Playful Haptic Environment for Engaging Visually Impaired Learners with Geometric Shapes

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‘Computing today is about

What computers can do;

The new Computing will be about

What people can do’

Ben Shneiderman

Στους αγαπημένους μου φίλους που βλέπουν με τα μάτια της ψυχής:

"...η δικτατορία της εικόνας πρέπει να ηττηθεί..."

To my dearest friends who see with the eyes of their heart:

"...the dictatorship of the image must be defeated..."

To my parents & brothers

Abstract

This thesis asserts that modern developments in technology have not been used as extensively as they could to aid blind people in their learning objectives. The same could also be said of many aspects of other areas of their lives. In particular in many countries blind students are discouraged from learning mathematics because of the intrinsically visual nature of many of the topics and particularly geometry. For many young people mathematics is also not a subject that is easily or willingly tackled. The research presented here has thus sort to answer whether a playful haptic environment could be developed which would be attractive to blind users to learn and interact with geometric concepts. In the study a software tool using a haptic interface was developed with certain playful characteristics. The environment developed sought to give the blind users practice in interacting with three dimensional geometric shapes and the investigation of the size of these shapes and their cross-section. The playful elements were enhanced by adding elements of competition such as scores and time limits which promote competition between the users. The tests have shown that blind users can easily use the system to learn about three dimensional shapes and that practice increases their confidence in recognising shape and size of these objects.

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Glossary

3D = Three Dimensional

VE = Virtual Environment

VR = Virtual Reality

VLE = Virtual Learning Environment

M&O = Mobility and Orientation

GUI = Graphical User Interface

PC = Personal Computer

TTT = Talking Tactile Tablets

WAI = Web Accessibility Initiative

SST = Smart Screen Technology

CCTV = Closed Circuit Television

HCI = Human Computer Interaction

DOF = Degrees of Freedom

TTS = Text-To-Speech

CAD = Computer Aided Design

CAS = Computer Assisted Design

VO = Virtual Objects

HAVE = Haptic Audio Virtual Environment

HAID = Haptic Audio Interaction Design

CAI = Computer Assisted Instruction

HDAL= Haptic Device Abstraction Language

VRDTS = Virtual Reality Dental Training System

VNP = VoxelNotePad

TDI = Tactile Device Interface

ACM = Association for Computing Machinery

UCD = User-Centred Design

SDLC = System Development Life Cycle

NVDA = Non-Visual Desktop Access

MSVC = Microsoft Visual Studio

OOP = Object Oriented Programming

CHAPTER 1

Introduction

This thesis focuses on the needs of blind people in trying to learn concepts that are thought to require significant understanding of geometry. Fundamental amongst the geometric concepts are those of the shape of solid objects and their inter-relationship. These concepts can be considered foundational for other geometric concepts. The author's original motivation for undertaking the research reported in this thesis was experience of a blind colleague while the author was a student at school. It was clear that the author's colleague wanted to learn mathematics but the school was reluctant to support her needs because they believed that such study would not be easily undertaken as the student could not see and in their opinion understanding geometry would need vision. The colleague's parents paid for the child to receive private tutoring in mathematics and in the end she graduated with a degree in mathematics.

From the author's perspective the development of modern technology should be useful in allowing blind students to grasp fundamental geometric concepts of shape, size and displacement of objects. Another motivation – also from the author's perspective – was the need to add motivation for learning geometry itself. Computer based virtual environments and the development of haptic interfaces seem to offer a tool for making the right environment for blind students to be able to engage with geometric shapes and learn about the properties of those shapes. A playful environment (such as in a computer game) could potentially allow for better engagement with the process for those who were less motivated to learn about geometry.

The dominant human sense is believed to be vision. The visual system in humans allows individuals to incorporate information from the environment and interact with it. The earliest features that the visual system extracts from objects are spatial, in the form of oriented edges (Klatzky & Lederman, 2003) (Klatzky et al., 1985). It places the object (this can be a person) in space, establishes the relative distances of other objects from the principal reference (that is the body of the person) and makes a number of measurement types like size. Visually impaired people rely heavily on their sense of touch to orient an object in space comparing everything to the principal reference of their body (Dagman et al., 2010) & (Buchel, 1998). Many people today have visual impairment at some point in their lives, ranging from minor problems, like the inability to read from short/long distance to more serious problems caused by accidents or diseases. Minor problems occur for most people with age and can be treated with the use of contact lenses and glasses or with surgery. The major problems though occur when one or more parts of the eye or the corresponding brain part that processes images become diseased or damaged. Then severe or total loss of vision may happen. In such cases vision cannot be fully restored because the damage is not treatable at all or it can only be partially restored by undertaking medical treatments like surgery and/or corrective lenses and glasses.

