripping strategy was said to be more efficient because "it focused attention on the front edge of the stimulus, an arc in a different plane than the sweeping arm movement" (Davidson, 1972, p54). When sighted individuals were restricted to the use of the gripping EP, their performance was no longer significantly different to that of the blind

individuals. The incidence of the RTE in both blind and sighted individuals in this study may well of been due to the fact that both groups of participants were restricted to the EP of contour following i.e. the top sweeping strategy used by the majority of the sighted participants in Davidson (1972), which brings the curvature illusion into play. It would, therefore, be interesting to re-run this experiment in the real world under a condition where the sighted and blind participants are permitted to examine real counterparts to the virtual extents in any fashion they wished, and another condition in which the EP of enclosure is imposed on the participants. Under such conditions one would anticipate that the RTE would not be evident in the enclosure condition for either group of participants. It is interesting to note the correspondence between this line of thought and rare non-occurrence of the RTE in Heller and Joyner (1993), in which participants used the EP of enclosure to indicate the extents of the stimuli.

Beyond the content of the RTE, it is interesting that the participants' estimates of extent did not differ as a function of whether their exploratory movements were active or passive. The effect of active vs passive movement on the perception of extent is not an area of research that has received systematic study, comparisons between active and passive touch tend to occur with respect to the identification of 2-D forms (e.g Gibson, 1962; Schwartz, Perey, and Azulay, 1975; Symmons and Richardson, 1996; Symmons and Richardson, 1999b). Wong (1977) noted a similarity in the perception of extent between active and passive touch, in that that slower movements give rise to longer perceptions of extent and faster movements give rise to shorter perceptions of extent in both passive touch (Wapner, Weinberg, Glick and Rand, 1967) and in active touch (Ono, 1969). It is also interesting that the non-significant effect of active vs passive movement in these experiments corresponds with the non-significant effect of active vs passive movement in the perception of roughness (Lederman 1981)

#### **4.4.3 The effect of the direction of movement on perceived extent with the PHANTOM™ device**

The effect of the direction of exploration within each of the 3-D axes on perceived extent was not found to be significant in experiment five, nor did this variable interact significantly with any of the other experimental factors. This is consistent with Armstrong and Marks (1999) who also found that the direction of motion within radial and tangential movements was not significant.

Given the non-significant effect of movement direction, one is drawn to the conclusion that there should not be a significant difference in the results obtained in experiment 5, where participants were allowed to retrace their exploration along each of the lines in the opposite direction and in experiment 6, where subjects were constrained to exploring the lines in one direction. When the results of experiment 5 (collapsed over visual status and active and passive movement) were compared with those obtained in experiment 6 (collapsed over visual status and active/passive movement and line direction), no significant difference was found. Being restricted to the rather unnatural uni-directional method of scanning did not, therefore, have a significant effect on the participants' estimates.

Interestingly, in experiment six, the participants' estimates for the vertical lines were significantly greater than their estimates for objectively equivalent horizontal lines in both the active movement and passive movement conditions. The overall average overestimation of vertical extents relative to horizontal extents was 5.98%. i.e. a haptic Horizontal Vertical illusion. This was rather unexpected, since the literature indicates that the HVI does not tend to occur in the haptic modality. Overestimation of the vertical component of a figure relative to the horizontal component is usually attributable to the movement used to explore the vertical component being radial and the movement used to explore the horizontal component being tangential. However, in this

experiment, vertical and horizontal motions both involved tangential movements. Other instances of a haptic horizontal illusion e.g. Day and Avery (1970) are attributed to inverted T stimulus configuration producing a bisection illusion. However, this could not have been the case in this experiment, since the virtual lines were presented sequentially.

The one exception to the rule of the absence of a HVI independent of the RTE or the bisection illusion was found by Over (1966). In this experiment, vertical extents judged by tangential motions were overestimated relative to horizontal motions also judged by tangential motions. Since the effect occurred in both the active and passive movement conditions of experiment six, and there was no effect of direction of movement, it seems unlikely that the effect could be attributed to a higher moment of inertia, causing slower movements, for upwards motions than for downwards, left, right, or back and forth motions. A similar explanation of the RTE was proposed by Wong (1977), which posited that slower radial movements were the result of a higher moment of inertia relative to equivalent tangential movements. However, Marchetti and Lederman (1983) found that increasing the moment of inertia associated with radial and tangential movements by manipulating the distance of the participants' hands from the stimuli, or by changing the mass of the exploring hand, had no effect on the magnitude of the illusion.

This HVI was not observed in experiment 5. Thus, it would appear at this time that the presence of the HVI experiment 6 was anomalous.

#### **4.4.4 The effect of visual status on the isotropy of perceived extent with the PHANTOM™ device**

There was no statistically reliable difference between estimates of extent from sighted and blind participants, nor did the variable of visual status interact significantly with either the line extent, dimension or direction



factors. The results of this experiment do contrast somewhat with Heller and Joyner (1993). Heller and Joyner found that sighted and late blind participants failed to show the RTE for the L shaped figure used by numerous other studies of the RTE (e.g. Davidon and Cheng, 1964; Cheng, 1968; Day and Wong, 1971 and Wong, 1977). The absence of the RTE in Heller and Joyner (1993) might be due to the incongruity between the exploratory procedures (EPs) the participants were instructed to use for examining and reproducing the extent of the stimuli. Participants used the tip of their index finger to explore the horizontal and vertical extents of the figures (contour following), but were then asked to give a response by using the index finger and the thumb in a pincer gesture (enclosure) to indicate the size of the stimulus that had just been explored. Therefore, the participants had to translate an estimate gained by one EP into an equivalent estimate using another EP. The effects of such a translation have not been investigated.

Heller and Joyner (1993) did find that the vertical component of an inverted T stimulus configuration laid before the participants was overestimated relative to the horizontal component, with both late blind and sighted individuals. However, they correctly noted that this might not represent an occurrence of the RTE, but rather a haptic version of the bisection illusion, in which a horizontal line bisected by a vertical line is perceived as being longer than an equivalently sized horizontal line without the bisection. The Bisection illusion has been previously demonstrated in the haptic modality (Tedford and Tudor, 1969; Day and Avery, 1970). The work of Heller and Joyner (1993) does suggest two areas of research in need of more attention. Firstly, the accuracy of the translation of an estimate of extent gained with one EP into another EP and the robustness of haptic illusions, such as those found by Suzuki and Arashida (1992), across different EPs. The impact of the use of different EPs on the incidence and magnitude of haptic illusions is interesting in its own right, but is also potentially informative with respect to comparisons between sighted and blind individuals, as some authors have attributed differences between the two groups to the use of

different EPs in examining the illusory stimulus (Hatwell, 1960; Davidson, 1972; Davidson, 1976; Davidson, 1986).

In summary, experiments five and six both indicated that perceived extent with the PHANTOM™ device is subject to a an anisotropy that has been frequently reported in the real world, namely the radial tangential effect. Furthermore, experiment six indicated that perceived extent with the PHANTOM™ is also subject to the horizontal vertical illusion, which has only been demonstrated once in the real world under conditions that do not confound this illusion with the bisection illusion. However, the horizontal vertical illusion was not evident in experiment 5, thus may be anomalous.

There were no significant differences in the participants' estimates of extent between the active and passive movement conditions in either experiment 5 or 6. It was highly significant that the RTE persisted even when the velocity of participants' exploratory movements was equated over radial and tangential movements in the passive movement conditions of both experiments. This undermines the notion that the RTE can be accounted for by differences in the velocity at which radial and tangential movements are performed.

The direction of the exploratory movements within each of the 3-D axes was not found to exert a significant influence on perceived extent, which is consistent with the real world based literature. Estimates of extent were also consistent between sighted and blind individuals, which is in agreement with the results of experiment 3.

## **5. Chapter 5: General discussion**

### **5.1 Overview**

This chapter discusses the empirical results of the reported experimentation and considers their theoretical and practical implications. Section 5.2 outlines the implications of the reported work for existing theories of haptic perception in both VR and the real world. Section 5.3 considers ideas for further research that arise from the reported experimentation. Section 5.4 considers the implications of the reported work for future haptic devices, applications and software. Finally, section 5.5 summarises the contribution to knowledge, with respect to the issues raised in the introductory chapter, made by this thesis.

In commenting on the overall findings of this thesis, it should be noted that the reported experimentation was rather analysis intensive. Under conditions in which a large number of individual analyses are conducted it is important to be aware of the risk of a type-one error occurring, particularly if the .05 significance level has been adopted. However, the vast majority of the statistically reliable effects found in this thesis were significant to the .01 level and above. Therefore the possibility of a type one error being present in the data is unlikely.

### **5.2. Summary of empirical findings and their implications for theories of haptic perception in VR and the real world**

This section summarises the empirical findings of this thesis and looks at their theoretical implications. It is organized such that it systematically

addresses the contributions made to the issues raised in the sections 1.10.1 through 1.10.8 of the introductory chapter.

### **5.2.1 Perception of object attributes in VR**

- **Roughness**

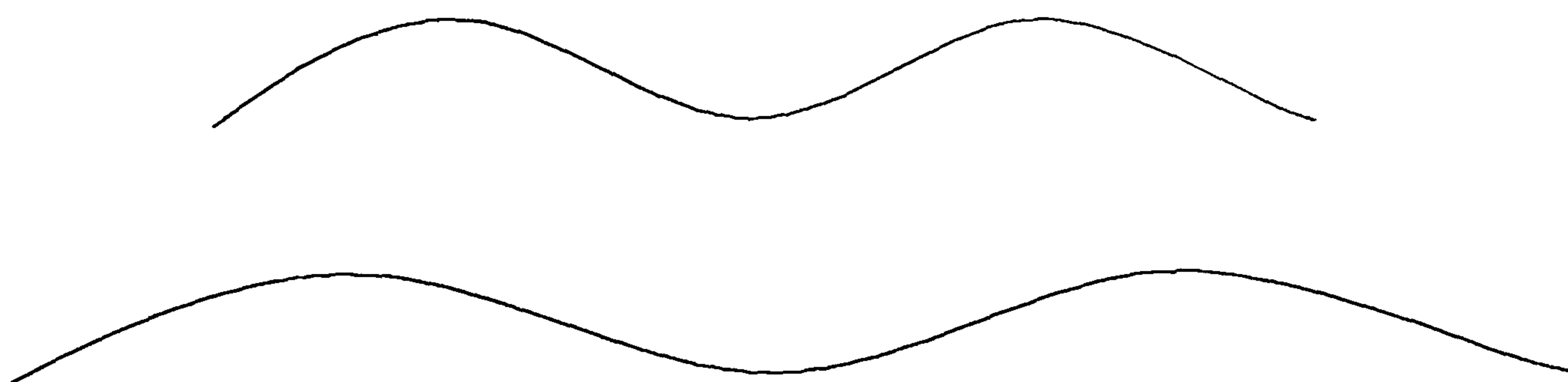
Contrary to the real world based research on roughness perception with the bare finger/s, which has invariably indicated that increases in the inter-element spacing of which a texture is comprised result in increases perceived roughness (e.g. Lederman and Taylor, 1972; Lederman, 1974; Lederman, 1981), perceived roughness in VR with the PHANTOM™ device was found to decrease with increasing inter-element spacing (groove width). This is in agreement with Colwell et al (1998) and Wall and Harwin (2000).

However, what are the broader implications for the formulation of a theory of roughness perception in VR? Clearly, the model of roughness perception in the real world posited by Lederman and Taylor (1975) in which perceived roughness increases as a function of increasing cross sectional area of deviation of the skin from its resting position is not appropriate for roughness perception with a force feedback device. However, real world based research that has examined of the effect of perceiving texture via a probe might be able to account for the findings in VR. Klatzky and Lederman (1999) found that perceived roughness of textures with a rigid probe peaked at the texture featuring an inter-element spacing that corresponded to the contact diameter of the rigid probe. Beyond this point perceived roughness would begin to decrease as a function of increasing inter-element spacing. Klatzky and Lederman argued that the shape of the psychophysical function relating groove width to perceived roughness produced by a rigid probe could be explained in terms of the effect of the diameter of the contact point of the probe on the amplitude of the vibrations it generates as it contacts the raised elements of the textures. They argued that for the textures with

the smallest inter-element spacing relative to the contact diameter of the probe, the amplitude of the vibrations generated by the probe would be minimal, as the probe could not descend into the gaps between the raised elements. Rather, it rides over them and contacts the tops of the raised elements. For textures with intermediate inter-element spacing relative to the contact diameter of the probe, the depth to which the probe will descend between elements will increase as a function of increasing inter-element spacing. Therefore, the amplitude of the vibrations generated by the probe contacting these textures will also increase. For textures featuring inter-element spacing as wide and wider than the contact diameter of the probe, the amplitude of the vibrations generated by the probe cannot increase any further, as the probe is able to traverse the flat base between the raised elements. However, Klatzky and Lederman believe that the perceived roughness of textures featuring inter-element spacing greater than the contact diameter of the probe is attenuated over space/time by the relatively long periods spent in the smooth bases between the elements. Therefore, the amplitude of vibratory signals generated by textures featuring a range of inter-element spacing that encompasses values below, within and beyond the dimension of the contact point of a probe can be said to increase and then decrease with inter-element spacing. The point at which the decrease begins being approximately that of the contact diameter of the probe. This trend corresponds to the tendency for perceived roughness to increase with inter-element spacing, up to the point at which said spacing is such that it can fully accommodate the diameter of the exploratory probe.

Given that the size of the contact point of the IE3000 and PHANTOM 's probe is smaller than any of groove widths of the virtual textures utilised, the negative exponent relating groove width to inter-element spacing makes sense in the context of the findings of Lederman and Klatzky. Indeed, the above explanation could provide a basis for a model of roughness perception in VR. However, there is an alternative explanation. The negative exponent relating inter element spacing to

perceived roughness found with 3-D force feedback devices to date might be an artefact of the sinusoidal stimuli used in all of the experimentation. By way of explanation, consider the following: when one adjusts the widths between the peaks of a sinusoidal profile, but makes no adjustment to the amplitude of this profile, the steepness of the vertical transitions between the base and peak of the sinusoidal grooves diminishes. This may have the effect of making sinusoidal textures featuring smaller groove widths feel rougher than textures featuring larger groove widths. This is illustrated in figure 5.1. Both diagrams feature sinusoids of identical amplitude, the second one simply features a larger peak-to-peak groove width. The effect is similar to pulling a crumpled piece of string taut and is therefore referred to as the 'taut smoothing effect'



**Figure 5.1 The taut smoothing effect**

At this time, it is not clear whether the negative exponent relating groove width to perceived roughness in VR is due the point of contact in HVR being smaller than any of the groove widths utilised or to the sinusoidal waveforms used in HVR per se.

Models of roughness perception in VR may also need to take account of cognitive factors. The pre-test stages of experiments one and two identified a conflict, expressed by some participants, between what “should feel” rougher and what “actually feels” rougher, from the outset of the experiments. They claimed that in the real world they had noticed that roughness tends to increase with increases in the spacing between the raised elements that formed the textured surface. However, with the virtual textures, they felt that roughness decreased with increases in inter-element spacing. They therefore wondered whether to simply say what “actually felt” rougher or adjust their responses in line with their knowledge of what “should feel” rougher based on their experience of judging roughness in real world. In experiments one and two, the author stressed that participants should base their roughness estimates on “the way the textures actually felt in VR”, not on “the way the textures should feel, based on their experience of perceiving texture in the real world”. It was stressed that the experiment was not a test of the validity of their responses relative to what feels rough in the real world, but an attempt to determine what feels rough in HVR.

- 3-D object size and angular extent in HVR

The literature review indicated that a general theory of the haptic perception of 3-D object size and angular extent in both the real world and virtual reality is lacking. What is evident from the reported research is that a general characterisation of size and angular extent needs to take account of the exploratory procedures used in arriving at estimates of these attributes. For example, when judging the size of an object, an individual may elect to trace the contours of the object or enclose it in their hand/s. However, this is not so much of a problem with single point of interaction force feedback devices in VR, since users are restricted to the EP of contour following.

The reported work with the PHANTOM™ device indicated that a linear increase in the size and angular extent of 3-D virtual objects was reflected in a corresponding linear increase in the perceived size and angular extent of these objects. The sizes of the cubes and spheres presented in an external mode of presentation were reliably underestimated. The examination of the perception of 3-D object size in VR led to the emergence of a number of interesting influences on the perception of 3-D object size that need to be taken into account when characterizing perceived size in VR. Firstly, equivalently sized virtual cubes and spheres were not perceived as such; cubes were judged larger than equivalently size spheres with the PHANTOM™ device. The single point nature of interaction with the PHANTOM™ device is unaffected by the object type being explored; the participants were restricted to the use of contour following irrespective of object type. Therefore this difference cannot be explained by participants using different EPs in arriving at their size estimates for cubes and spheres. However, even when limited to the EP of contour following, participants exhibited more than one way of executing this EP when exploring virtual objects. For example, there are two possible ways of determining the diameters of the virtual spheres. One way is to trace the circumference of a sphere and infer the Euclidean distance from the top of the sphere to its base, the other is to try and memorise the spatial location of the top and bottom of the sphere and traverse the Euclidean distance between these points. It may be the case that one method leads to smaller estimates than the other. At present, the implications of such differences in the execution of an EP for the perception of 3-D object size are unknown.

The perceived size of the virtual 3-D objects was also not found to be uniform across the modes in which the objects were presented. Virtual cubes and spheres examined in the internal exploration mode were perceived as larger than their equivalently sized counterparts examined in the external exploration mode (the Tardis effect). The Tardis effect seems most likely due to context influencing perceived size: objects



presented in the external mode are perceived as comparatively small in relation to the volume of empty space surrounding them. This is not the case with the internal objects, however, as they are judged purely on their own dimensions. Although a distortion in the perception of size owing to context has been previously documented i.e. the kinaesthetic after-effect (e.g. Baker, Mishara and Kostin, 1986). The Tardis effect furthers our knowledge of the perception of the size of 3-D objects by demonstrating that context related distortions can derive from the wider experimental context, as well as from the experimental stimuli per se.

### **5.2.2 The effect of the endpoint used with the PHANTOM™ device**

The lack of cutaneous information and single point interaction characteristics of perceiving virtual objects with the PHANTOM™ remains irrespective of whether an individual uses the device's thimble or stylus endpoint. However, it was not known whether the endpoint being used would exert a significant impact on the perception of virtual object attributes. Understanding the role of the endpoint is an important issue in elucidating the parameters that influence haptic perception in VR. In this respect, this thesis has made a number of contributions.

It transpired that whether the endpoint used with the PHANTOM™ device exerted a significant perceptual effect depended on the attribute being studied. It is not the case that haptic perception with the PHANTOM™'s endpoints can always be easily distinguished, or simply that one endpoint is superior to the other per se: the endpoint used with the PHANTOM™ had a significant, but inconsistent effect on the exponent relating groove width to perceived roughness; no significant effects on the perceived size of the virtual 3-D objects and a significant effect on the perceived angular extent of the virtual sheared cubes.

It seems likely that the fundamental similarity between the characteristics of haptic perception in VR with the two endpoints may be more important than any other differences that may exist between the two endpoints for the perception of some attributes. This was most likely the reason that the participants' estimates of the sizes of the 3-D virtual objects did not differ significantly between the thimble and stylus endpoints. It was thought possible that participants might imagine the size of the contact point with virtual objects to differ according to which endpoint was being used and take this into account in their size estimates. However, this does not appear to have been the case. Rather, it appears that the corresponding size of the contact points between the thimble and stylus endpoints were reflected in corresponding size estimates.