Definition of degrees of visual impairment

In their document "VISUAL STANDARDS ASPECTS and RANGES of VISION LOSS with Emphasis on Population Surveys", Colenbrande (2003) recommends the following terminology:

- "Blindness – to be used only for total vision loss and for conditions where individuals have to rely predominantly on vision substitution skills.
- Low Vision – to be used for lesser degrees of vision loss, where individuals can be helped significantly by vision enhancement aids and devices.

- Visual Impairment – to be used when the condition of vision loss is characterized by a loss of visual functions (such as visual acuity, visual field, etc.) at the organ level. Many of these functions can be measured quantitatively.
- Functional Vision – to be used to describe a person's ability to use vision in Activities of Daily Living (ADL). Presently, many of these activities can be described only qualitatively.
- Vision Loss – to be used as a general term, including both total loss (Blindness) and partial loss (Low Vision), characterized either on the basis of visual impairment or by a loss of functional vision."

Within these definitions the participants of the experiments reported in the current work would all be described as blind rather than having low vision. Many of the participants have experienced progressive degeneration of their visual acuity often in the recent past and some have had no vision since birth.

Many visually impaired people use Braille as a medium for reading and writing and/or more recent innovations of audio feedback systems. Sometimes they may use some form of force feedback haptic devices. "Haptic" describes the sense of touch. The haptic system is not very good at extracting information about the spatial layout of edges although today's research results are not clear as to what extent a visual impairment negatively influences the spatial ability (D'Angiulli & Maggi, 2003).

Human Computer Interaction and Virtual Environments

Since the invention of the Braille system that is widely used by many blind users to help them read and write and in combination with the advancement of today's technology, one could have expected a dramatic improvement in the field of human computer interaction for visually impaired people. However, this is a change that is yet to come.

Having in mind the advancement of today's technology and how it can contribute towards the improvement of life, one can ask if this improved lifestyle has included all groups of people – deaf people, blind people etc.

Today's society is becoming more electronically based day by day and people with a visual impairment can be more and more excluded from this e-society. If one considers that the most commonly used interface for providing information to a computer user is the screen display a question arises: *What have technology and research done to promote the inclusive society and equally shared opportunities?*

Unfortunately, when the user is a blind person then automatically the use of screen and visual feedback is completely useless. Therefore, the most widely used interfaces involve the audio channel to provide information and feedback to the blind user. In the recent past force feedback interfaces have allowed *"blind and visually impaired users to access information presented in three-dimensional (3D) virtual reality environments (VE)"* (Petrie et al., 1998). It is anticipated that such environments will form the most accepted and natural way of interchanging information in the near future (Nikolakis et al., 2004).

The greatest potential benefits from VE can be found in applications relating to areas of training, education and exchanging of general ideas and concepts (Sjöström, 1999). The technical compromises and limitations of existing virtual reality (VR) systems are related to the "*visual complexity of a virtual environment and its degree of interactivity*" (Sjöström, 2001).

Nowadays, haptics research groups typically make use of the PHANToM and/or the CyberGrasp and/or CyberGlove data glove or a combination of the three. The first device is considered to be one of the best on the market and the one which is most widely used. PHANToM's hardware design allows a single point of interaction at a time and this is completely different from the way people interact with their surroundings. *"Thus the amount of information that can be transmitted through this haptic channel at a given time is very limited"* (Tzovaras, 2008) and time consuming. However, research has shown that even though it is time consuming, it can actually produce the correct tactile cues that will enable the user to understand and recognise some basic 3D objects. One of the advantages of the PHANToM is that it has the power to provide the sense of touch by applying force feedback to the user's fingers. On the other hand, one of its major disadvantages has to do with the recognition of small objects. One of the major drawbacks of these technologies has to do with their high price, which make them very difficult for potential users to buy for private use. All three devices along with their characteristics, advantages and limitations are explained in detail in section 3.3 Current Haptic Technologies.