However, clearly the aforementioned similarities between the two endpoints are not sufficient to prevent perceptual differences arising between them for all virtual attributes, hence the significant effect of endpoint for the attributes of roughness and angular extent. The question that needs to be addressed is: what is the mechanism underlying the effect of endpoint? At first glance there would seem to be three possible explanations for significant effects of endpoint.

Firstly, it is possible that the use of different endpoints might cause differences in an interaction related determinant of the perception of an object attribute. This possibility was investigated in experiment 2 with respect to the perception of roughness. In this instance it was hypothesised that the effect of endpoint on the exponent relating groove width to perceived roughness, found in experiment one, might be due to the interaction related parameter of contact force. The experimenter had noted that the thimble endpoint was more conducive with the application of a greater degree of contact force than the stylus endpoint. In the case of the thimble endpoint, the individuals finger is secured and would not slip with increasing contact force, as would be increasingly likely to occur with the stylus endpoint. However, this hypothesis was not supported in experiment two. Curiously, there were no significant differences in the

amount of contact force participants applied to the virtual textures between the two endpoints. Although the effect of endpoint on perceived roughness cannot be attributed to the exploratory variable of contact force, it is possible that it might arise from differences between the endpoints in another exploratory variable, such as the velocity of participants' scanning motions across the virtual textures. Although research has indicated that individuals are able to take the velocity of their scanning motions into account when examining textured surfaces with their bare fingers (Lederman, 1974) a significant, albeit small effect, of scanning velocity has been found in studies of perceiving texture with a rigid probe (Lederman, Klatzky, Hamilton and Ramsay, 1999).

The second explanation for effects of endpoint relates to possible differences in the way users interact with them. For example, Jansson (2000) identified two methods participants used in interacting with the stylus endpoint of PHANTOM™: a 'palm vertical' method, in which participants held the stylus in the manner in which they would hold a pen, and a 'palm horizontal' method, in which the participants held the stylus from above with their palm orientated in horizontal plane. However, not one participant in the reported experiments was observed to have used the latter method; all chose the palm vertical method of their own volition. It is, however, possible that more subtle differences associated with the manner in which a user interacts with the PHANTOM's endpoints might account for significant effects. It seems probable that such differences are most likely to be limited to the stylus endpoint, as there is more scope to choose how one interacts with the stylus endpoint than with the thimble endpoint. For example, individuals can alter the point at which they hold the stylus and the configuration of their grip on the stylus, neither of which is possible with the thimble. It might, for example, be the case that holding the stylus further from the end attached to the PHANTOM's arm progressively reduces the extent to which participants can detect the displacements in the vertical plane that characterise a virtual texture. This might result in a lower exponent relating groove width to perceived roughness.

The third explanation involves the possibility that the physical dimensions of the endpoint itself may facilitate or obstruct an individual's judgment of a particular virtual object attribute. For example, as has been suggested in the discussion section for experiment 3, the participants may have been using the stylus endpoint as a reference against which to judge the angular extent of the sheared cubes. Alternatively, it may be the case that participants were unintentionally receiving cues from the mere act of wielding the stylus endpoint that were instrumental in their judgments. For example, recall that Gentaz and Hatwell, 1995; Gentaz and Hatwell, 1996 and Gentaz and Hatwell, 1998) argued that gravitational cues played a significant role in the perception of angular extent. In these instances perception of vertical and horizontal orientations were more veridical in the presence of gravitational cues provided by the participants' forearms and wrists being unsupported. Perhaps the stylus held in the palm vertical mode served as an additional salient indicator of the vertical plane, which resulted in the generally more veridical estimates of sheared cubes with the stylus endpoint than with the thimble, which provides very little in the way of orientation cues.

There is the possibility that there is not a single basis for significant effects of endpoint. Rather, it seems more probable that the basis for the effect of endpoint might vary according to the particular object attribute being examined. For example, the possibility that the significant effect of endpoint on perceived roughness might be due to another exploratory variable, or a variable associated with the manner in which the participant holds the stylus endpoint seems intuitively pleasing. The possibility that the difference might be due to the physical characteristics of the endpoint facilitating the participants' judgments seems less probable intuitively. The converse applies to the significant effect of endpoint on the perceived angular extent of 3-D objects.

### 5.2.3 Perception in haptic VR across different devices

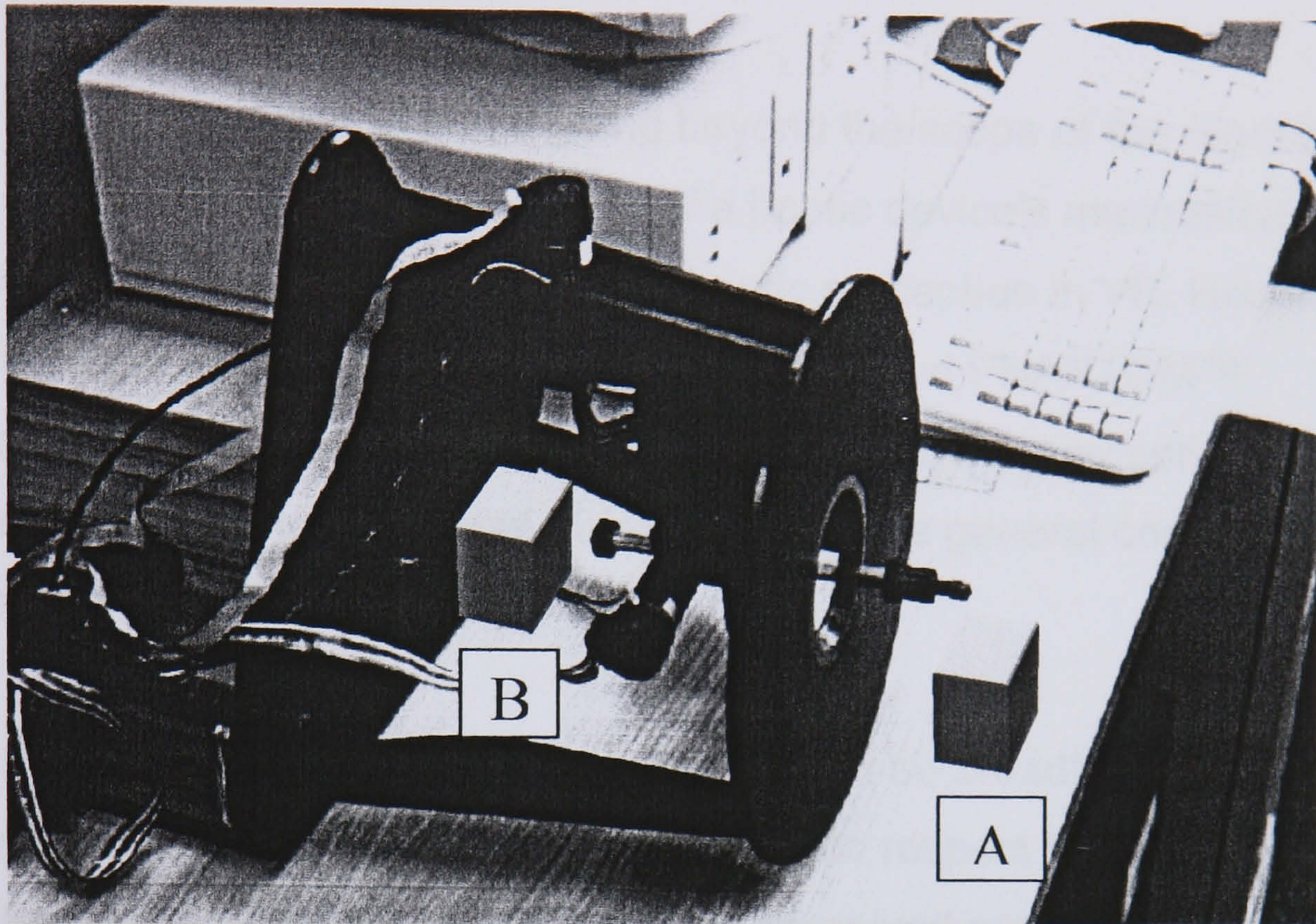
An important issue in understanding haptic perception in VR is determining the impact of the specific device used on the perception of virtual object attributes. Resolving this issue provides information on which parameters of the device exert a significant influence on haptic perception in VR. This information provides some broad guidance as to the optimal design of future devices.

Unfortunately, investigating the role of the device used on haptic perception in VR is far from an easy task. Haptic devices can be distinguished with respect to a multitude of measures. Furthermore, there is, as yet, little agreement between researchers about how to measure the performance of a haptic device (Hayward and Astley, 1996) and little information on which aspects of a haptic device's performance are of perceptual significance (Biggs and Srinivasan, 2001). This most likely explains why research has remained virtually silent on this issue.

A broad categorisation of haptic devices is possible, however. Therefore, the question asked by this thesis in respect of the role of the specific device used on haptic perception in VR was necessarily broad in nature: does the perception of object attributes differ significantly between two 3-D, single point of interaction force feedback devices?

First and most generally, it transpired that even with two 3-D force feedback devices of a similar specification, it is possible for differences to occur in individuals' perception of the location of location of virtual space (see figure 5.2 on the following page). Hardwick, Furner, & Rush (1998) observed that, with the IE3000 device, some individuals tended to think that the virtual environment was located outside the device, such that contact with the virtual objects occurs at the end of the probe nearest the hand (see 'a' in figure 5.2). However, other individuals imagined the virtual environment to be located within the mechanism of

the device, such that contact with the virtual objects occurs at the end of the probe furthest from the individual's hand (see 'b' in figure 5.2).



**Figure 5.2 Different mental models of the location of virtual space with the IE3000 device a) Virtual environment located on the outside of the device's mechanism b) Virtual environment located in the device's mechanism.**

It seems probable that the physical configuration of the device has a role to play in suggesting to the user where the virtual environment lies. The IE3000's probe articulated in the mechanism of the device and was not accessible to the participants, this probably created ambiguity as to whether the participants were remotely probing an environment within the device's mechanism, or probing a more proximal environment external to the device's mechanism. The PHANTOM™ device articulates at points external to the device's mechanism, so there was no reason for any ambiguity about the location of the virtual environment. Indeed, participants in experiments one through six were asked informally about their opinion of the location of the virtual environment relative to the PHANTOM™ device. Without exception, all of them reported perceiving the virtual environment as being external to the device's mechanism i.e.

a) in figure 5.1. Unfortunately, Colwell (1998) did not assess whether the different mental models about the location of virtual environment impacted upon the perception of the attributes of roughness or 3-D object size and angular extent.

One should be cautious about going beyond the scope of the reported data in trying to infer which aspects of a haptic device's mechanical specification might exert an effect on haptic perception in VR. However, the reported comparisons between the IE3000 and PHANTOM™ devices taken together with some of the results on the perception of the real counterparts to the virtual objects allow some general comments to be made.

The first comment is that haptic perception can be broadly comparable between two 3-D force feedback devices. With respect to perceived roughness, a negative exponent relating perceived roughness to groove width predominated for both devices. Furthermore, there were no overall differences in the rate at which perceived roughness decreased as a function of increasing groove width between the two devices. With respect to the perceived size of 3-D objects, the general trends for external objects to be underestimated and internally presented objects to be overestimated relative to their external counterparts was also apparent with both devices. These broad similarities between two 3-D force feedback devices are most likely a reflection on the broad similarity between the general characteristics of interaction with virtual objects between the two devices. With both the IE3000 device and the PHANTOM™, participants are restricted to a single point of interaction with virtual objects and deprived of any direct cutaneous information about the virtual objects. Correspondence between these fundamental characteristics are likely to be of paramount importance in determining the consistency of perception between any two haptic devices across the attributes reported in this thesis. It is also likely that the same similarity would be noted in the perception of other geometric attributes, such as curvature, and other material attributes such as friction and viscosity.

The attribute dependent significance of the single point interaction and lack of direct cutaneous information characteristics are shared between the IE3000 and PHANTOM™ devices. The lack of cutaneous information was of more consequence in the perception of the material attribute of roughness with both devices, as roughness would normally be perceived via kinaesthetic *and* cutaneous information as opposed to just kinaesthetic information. In contrast, the single point interaction nature of both devices was of more consequence in the perception of the geometric attributes of 3-D object size as it precludes the use of the preferred EP of enclosure for perceiving this attribute.

However, this is not to say that differences in the perception of virtual attributes do not occur between devices of the same genre. As has been noted, virtual cubes were deemed to be larger than equivalent sized virtual spheres with the PHANTOM™ device. However, this trend was not evident with the IE3000 device in either Colwell (1998) or Bruns (1998). At this stage, however, it is not clear whether this is due to a difference between the devices per se, a difference between the strategies used to measure the spheres precipitated by differences between the devices, or differences in said strategies that might occur between different populations of participants independently of the device being used. The fact that the effect of object type was not found with the real counterparts to the virtual objects in the condition in which participants explored the objects with the de-activated PHANTOM™ tentatively suggests that the latter explanation may be a possibility.

What can be said of the role of differences in mechanical performance measures between devices? It must be stressed that these variables were not manipulated by this research, so one must be cautious in making inferences. However, there is evidence from experiment 4 that the perception of the attributes of 3-D object size and angular extent may be quite robust over variables such as the mass of a device's endpoint and the inertia associated with a device's movement, since the estimates



of 3-D object size and angular extent for the virtual objects and their real counterparts examined in the de-activated PHANTOM™, detached stylus and bare finger conditions were statistically indistinguishable.

Although it is too early to account for the role of the mechanical performance measures of a device in detail, one can perhaps lay down the parameters within which any effects are likely to occur. For example, it is a point of common sense that any mechanical variations that exceed the sensitivity of the human haptic system will be redundant. Of greater importance are instances where the capabilities of the human haptic system exceed the capabilities of the haptic device. One good example of this would be the disparity between the maximum controllable exertable force produced by the PHANTOM™ and the finger (8N vs. between 50-100N) depending upon whether the finger muscles are used alone or in conjunction with the shoulder muscles (Srinivasan and Basdogan, 1997). Indeed, the participants in Colwell (1998) with the IE3000 and those in the reported work with the PHANTOM™ were able to penetrate the surfaces of even the stiffest virtual objects at will. However, they did not do so inadvertently and reported that the forces exerted by the PHANTOM™ were more than sufficient to create the impression of solid objects. Bruns (1998) found that altering the elasticity of virtual 3-D objects did not significantly affect perceived size. The implication of these observations and findings is that just because a haptic device cannot match the human haptic system does not necessarily mean that its performance will not be “good enough”.

Although it would appear that users are capable of, to use Srinivasan and Basdogan's words, “suspension of disbelief” (1997, p395) when the performance of a haptic device falls below that of the human haptic system. There will, almost certainly, be limits to the extent to which such liberties can be taken. In the absence of more extensive knowledge in this regard, the author would argue that the design and specifications of the PHANTOM™ device provide a sound baseline for the development of knowledge about this issue.

In summary, the main contributions to the issue of the consistency of haptic perception between two 3-D force-feedback devices are as follows. Unprecedented comparisons between the PHANTOM™ and the IE3000 revealed that haptic perception is broadly comparable between the devices. It is argued that this was due to the fundamentally similar nature of the interaction with virtual objects between the two devices. As yet, variations in the performance measures that characterize a device are not clear. However, it is argued that the critical factor is likely to be the extent to which such variables confound the haptic cues that indicate a particular object attribute.

#### **5.2.4 Haptic perception in virtual and physical reality**

The issue of whether haptic perception differs between the real world and HVR is important for a reason other than its intuitive interest. Elucidating which, if any, of the differences between HVR and the real world are responsible for any observed perceptual differences is also potentially informative with respect to the development of future haptic devices.

Of critical importance in determining whether haptic perception in VR and naturalistic haptic perception in the real world will differ is the interaction between the characteristics of the haptic device and the attribute being studied. For example: the lack of cutaneous information inherent in exploration of virtual stimuli with the PHANTOM™ had significant implications for the perception of roughness in VR: negative exponents relating groove width to perceived roughness have not been reported in the real world literature. Furthermore, the Lederman and Taylor (1975) model of roughness perception, in which perceived roughness increases as a function of increasing cross section of the area of skin deviating from its resting position, clearly cannot account for roughness perception with the PHANTOM™. In contrast to impact of the

lack of cutaneous information on perceived roughness, its implications for the perception of 3-D object size were minimal. Here, the single point of interaction seemed to be of more consequence, due to the fact that it restricted the participants to the EP of contour following, which the results of the reported research and previous research (e.g. Lederman, & Klatzky, 1987a; Lederman and Klatzky, 1987b) indicated is not the participants' preferred EP for assessing the size of the 3-D objects.

Even when broad differences between naturalistic haptic perception in the real world and VR do occur, they do not appear to be artefacts of VR per se, but rather would appear to be replicable in real world. Taking the perception of roughness as an example, research that has examined of the effect of perceiving texture via a probe has suggested that the relationship between the size of the contact point of a virtual device and the dimensions of the inter-element spacing of which texture is comprised can account for perceived roughness in VR.

Although one can distinguish natural unconstrained haptic perception in the real world with haptic perception in VR, the differences can be quite subtle: there was no overall significant difference between the perceived size of the virtual 3-D objects and their real counterparts explored via single point interaction. However, unconstrained haptic perception and haptic perception with the PHANTOM™ could be distinguished by the incidence of other effects. For example, the Tardis effect did occur in the real world when a single point style of interaction was imposed on the participants' exploration of the real objects, but not when participants were permitted to examine the objects in an unconstrained fashion. It would be fair to say that this difference between VR and the real world is most likely due to the single point interaction characteristic of the PHANTOM™, since perusal of participants' use of EPs in the unconstrained real world exploration condition reveals that they were more inclined to use the EPs of enclosure in reaching their estimates than that of contour following. If the explanation of the Tardis effect

posited in the discussion for experiment 3 holds water, then the effect would not be evident with the EP of enclosure.

There was also a significant difference between the perceived angular extent of the virtual 3-D sheared cubes and their real counterparts explored in an unconstrained manner. It seems likely that this can be solely attributed to the use of different EPs to examine the sheared cubes, since the effect did not occur in the real world under conditions in which the participants were constrained to a single point method of interaction with the real objects.

Real and virtual 3-D space were also shown to be subject to similar anisotropies, in particular, the RTE. It could be argued that the correspondence between HVR and the real world in this respect is due to the fact that single point interaction seems particularly conducive to generating the illusion, irrespective of whether it occurs in the real world or VR, as was outlined in the discussion section for experiments 5 and 6.

One interesting aspect of the data on the perception of real 3-D objects in the reported experiments was the consistency of perceived size and angular extent across the 3 single point conditions. Neither the mechanics of the PHANTOM™ nor the lack of cutaneous information about the object being presented had a significant impact, indicating that estimates of size made via contour following is robust when cutaneous information is deprived. However, this does not mean that cutaneous information is not important in the perception of 3-D object size per se per, but rather that it is of little consequence when participants are constrained to the use of contour following, as they were in the bare finger condition.

### 5.2.5 The isotropy of perceived extent in VR with the PHANTOM™

The ability to explore objects in a 3-D virtual environment with the PHANTOM™ combined with the fact that real world based research has indicated that haptic perception across the 3-D axes is anisotropic (e.g. Cheng, 1968; Wong, 1977 Armstrong and Marks, 1999) means that the perception of 3-D space and specifically, the uniformity of the perception of an attribute over the 3-D axis is an important issue in understanding haptic perception in VR.