Geometry and Visually Impaired Students

If Geometry is generally accepted as the main theory of space then it is obvious why blind students find it the most challenging subject in the school curriculum. Geometry as a school subject is very likely to challenge not only the students with visual impairments but also their sighted peers, as well as the teacher in the approach they will use to teach it.

Blind students in some European schools, e.g. Norway (Klingenberg, 2007) and Cyprus, may get exemptions for geometry classes, since teachers see it as almost impossible to teach geometry to students who are blind, mainly because its content is rich in visual representations that require spatial content and perception. Thus they believe it is more appropriate to give priority to other subjects of the school's curriculum that come readily to students. Yet there is no overwhelming reason why a person of sufficient ability should fail to become a successful mathematician simply because he or she is blind (Jackson, 1968). The approach of not teaching a subject because it is difficult to do violates the norms of *'equally shared opportunities'* and *'the inclusive society'.*

The same question arises again: "How can technology research contribute to the improvement of disabled people's lives?"

Mathematics in general requires thinking and reasoning skills. It lays the foundation for systematic thinking through the numerical and spatial aspects of objects. It mainly relies on visual notations and people with low or no vision are at a serious disadvantage when studying mathematics (Edwards et al., 2006). Mathematics as a subject is very important not only within the school curriculum but also in everyday life where it cultivates thinking and solving a variety of problems. It is a very crucial subject in schools and one that is given a central and significant role in school prospectuses. For this reason students are taught mathematics from the very beginning of school life until the very last grade.

Is this lack or "Achilles' heel" of the system the result of the limited number of educators that have the appropriate knowledge and experience to teach geometry to students with special needs? Is it because technology has failed to provide education with appropriate means for the teaching of blind students efficiently and effectively? Is it the educational system and the people who manage it that have failed to approach the problem with the appropriate sensitivity? Or is it a combination of all three?

Edwards et al, through their study on the Lambda system, argue that *"educators systematically avoid the complexities of the formal mathematical braille codes by using simpler, self-defined encodings"* (Edwards et al., 2006). This opinion supports the view that there are a limited number of teachers who have the appropriate knowledge to demonstrate mathematical concepts to students with visual impairments. Failing to use the standard mathematical notations has an impact on students who wish to proceed with further studies since it limits the level of mathematics they are taught (Edwards et al., 2006).

Aims, Objectives and Literature Questions

Aims

It is hypothesised that a playful haptic virtual environment (VE) will provide an engaging way for blind students of school age to engage with, and learn about geometric shapes. The main aim is to test and explore this hypothesis. Furthermore use of this VE will empower them to practise with basic geometrical objects and their literature in this playful environment.

The method deals with one way of designing and developing a user - worthy playful prototype by involving users in the process and *"by doing so in an arena where the cost for audio-haptics may easier be justified"* (Grohn, 2008).

A method to allow for evaluating the interaction with the VE was the design and development of an interactive haptic virtual reality system that allows visually impaired users to study and interact with a haptic VLE in the form of a game. The system would be used to encourage participants to investigate 3D geometrical shapes by performing object manipulation and furthermore potentially enhance their navigation and scene exploration skills as it would require them to investigate and navigate around the virtual scene. This research will eventually indicate whether these types of game-based learning environments may form a medium for blind participants to test and practise geometrical concepts. If this new technology can be successfully adopted by this specific group of participants, then this will open up new avenues for future designers and developers to build systems for other subjects in the curriculum using haptics. Furthermore, this research aims to examine the potential strengths of game-based learning among visually impaired participants and to explore the potential of enjoyable and playful educational environments for these participants. Moreover, findings of this research may introduce a new method by which teachers can engage visually impaired participants with geometrical concepts and encourage and promote collaboration with sighted peers. Therefore, this thesis has the following aims:

- To investigate and explain how Interactive Systems can be used to produce a useful VE for learning about 3D shapes through auditory and haptic feedback.
- To suggest a new way of teaching and learning mathematics, specifically the main theory of space – geometry.
- To examine the potential strengths of game-based learning and to emphasize the need of enjoyable and playful educational environments.