For the first time, haptic perception with the PHANTOM™ was shown to be subject to the RTE. Thus haptic perception in VR with the PHANTOM™ device was subject to an anisotropy of extent that is also characteristic of haptic perception in the real world. It could be argued that the presence of the RTE in VR can be attributed to the fact that there is nothing about examining extents in VR that would undermine the mechanism thought to be responsible for the RTE in the real world. Research has posited that unintentionally lower radial movement velocity relative to tangential movement velocity confounds the use of temporal cues to judge extent, thus producing the RTE. However, the results of experiments 5 and 6 indicated that this explanation is unsatisfactory, since the RTE occurred even when the velocity of radial and tangential movements was equated and the participants were explicitly aware of this. If, as suggested in chapter four, the RTE is functionally related to the curvature illusion, one would expect it to disappear under conditions in which the curvature illusion is not evident. Resolution of this issue has wider implications for determining the heuristics (i.e. temporal or spatial) individuals tend to use when making judgments of extent. Lederman, Klatzky and Barber (1985) and Lederman, Klatzky, Collins and Wardell (1987) offer evidence that estimates of extent are mediated by primarily spatial cues with movement duration exerting a secondary influence, which is more pronounced for longer extents (over 20 cms).

Experiment six also indicated 3-D haptic space in VR is subject to a horizontal vertical illusion (HVI). The presence of this effect was most surprising given that the real world based literature has indicated that the haptic HVI does not occur when vertical and horizontal extents are both explored via tangential motions (e.g. Day and Avery, 1970; Wong, 1977). However, the size of his illusion was smaller than the RTE and its presence was not found to be reliable, since it did not occur in experiment five. Interestingly, Over (1966) also reported the instance of an anomalous appearance of the HVI in the real world, unfortunately he did not offer an explanation as to why this may have occurred. It would be logical to assume that a difference in the methodology between experiments 5 and 6 might be responsible for the effect. However, this seems unlikely given that estimates of extent gained from unidirectional movements (in experiment 5) and bi directional (in experiment 6) were not found to be statistically distinguishable. Furthermore, the configuration of the stimuli in both experiments could not have confounded the HVI with the bisection illusion (Day and Avery, 1970). In the light of the above it is argued that the incidence of the HVI may just have been anomalous.

### **5.2.6 The impact of exploration variables on haptic perception in VR with the PHANTOM™**

In developing knowledge of haptic perception in VR, it is important to make progress in understanding how parameters of a person's interaction with the virtual stimuli impacts upon perception. These parameters can then be taken into account not only when formulating theories of the perception of particular attributes in VR, but also when designing haptic VR environments that incorporate said attributes. Having made some progress in understanding how the attributes of roughness and size are perceived in VR, the intention was to then determine how the perception of these attributes might be affected by

exploratory variables of contact force and active vs passive movement, respectively.

It transpired that the impoverished nature of haptic perception with the PHANTOM™ relative to haptic perception in the real world does not preclude exploratory variables exerting an impact on the perception of a virtual object attribute. However, it also transpired that although a change in a given exploratory variable instigated by an experimenter may well exert an impact on the perception of a virtual object attribute, when left to their own devices, users may be consistent in their use that exploratory variable. Under these circumstances, in practice, the exploratory variable is then redundant as an influence on the perception of an attribute. This was noted in experiment 2, where the amount of contact force applied to the virtual textures was found to be a significant determinant of perceived roughness. However, the amount of contact force that participants chose to apply to the virtual textures of their own volition did not significantly differ as a function of the groove widths of the virtual textures.

The above overlaps with the next point, which concerns the mechanism of the effect of an exploratory variable on the perception on a virtual object attribute. Although the effect of contact force on the perceived roughness of virtual textures was significant, the mechanism posited for this effect in the real world is not appropriate for roughness perception with a force feedback device. This is not just because a model that accounts for roughness perception in terms of cutaneous deformation is inappropriate for a force feedback device (as previously discussed), but also because the contact point of the PHANTOM™ fully penetrated all of the groove widths utilized. Thus, there would have been little point in increasing applied contact force with increasing groove width, a point that is borne out by the results of experiment 2.

In contrast to the effect of the exploratory variable of contact force on perceived roughness, the role of the exploratory variable of active vs.

passive movement on the perception of extent was found to be negligible. As has already been discussed, this was an important and novel finding, as it undermines the notion, posited by some researchers, that the RTE can be explained in terms of unnoticed differences in the speeds at which radial and tangential movements are performed (Wong, 1977; Marchetti and Lederman, 1983; and Armstrong and Marks, 1999).

There is an important qualification to be made in respect of the role of exploratory variables in VR, however. The significance of an exploratory variable is likely to be stimulus contingent. For example, although active vs passive movement had little effect on perceived extent, it is not clear if it would impact significantly on the perception of angular extent. As will shortly be discussed, there is certainly reason to believe that passive movement would facilitate navigation around haptic virtual environments. There is also evidence to indicate that passive movement may prove superior to active movement in the identification of 2-D objects in VR (e.g. Richardson 2000). There may also be some interactions between exploratory parameters and device parameters. For example, it is not known whether active and passive movement would produce similar estimates of extent with a haptic device that permits EPs other than contour following to be utilized i.e. a device featuring more than one point of contact with the virtual environment.

### **5.2.7 The impact of Visual status on haptic perception in VR with the PHANTOM™**

Section 1.10.8 of chapter one identified that one of the applications of HVR is as an accessibility tool for blind individuals. Therefore, it was important to make some progress towards understanding haptic perception in VR in blind individuals and how they compared to their sighted counterparts. The author wanted to gain a broad understanding about not only how sighted and blind individuals perceived virtual object attributes, but also on the interaction between the variable of visual



status and parameters associated with the haptic device (i.e. the endpoint used with the PHANTOM™ device and the specific device used) and parameters associated with the exploratory variables used in interacting with virtual object attributes.

It is certainly fair to conclude from the reported experimentation that, at this point in time, it would seem that the haptic perception of the object attributes of roughness, object size and angular extent with the PHANTOM™ device is broadly consistent between sighted and blind individuals.

The argument can be made that sighted and blind individuals can be expected to perform similarly given that i) purely haptic perception was being compared ii) the tasks used did not require mental reorganisation or were particularly visual imagery intensive (Gentaz and Hatwell, 1998) iii) involve tasks/stimuli that are much less familiar to blind individuals than their sighted counterparts (Juurmaa, 1967; Juurmaa 1973) iv) or provided scope for differences to occur between the two groups in terms of the use of different EPs (e.g. Hatwell, 1960; Davidson, 1972). Certainly, sighted and blind individuals were equally subject to the constraints of touch in VR imposed by the PHANTOM™ device, meaning that there was little scope for differences associated with EPs to arise between the two groups. Examination of the EPs used by participants in judging the size of the real 3-D objects indicated that both groups of participants would, by choice, have used an EP other than contour following. Therefore it is unlikely that either group was particularly accustomed to haptic perception under conditions analogous to haptic interaction with the virtual objects via the PHANTOM™. Informal conversations with the participants indicated that this was indeed the case.

Certainly, there is also some evidence in this thesis that consistent perception of a virtual object attribute between sighted and blind individuals was accompanied by consistent use of exploratory variables

between the two groups. Experiment two indicated that the amount of contact force sighted and blind participants chose to apply to the virtual textures with the PHANTOM™ device was statistically indistinguishable. The reported research also indicated that the consequences of the imposition of exploratory variables had a consistent effect on the perception of virtual object attributes between sighted and blind individuals. The effect of the imposition of contact force on perceived roughness was consistent between sighted and blind individuals, as was the effect of active vs passive movements on perceived extent.

There is some evidence that haptic perception between blind and sighted individuals is consistent across different 3-D force feedback devices. The lack of any significant main effects of visual status on the perceived roughness of the virtual textures and perceived size and angular extent of virtual 3-D objects with the PHANTOM™ device is consistent with the work of Colwell et al (1998) with the IE3000 device. This is most likely due to the fundamental similarity between the tasks used between the two sets of experiments and the characteristics of haptic perception between the two devices. It is not clear at this stage whether haptic perception in VR will remain quite so broadly consistent with haptic devices that afford greater scope for the use of different EPs at arriving at judgments of virtual attributes, i.e. devices that provide more than one point of contact between the user and the virtual environment.

It is also currently not clear whether differences between the two groups will be obtained when visual information is made available to sighted individuals. This will most likely be determined by the extent to which the impoverished nature of haptic perception via a force feedback device, such as the PHANTOM™, affects how heavily haptic information about a particular attribute will be weighted relative to visual information.

## 5.3 Implications of findings for future research

This section considers ideas for future research suggested by the empirical work reported in this thesis. It does this with respect to the issues raised in the sections 1.10.1 through 1.10.8 of the introductory chapter.

### 5.3.1 Perception of object attributes in VR

- Roughness perception.

The magnitude estimation methodology used in experiments one and two could be used to determine whether the negative exponent relating groove width to perceived roughness in VR is due to the sinusoidal waveform used in HVR research, or can be accounted for by an extension of Klatzky and Lederman's model of roughness perception in the real world via a probe. Given the problems with simulating rectangular waveform textures in VR, or manufacturing sinusoidal waveforms in the real world, the best approach would seem to be to replicate the methodology used in experiments one and two using the type of quasi sandpaper stimuli used by Lederman and Klatzky (1999). This type of textured surface can be presented in both the real world and HVR. Should perceived roughness in HVR still decrease with increasing inter-element spacing, the argument that perceived roughness in VR can be accounted for by the model of roughness perception via a probe in the real world would be supported.

It should be noted that previous research in both virtual reality and the real world was not providing an entirely comprehensive picture of roughness perception, since previous real world based research had dealt with only the impact of variables on magnitude estimates of perceived roughness (e.g. Lederman and Taylor, 1972; Lederman, 1974; Lederman, 1981). Virtual based research, on the other hand, had dealt with only the exponents yielded by experimentation (e.g. Colwell et al,

1998; Wall and Harwin, 2000). Experiments 1 and 2 examined the impact of experimental variables on both exponent and magnitude estimate data. This led to the significant novel finding that the two don't always correspond e.g. the exploratory variable of contact force was found to exert a significant impact on the participants' perception of the roughness of the respective virtual textures, but not on the participants' exponents relating groove width to perceived roughness. Future models of roughness perception should incorporate both magnitude estimation data per se and exponent data derived from those magnitude estimates.

- The perception of 3-D size and angular extent.

The Tardis effect is a reliable effect in HVR and has also been shown to occur in physical reality when exploration is constrained to a single point of interaction. This effect warrants further investigation. If, as suggested in chapter 3, the Tardis effect can be attributed to the size of the empty virtual environment surrounding the 3-D objects presented in the external exploration mode, one would expect the effect to disappear if the participants could not stray into this empty space. This could be achieved in HVR by conducting an experiment, similar to experiment three, in which the participants' exploration of the virtual objects presented in the external exploration mode is constrained to the surface of the virtual objects at all times.

The internal objects used were simple in their geometry. They did not, for example, feature any intruding internal features. An internal object comprising such features might present a similar problem of maintaining contact with the contours that define the object as its external counterpart. If this problem does underlie the Tardis effect, then one would anticipate the nature of the effect might be subject to the geometry of the virtual object being used. For example, external objects comprising concave features would be easier to examine and maintain contact with in the external mode of presentation than in the internal

mode of presentation. Future experimentation into the Tardis effect should utilise stimuli featuring both concave and convex features.

Any replications of experiment three should consider examining the participants' execution of the EP of contour following in arriving at their estimates of size and angular extent, in detail. This was not initially thought to be necessary, since it was not anticipated that differences *within* a particular EP would occur. However, it transpired that even when limited to the EP of contour following, participants exhibited some variation in the way in which they executed this EP. This may be the reason for the significant effect of virtual object type found in experiment two, as described in discussion for experiment 3.

An extension of the methodology used in experiments 2 and 4 would be useful in determining whether the perception of angular extent in HVR is subject to the oblique effect, frequently demonstrated in the real world (e.g Lachelt and Verenka, 1980; Gentaz and Hatwell, 1995; Gentaz and Hatwell, 1998; Kappers and Koenderink, 1999; and Kappers, 1999). This experiment could take the approach used by Gentaz and Hatwell (1995) and present angular extents in the vertical and horizontal planes, which would determine if gravitational cues might account for any observed effect.

### **5.3.2 The effect of the endpoint used with the PHANTOM™ device**

Given the numerous possibilities identified in section 5.2.1 for the basis of an effect of the endpoint used with the PHANTOM™ device, future research will need to closely monitor participants' use of the device's endpoints. It would be possible to program a facility that monitors variables such as the path, contact force, velocity and acceleration of a user's movements in examining a virtual object or attribute. This might provide some insight should the basis for the effect of endpoint on the perception of an object attribute be related to variations in such

exploratory variables. Further research could also examine the precise way in which participants interact with the PHANTOM's endpoints, paying particular attention to variations in the configuration and position of participants' grip on the stylus endpoint. This would uncover whether there were any consistent variations in parameters associated with participants' interaction with the stylus and thimble underlying any significant effects of endpoint. Finally, experimenters should consider videotaping a participant's use of the endpoints lest the characteristics of the endpoint itself underlie an effect. Administering a questionnaire on the participants' use of the endpoints may also be wise, lest participants' use of the endpoint is not immediately evident from examining the video footage. Given that the basis for the effect of endpoint on the perception of roughness and angular extent in VR is not yet evident, it would be interesting to adopt the above recommendations in the experimental designs used in experiments 1 and 3.

### **5.3.3 Perception in haptic VR across different devices**

As ever more sophisticated HVR devices become available, it will be increasingly important to monitor which effects are consistent across devices. The present work on the PHANTOM™, together with earlier work on the IE3000 will provide a valuable baseline for any future research.

Perhaps the experiment most obviously suggested by the reported research would be one which compared the perception of the object attributes studied here between the PHANTOM™ device and a device featuring multiple points of contact with virtual environment. This particular feature has been singled out since the restricted nature of single point interaction would seem to be the characteristic of VR that was responsible for the differences observed between VR and the real world in the perception of the geometric attributes of 3-D object size and angular extent. It is also responsible for the problems associated with locating and maintaining contact with virtual objects, since the single

point of interaction also seems to be conducive with the Tardis effect and the RTE. Such a comparison would provide a means of assessing the explanations for these illusions posited in this thesis.

However, an experiment similar to that of experiment one featuring a within subjects device comparison would be useful in determining whether the significant effect of object type found with the PHANTOM™, but not with the IE3000 in Colwell (1998), might be due to the predominance of different methods of judging the size of virtual spheres between different populations of participants, as opposed to different devices.

Finally, Colwell (2000) pointed to the fact that participants were divided as to whether they imagined the virtual environment to be located at the end of the probe nearest to their hand on at the end of the probe located in the IE3000 device. It would be interesting to determine whether this difference exerts a significant impact on the perception of virtual object attributes. Unfortunately, the author cannot say at this time whether Colwell's records of this aspect of perception with the IE3000 are sufficient to provide the basis for a statistical analysis, or whether a new study would need to be conducted. This study would be more than just of intellectual interest given that the IE3000 is currently being used in medical training applications (see chapter one, section 1.1.1)

#### **5.3.4 Haptic perception in virtual and physical reality**

The reported work has a number of implications for real world based research and future comparisons of haptic perception in VR to the real world. The effect of endpoint on roughness perception and angular extent has implications for knowledge about haptic perception via a probe in the real world. For example, studies of roughness perception with a probe in the real world have, without exception, used a rigid stylus probe, the assumption presumably being that the relationship between the contact point and the dimensions of the textured surface is the most

important determinant of perceived roughness. However, given the impact of endpoint on perceived roughness in VR, parameters other than just the contact diameter of the probe may also impact upon roughness perception in the real world. The same point can be made in respect of the attribute of the angular extent of 3-D objects, where a significant effect of endpoint was also discovered in VR. The first step in resolving this issue would be to compare the perception of the roughness of real textures with a stylus and thimble featuring equivalent contact point dimensions. Should an effect occur, it will then be necessary to determine the mechanism for the effect in much the same way as has been suggested for determining the mechanism for the effect of endpoint in VR.

Research on the implications of the use of different EPs for judging object attributes in reality is lacking. Further studies on variations in the execution of a particular EP are also warranted on the basis of the reported work. The former is relatively easy to investigate: one simply asks participants to make judgments of a particular attribute under various EPs. The latter is slightly harder to investigate since one must first conduct preliminary studies, like experiments 3 and 4, to delineate what variations in the execution of an EP might occur. The implications of these variations for the perception of object attributes can then be assessed in the same manner as the implications of the use of different EPs.

As haptic devices incorporating more than one point of contact with a virtual environment become available it will also be possible to compare the relative efficacy of the use of different EPs for various object attributes between VR and the real world.

There are also several other attributes where differences between HVR and the real world could be important. For example, the perception of the curvature of objects is one attribute that merits further investigation for a number of reasons. Studies of this attribute are relatively scarce in the



real world and VR; its study could also be informative with respect to explaining the RTE and providing the basis for further comparisons between sighted and blind individuals.

### **5.3.5 The isotropy of perceived extent in VR with the PHANTOM™**

Comparing HVR and physical reality has the potential to provide new insights into the RTE, and thus the general mechanisms of the perception of extent in space. If, as suggested in chapter four, the RTE is functionally related to the curvature illusion, one would expect it to disappear under conditions in which the curvature illusion is not evident. If participants were asked to explore real counterparts to the virtual lines used in experiments five and six using the EP of enclosure, one would anticipate that the RTE would no longer be evident.

Although experiments five and six indicated that the velocity of movement is not the mechanism for the RTE, this parameter of exploration warrants further attention. Do participants vary this exploratory parameter when exploring extent? Furthermore, what are the implications of participant mediated and device mediated variations in this parameter on perceived extent.

A replication of the methodology used in experiment six also seems in order to determine whether the incidence of the HVI was anomalous.

### **5.3.6 The impact of exploration variables on haptic perception in VR with the PHANTOM™**

The PHANTOM™ device provides a good means for assessing the role of exploratory variables as, with appropriate software, participants' use of the device can be closely monitored. As has been previously mentioned, it would be interesting to examine the effect of the velocity of exploratory movements on perceived roughness and perceived extent.

The findings of this thesis would provide a baseline of unconstrained velocities to compare with more extensive variations in constrained and unconstrained exploration.

It would also be interesting to expand the data on the impact of active vs passive movement on stimuli other than perceived extent. Particularly interesting topics for study would be the implications of active and passive movement for the perception of roughness, angular extent and the identification of 2-D and 3-D virtual objects.

### **5.3.7 The impact of Visual status on haptic perception in VR with the PHANTOM™**

It would be informative to extend the methodology of experiment four to incorporate a blind sample of participants in each of the real world exploration conditions used. Perceived 3-D object size and angular extent was found to be very consistent between sighted individuals under the exploration conditions that sought to examine the impact of some of the characteristics that distinguish the exploration of 3-D objects with the PHANTOM™ in HVR from the real world. At this time, it is not clear whether this would also be the case for blind individuals.

The blind participant samples used in this thesis included congenital, early and late blind participants. It would be interesting to replicate the reported studies with stratified samples of congenital, early and late blind participants. Unfortunately such stratified samples of blind participants are very hard to obtain. Even if such a sample can be obtained, blind participants can vary considerably in terms of more than just visual experience (Warren, 1978).