- To present an activity-based user-centred repetitive process to design and develop a prototype of a non-visual application to encourage and engage visually impaired participants to practise geometrical literature, to promote collaborative learning and powerful homework and individual learning.
- To investigate the potential influence game-based virtual learning environments have on visually impaired participants.
- To demonstrate the possibilities to promote collaborative work between participants with visual impairment and their sighted peers and teachers on graphical teaching material.

Objectives

In order to investigate this hypothesis the following objectives were established:

- Blindfolded users would test one of the tutorials that come with Novint Falcon - the haptic device chosen for the specific research – with the goal of investigating its robustness and the meaningful tactile cues it can provide to users.
- Real 3D geometrical objects will be explored by participants who are blind to evaluate and define the mechanisms they use to explore and identify an object’s type.
- A pilot group of visually impaired participants would be set up to test how participants cope with the interaction with haptic environments. The Novint Falcon has a number of games associated with it and the pilot group would be observed using these games.
- A series of prototype games would be developed to test different parameters, i.e. objects with different texture. This set of prototypes would be tested by the research group and findings will contribute towards the final design of the game.
- The game levels to be developed would be determined in line with the needs of the taught curriculum and the collaboration with teachers.
- Development of the educational game environment would be based on findings and data collected from the interaction with research group.

- The game would be tested by the research group and the validity of the hypothesis would be evaluated at the end of this thesis. Experiments to be conducted in St Barnabas School for the Blind, Nicosia Cyprus and New College Nottingham, England.
- Collaboration of sighted and blind class mates on common school tasks e.g. a common exercise task.

Literature Questions

Following the growth of haptic and force feedback technology from the very first devices to date (2013), it must be possible to identify the weaknesses and the voids in this area and try to answer the questions of *why* things have remained stagnant; *how* can new ideas make good educational aids for the visually impaired community and *what* are the most crucial needs of this group of people? Having in mind all the above, along with the literature review presented in chapters two and three one can ask the following legitimate questions:

- Do educational games based on haptic-audio feedback make good tools for education?
- Can the Novint Falcon bridge the gap in communication between sighted and blind people while offering entertaining learning?
- Is geometry as a concept intrinsically more difficult for students who are blind and, therefore, should time devoted to this concept be invested in perhaps more readily mastered modules, such as algebra or arithmetic?

The research made use of the Novint Falcon as a haptic interface device. It has been on the market since 2007. It is a consumer-affordable force feedback device and its price is not prohibitive for schools and parents to buy. This is one of the major reasons why the specific device was selected to form the medium of interaction with the designed haptic learning environment. Software was built in C++ based on the open source CHAI3D library, more on software design can be found in Chapter 6: Software Design. Moreover, the proposed system is aiming to form a communication channel between students and the educator in such a way that the latter need not have knowledge of special education as a prerequisite.

Educational Institutes Participated in this Research

Participants were from two European educational institutes, St Barnabas School for the Blind, Nicosia, Cyprus and New College Nottingham, England. In Cyprus blind students have to attend schools for the blind until the age of 9 where teachers specialise in teaching students with visual impairments. After the age of 9 students attend conventional schools and classes and are accompanied by dedicated teaching assistants to help them with mobility and issues relating to learning material. In conventional schools there is, if any, only a small number of teachers that have the appropriate education and experience to coach blind students, having as a result an inadequate educational methodology. Teachers do receive some sort of training on how to teach this group of students but this is limited to very theoretical topics covered in one or two seminar sessions. Also, the school works as an assistive educational institution for blind participants at school level but for adults as well, offering a number of different courses like sculpture, cooking, music, computer science and many more.

New College Nottingham is a conventional college and there is a small number of blind students who enrol every year. There are teaching assistants to help these students. Teachers and teaching assistants explained that blind students choose to pursue degrees that come more readily to them, like history and philosophy.

Approval was needed to enter either of the educational institutions. The School of Computer Science ethics approval process was fully followed CRB check undertaken. Also, to apply for the school in Cyprus, the researcher had to obtain the written approval of the Ministry of Education, the School's Administration and students' parents to enter the school and work with the students. Prior to the first meeting, the researcher has was interviewed by the school's administration. Taking this opportunity, the research group wish to express their sincere appreciation for all the support they have received from the people working in the two institutions but most of all special thanks are due to all the participants.