Both real world and VR based research is very lacking on the interaction between the variables of visual status and important parameters of haptic perception, such as exploration determinants of object attributes,

EPs and active and passive touch. There is also currently very little work on the interaction between touch and vision in VR. Research is required to determine the relative efficacy of touch vs vision in judging various virtual object attributes such as texture, size and angular extent. Real world based literature is available for reference on this matter (Lederman and Abbott, 1981; Jones and O'Neil, 1985; Heller, 1989; Lederman, Thorne and Jones, 1986; Teghtsoonian and Teghtsoonian, 1970; Appelle, Graveter and Davidson, 1980; Lakatos and Marks, 1998) Research is also required on the weight participants ascribe to touch information when vision is available for a wide range of object attributes. Such work has also been conducted in the real world (e.g. Klatzky, Lederman and Reed, 1987 Lederman, Summers and Klatzky, 1996; Klatzky, Lederman and Matula, 1993).

## **5.4 Implications of findings for future VR devices and applications**

This section considers some broad implications of the reported experimentation for future haptic devices, applications involving haptic information and software for the creation of haptic stimuli.

### **5.4.1 Device implications**

The question that arises from the existence of different haptic devices is delineating which aspects a device are of perceptual consequence i.e. which ones will facilitate or obstruct haptic perception in VR. This issue has implications for the design of future devices. Answering this question will not prove to be an easy task as there is, as yet, little agreement between researchers about how to measure the performance of a haptic device (Hayward and Astley, 1996) However, the reported research can make a few general contributions to this issue.

First and most generally, comparisons between participants' experience of the IE3000 and PHANTOM™ devices revealed that the physical configuration of the device has a role to play in suggesting to the user where the virtual environment lies. The location of the IE3000's probe, which articulated in the mechanism of the device not accessible to the participants, created ambiguity as to whether participants thought they were remotely probing an environment within the device's mechanism, or probing a more proximal environment external to the devices mechanism. There was no such ambiguity with the PHANTOM™ device. This indicates that the basic configuration of the PHANTOM™ device is a sound basis for the development of future 3-D force feedback devices.

It has also become clear that the endpoint used with a 3-D force feedback device can exert a significant influence on haptic perception in VR. At this stage it is possible to say that effects of endpoint are stimulus dependent and are not always consistent. From a research perspective it would be interesting for the manufacturers of future devices to follow in the PHANTOM's footsteps and provide a number of endpoints for evaluation, so that more work can be undertaken to uncover the basis for the effect of different endpoints and determining which endpoint (if any) is optimal for the perception of a given attribute.

The general characteristics of interaction with virtual objects via a haptic device are of paramount importance in determining the consistency of perception between two devices. With both the IE3000 device and the PHANTOM, participants are restricted to a single point of interaction with virtual objects and deprived of any direct cutaneous information about the virtual objects; perception of the virtual stimuli was broadly consistent between the two device.

At this stage, it is too early to comment on the role of differences in mechanical performance measures between devices. However the non-significant differences between the perception of virtual objects with the PHANTOM and real counterparts to the virtual objects with the de-

activated PHANTOM™ and a stylus, tentatively suggests that perception may be quite robust over variables such as the mass of the endpoint and inertia associated with a devices movement etc. The important point in this regard is that such mechanical variables do not interfere with the stimulus. For example, Srinivassan and Basdogan (1997) point out that participants should not be able to feel unintended vibrations due to problems with “Quantisation of position or low servo rate” (p395). It is undesirable to have participants confusing the haptic cues associated with the mechanical aspects of a device with the stimuli. The challenge for researchers is to determine where such overlaps between the characteristics of the device and the intended stimuli are likely to occur and the lowest level of performance acceptable to prevent such an overlap occurring. If this seems a bit vague, it should be noted that all participants reported being comfortable using the PHANTOM™ device, with both of its endpoints. Given the limitations of the single point of contact with the virtual environment, none complained that the device's mechanism was either obtrusive or restricted or the movements they wished to perform. Participants also commented that the device created very unambiguous and clear virtual stimuli that were not obfuscated by the mechanics of the device itself. It would, therefore, seem that the PHANTOM™ device provides a good platform for experimentation into such device variables.

The reported experimentation suggests that the single point of interaction with the virtual objects is the characteristic of the PHANTOM™ device that is of particular perceptual significance. This could be overcome by a device, similar in design to the PHANTOM™, but featuring the capacity for the user to use multiple points of contact with the virtual environment. Happily, such a device exists: Sensable technologies, under license to the Immersion Corporation, have recently developed the CyberForce device (depicted in figure 5.3). This device is used with the CyberGrasp device, described in section 1.9.2, to provide force feedback to both the hand and the arm. This is achieved by connecting the CyberGrasp device to the CyberForce's linkage arm,

which is attached to a fixed base. Therefore, this device allows the user's hand to apply unbalanced forces, i.e. probe virtual objects, in much the same way as users of a ground based device such as the PHANTOM™ can, in addition to being able to interact with the virtual objects with their whole hand.



**Figure 5.3 Illustration of the CyberForce device simulating grasping and manipulating a steering wheel.<sup>18</sup>**

#### **5.4.2 Application implications**

It should be noted that it is not the intention of this section to go into detail about the possible implications of the reported experimentation for each of the application domains identified in section 1.1.1, but rather to make a few general observations about the implications of the literature and reported findings for application domains generally.

Single point interaction makes the haptic location, navigation and identification of virtual objects challenging and time consuming. This has been noted in Colwell (2000); Sjostrom (2000) and this research.

Participants often spend some time attempting to find an object in a virtual environment, once found, they often initially experience trouble in maintaining contact with the object and have trouble in identifying shapes more complex than simple geometrical figures. This stands in contrast to real world based research, which indicates that the identification of 3-D objects via touch alone is fast and accurate (e.g. Klatzky, Lederman and Metzger, 1985). However, Klatzky, Loomis, Lederman, Wake and Fujita, (1993) found that participants' capacity to identify 3-D objects significantly diminished when access to an objects 3-D structure was restricting by constraining participants to the use of one finger in exploring the objects.

Single point interaction would also seem to be conducive with a number of haptic illusions reported in this thesis: the Tardis effect and the RTE. It seems likely that the Tardis effect would not be evident if participants were constrained to the geometry of the virtual objects. The RTE is more difficult to negate without introducing more than one point of interaction with the virtual objects, but it could be accounted for by appropriate scaling of stimuli.

There are steps that developers of applications for haptic VR can take to minimize the problems associated with single point interaction. For example, haptic cues can be used to provide indications as to the location of virtual objects, suggestions for such cues are provided by Sjostrom (2000). Object geometry can also be manipulated such that individuals find it much easier to use the single point of interaction to examine the object's contours. For example, the problems of losing contact with a virtual object and getting lost in virtual space do not occur with objects presented in the internal mode. Finally, passive guidance can be used to guide participants to a virtual object and around the contour of that object to in order to familiarise users with its location and spatial layout. Indeed, there is evidence that passive guidance around

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<sup>18</sup> Picture taken from [www.immersion.com](http://www.immersion.com)

the contours of a stimulus facilitates individuals' ability to identify that stimulus (Richardson et al 2000). However, it should be noted that Richardson used 2-D as opposed to 3-D stimuli.

The comparisons between the results obtained in this work and that of Colwell (1998) with the IE3000 device indicate that it is feasible for designers to create applications involving the attributes of roughness size and angular extent that support a number of force-feedback devices. Indeed, it would be fair to say that force feedback devices featuring a single point interaction will present the same difficulties associated with locating, maintaining contact with and identifying virtual objects. However, it would be wise for such cross platform support to continue to be informed by comparisons such as those undertaken in this thesis. Research is still in its infancy and the interactions between the specifications of a device and the perception of a variety of attributes are not yet delineated.

One feature of a device that has shown itself to influence of the haptic perception of some attributes in VR is the endpoint used with the device. Ideally, one would like to be in a position whereby one can identify the mechanism for the effect of endpoint on perceived roughness and angular extent. This might also permit an educated guess as to what other attributes might be affected by the endpoint used. However, although it is possible to identify which attributes are affected by the endpoint used. It is not, as yet, possible to determine and control the mechanism underlying the effect and thus the effect itself. It may, therefore, be wise for users of virtual applications involving a device with more than one endpoint to be restricted to the use of one endpoint only. Once research has uncovered the basis for the effect of endpoint with various object attributes, recommendations can be made as to which endpoint is optimal for the perception of which attribute.

There are a couple of obvious points that can be made in respect of the implementation of texture in any prospective applications of haptic VR.



Firstly, designers of applications in haptic VR should consider using sinusoidal textures until research has examined the psychophysical function yielded by other virtual texture waveforms. At present, it is not clear whether perceived roughness in VR per se is comparable between different texture waveforms, or whether the data obtained in this thesis, Colwell et al (1998) and Wall and Harwin (2000) is an artefact of sinusoidal textures.

Perceived roughness should be manipulated by groove width alone until the relationship between this variable and concomitant variations in amplitude are better understood. Designers should also consider implementing practice trails to establish whether a particular user's perception of perceived roughness in VR is characterized by a positive or negative exponent. Since individual exponents did vary, it might be wise to implement a feature that allows the user to increase the increments in inter-element spacing to make discriminating between the roughness of different textures easier.

There are also a couple of points that can be made in respect of the implementation of 3-D object size and angular extent in any prospective applications of haptic VR. Designers will need to take account of the effect of mode of object presentation on perceived size, possibly by calibrating object size to compensate for differences in users' perception of internal and external virtual objects. Alternatively, as has already been suggested, it may be possible eliminate the Tardis effect by constraining users movements to the surface of objects presented in the external presentation mode. Designers will also need to take account of the effect of object type on perceived size. However, as with the Tardis effect, until the mechanism of this effect has been conclusively determined, it is not possible to say with absolute confidence how this might be achieved. It may also be beneficial to constrain users movements to the surface of objects presented in the external presentation mode, as this would prevent the participants using different strategies for measuring the

virtual objects. It may be necessary to scale the size of virtual objects to take account of the RTE.

This thesis has indicated that just because an exploratory variable can exert an effect on the perception of an attribute, does not mean that it needs to be controlled for in practice. Designers need not control for the exploratory variable of contact force when utilising virtual textures. The lack of an effect of active vs. passive movement on perceived size may be a very helpful finding, since the provision of passive guidance in the exploration of virtual objects may prove very beneficial to sighted and blind individuals. However, this may have proved more problematical if active and passive movement led to significantly different perception.

The reported experimentation indicated that sighted and blind individuals perceived the attributes of roughness, 3-D object size and angular extent in much the same way and, as such, it would not be necessary to modify the stimuli in a virtual environment to accommodate both groups of users. However, in the absence of visual stimulus it will be necessary to implement some aids to navigation for both groups of individuals for the reasons identified in the device section.

### **5.4.3 Software implications**

One of the challenges in working in haptic VR is the actual implementation of ideas. Currently, the creation of a haptic environment with the PHANTOM™ device would be highly problematical and time consuming for anyone not versed in computer programming. It is fair to say that developers of haptic devices, such as Immersion and Sensable have gone to some lengths to produce “toolkit” software with their respective “TouchSense” and “GHOST” software. These pieces of software are intended to distance the developer from the very involved mathematics used to render a haptic environment and instead offer a series of objects and effects, which the developer can then configure in

any way they wish to create the desired virtual environment. Unfortunately, this toolkit software does require familiarity with C++, which makes it rather inaccessible to those with no formal training in computer programming.

Logitech offer a much more user-friendly way of manipulating the contents of a virtual environment with their 'I Feel Studio' which uses a graphical interface that allows the user to select and manipulate a variety of the effects that can be produced with the 'Wingman' force feedback mouse. Sensable also offer the 'Freeform' software, which allows a user to create and examine virtual objects from virtual clay, however this is designed as a creative tool and does not provide the degree of control over the force feedback process that the Ghost software affords to those with programming expertise. What is needed is an application that combines a user-friendly interface that enables haptic effects to be specified without recourse to program code, combined with the extensive control afforded by the GHOST toolkit.

In addition to the development of software that makes the manipulation of haptic environments easier for those not versed in computer programming, thought should also be given to ensuring that such software is accessible to blind individuals. Some lessons can be learned here from attempts to make other editing software accessible to blind individuals, for example the work of O'Modhrain (2002) who is examining ways of using haptic feedback to make sound editing software more accessible.

## 5.5 Summary

- The perception of the object attributes of roughness, size and angular extent with the PHANTOM™

The reported research constituted the first attempt to provide a broad characterization of the haptic perception of the size and angular extent of 3-D objects with the PHANTOM™ device.

The perceived roughness of virtual sinusoidal textures predominantly decreased with increases in the width of the grooves (inter-element spacing) of which the virtual textures were comprised. For the first time, this was demonstrated to be the case irrespective of the endpoint used with the PHANTOM™, or the visual status (sighted or blind) of the user. It is clear that the Taylor and Lederman (1975) model of roughness perception in the real world is not appropriate for VR. However, a real world based model of roughness perception with a probe might be an appropriate account of the mechanism underpinning roughness perception in VR. Whether this is the case depends upon whether the negative exponent relating groove width is specific to sinusoidal waveform textures.

Linear increases in the size and angular extent of virtual 3-D objects were accompanied by corresponding increases in perceived size and angular extent. The sizes of cubes and spheres presented in an external mode of presentation were reliably underestimated. A number of influences on the perception of 3-D object size with the PHANTOM™ were demonstrated for the first time. Firstly, virtual objects presented in the internal mode of exploration were judged as reliably larger than their counterparts presented in the external presentation mode (the Tardis effect). A novel explanation that posits that the effect can be attributed to the volume of unfilled virtual space influencing a users perception of the size of the virtual objects presented in the external mode has been

presented for further investigation. Secondly, virtual cubes were judged to be larger than equivalent sized virtual spheres, indicating that the perception of 3-D object size is not uniform across different virtual object types. It was speculated that the difficulty in estimating the diameter of the virtual spheres under conditions of single point interaction might have resulted in differences in the execution of the EP of contour following, which might account for this effect.

- The impact of the endpoint used with the PHANTOM™ device

Despite the fundamental similarities between the characteristics of interaction with virtual objects between the stylus and thimble endpoints, a series of novel comparisons between the two endpoints revealed that they can yield differences in the perception of a virtual object attribute. The impact of the endpoint is contingent upon the object attribute being judged and the mechanism for the effect of endpoint may be subtler than just differences in an exploratory variable. Furthermore, a number of possible ways of accounting for the effect of endpoint were outlined and it is speculated that it may well be the case that the basis for the effect of endpoint may vary according to the specific attribute being examined.

- The consistency of the perception of virtual object attributes between two 3-D force feedback devices.

Unprecedented comparisons between the PHANTOM™ and the IE3000 revealed that haptic perception is broadly comparable between these devices. It is argued that this was due to the fundamentally similar nature of the interaction with virtual objects between the two devices. As yet, variations in the performance measures that characterize a device are not clear. However, it is argued that the critical factor is likely to be the extent to which such variables confound the haptic cues that indicate a particular object attribute.

- Comparisons between haptic perception in HVR and the real world

The similarity of haptic perception between VR and the real world was shown to be dependant upon the attribute in question. Perceived roughness in VR differed significantly from perceived roughness via naturalistic haptic perception in the real world, owing to the predominance of a negative exponent relating groove width to perceived roughness. However, this relationship could potentially be accounted for by a real world based model of perceived roughness via a intermediary probe.

Novel comparisons between virtual and real world perception of 3-D object size and angular extent revealed that the perception of these attributes could be distinguished between VR and naturalistic perception in a number of respects.

The perception of real and virtual 3-D object size was broadly comparable. However, the impact of the variables of object type and mode of presentation on the perception of object size was found to differ between VR and the real world. In VR, virtual cubes were judged as being larger than equivalently sized virtual spheres. This did not occur in the real world, irrespective of whether participants' exploration of the real objects was constrained to a single point of interaction or was unconstrained. In VR, the virtual objects presented in the internal mode of presentation were judged as being larger than their counterparts in the external mode of presentation. This was also evident in reality, but only when the participants were restricted to a single point of interaction with the real objects. The magnitude of the Tardis effect in the real world was also smaller than the magnitude of the effect in VR.

The perception of real and virtual 3-D object angular extent was found to be comparable between VR and the real world when the participants' exploration of the real objects was constrained to a single point of interaction. However, when participants' exploration of the real objects

was unconstrained, they returned higher angle of shear estimates for the real sheared cubes than for the virtual sheared cubes.

- The isotropy of manipulatory space with the PHANTOM™

The perception of linear extent with the PHANTOM™ device was, for the first time, shown to be anisotropic. Specifically, extents explored via radial movements were overestimated relative to equivalent extents examined via tangential motions: the Radial Tangential effect (RTE). Furthermore, the results question the previously held, but untested, explanation for the RTE and tentatively suggest a new explanation for future assessment. Under conditions involving the bi-directional exploration of extent, vertical extents were also perceived as being larger than equivalent sized horizontal extents (the Horizontal Vertical illusion). However, this effect does not appear to be reliable, as it was not manifest in both experiments 5 and 6.

- The impact of exploration variables on haptic perception with the PHANTOM™.

The impact of two exploratory variables on haptic perception with the PHANTOM™ device was addressed for the first time: the effect of contact force on perceived roughness and active vs passive movement on perceived extent. It transpired that an exploratory variable could be shown to exert an effect in VR even though the force feedback process precludes the mechanism unpinning the effect of that variable in the real world (e.g. the significant effect of contact force on the perceived roughness of virtual textures). It was also evident from the study of this variable that the fact that an exploratory variable can be shown to exert an effect on haptic perception in VR by experimental manipulation does not mean that it will be instrumental in a user's judgment of an attribute in practice.

The use of active vs. passive movement did not have a significant effect on perceived extent with the PHANTOM™ device. This is a potentially helpful finding, since the use of passive movement could be useful in overcoming some of the navigational problems associated with single point interaction.

- The impact of visual status on haptic perception with the PHANTOM™

A broad range of unprecedented comparisons between sighted and blind users of the PHANTOM™ device were reported in this thesis. These comparisons encompassed the perception of virtual object attributes, device variables and exploratory variables. Overall, it is certainly fair to say that the impact of visual status in HVR was negligible. It should, however, be noted that the mean age of the blind samples of participants used in the reported experimentation was somewhat greater than the sighted samples. The implications of this for the reported results are not clear at this point.

In summary, the reported work has made some significant and novel contributions to a number of issues important to developing an understanding of haptic perception in VR in both sighted and blind individuals. It has provided a characterisation of the perception of the object attributes of roughness, size and angular extent with the PHANTOM™ device with both its endpoints. It has also investigated the isotropy of perception in a 3-D virtual environment and parameters of participants' exploration of virtual stimuli with the PHANTOM™. Comparisons were also undertaken between haptic perception with the PHANTOM™ and another 3-D, single point of interaction device and between haptic perception in VR with the PHANTOM™ and the real world.

This field of research remains in its infancy. It is hoped that this thesis has gone some way to identifying and contributing to some of the



important issues of haptic perception in VR and provides the impetus for further research.

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## **Appendix i) Raw data for the reported experimentation**

Any researchers interested in comparing the results from the reported experimentation with their own data should contact the author, Paul Penn (paul\_penn\_03@yahoo.com) or Dr. Diana Kornbrot (d.e.kornbrot@herts.ac.uk). A CD containing the raw data, stored as a Microsoft Excel file, for experiments one through six is available for perusal.

The relevant notation for the interpretation of the data is included on the Excel file.