Thesis Overview

This thesis has the following structure:

- **Chapter 2: Background** presents an overview of previous research in the field of non-visual haptic application design. It discusses the importance of haptics and how haptic technology may be advantageous to blind users. It introduces geometry as an educational aim and the role it has in every student's life. There is an in depth discussion and presentation of some visual phenomena, i.e. rotation and symmetry and how these are presented to blind participants and the problems they face in the process of understanding these phenomena.
- **Chapter 3: State of the Art – Haptic Technology** presents some of the most important and widely used haptic technology devices. Selected haptic devices that could be relevant to this research are also presented. Finally, there is a discussion of how applicable these devices may be to people with impaired vision.
- **Chapter 4: Methodology,** describes the methods used to collect the necessary data required to build i-HALE levels. It starts with an introduction to the approach used, the User-Centred Design and its main principles. It continues with an introduction to i-HALE and its aims. It also describes in detail the tutorials participants were offered to practise the main literature to be examined during the game. It describes in detail all the participants who took part in this research. It also describes the methods used in the blindfolded and feasibility studies and concludes with the description of the methods of i-HALE levels.
- **Chapter 5: Feasibility Study** describes and analyses all the steps and tests that have been undertaken to conclude with the final outcome of i-HALE. Preliminary testing with blindfolded users and first, second and third round of meetings.
- **Chapter 6: Software Design** talks in more detail about the technical aspect of the i-HALE's design and development. It describes the

development tools and methods used to build the software with the use of graphical representation. It also isolates and explains parts of the coding to emphasise some of the object oriented software engineering techniques used.

- **Chapter 7: i-HALE Level ONE: Identification of 3D objects** describes what this level's goals are along with a detailed description of its design concluding with results and discussion.
- **Chapter 8: i-HALE Level TWO: Reproduction of 2D illustration to 3D objects** describes what this level's goals are along with a detailed description of its design concluding with results and discussion.
- **Chapter 9: i-HALE Level THREE: Size Order** describes what this level's goals are along with a detailed description of its design concluding with results and discussion.
- **Chapter 10: i-HALE Level FOUR: Complex Environments** describes what this level's goals are along with a detailed description of its design concluding with results and discussion.
- **Chapter 11: Discussion** elaborates results collected and presented in the previous chapter. In this chapter there is an approach to justify the nature of i-HALE, that is an application that combines the playful and educational aspect. In addition, it describes and discusses a brief collaboration between blind participants and sighted peers on a common task.
- **Chapter 12: Conclusion**'s discussion goes back to the aims and questions that were set during the initial chapters and tries to give answers based on the evaluation of the results. Furthermore, it tries to justify the contribution this research may have to technological research and to the improvement of blind participants' learning opportunities.

CHAPTER 2

Background

2.1 Introduction

The main purpose of this research is to investigate the hypothesis that a haptic learning environment in the form of a game will enable and motivate participants with visual impairment to investigate the geometrical concepts of three dimensional shapes, their relative size and location. This chapter explores and discusses the dimensions of taxonomy on which this research is based on. Firstly there is an in-depth presentation of what research has to presents in the area of haptics, audio-haptic learning and virtual learning environments for blind users. It also, describes the haptic understanding of blind users in virtual environments. The second dimension discusses the importance of spatial awareness and the implications it has on education. It also presents the inability of the current educational system to allow visually impaired students to access mathematical modules and geometry in particular. The third dimension is educational games and the characteristics a game should have to engage users, but at the same time it fulfils its educational aim.

The availability of access to the Internet by blind people has allowed them access to a range of information that was previously almost inaccessible. The fact that digital text can be easily accessed nowadays has given blind people a completely new and innovative way of interacting with information, surroundings and the world. Most blind computer users use screen readers combined with synthetic speech and/or Braille displays to access digital data (Sjostrom, 2001). This, of course gives them access to text but graphical representations remain inaccessible.

Cognitive psychology and a number of different medical studies of brain functions or dysfunctions have pointed out the importance of sight or the consequences of sight difficulties with respect to learning. Studies that show how blind children acquire and use knowledge have focused less on cognitive compensations and more on delays in development. Klingenberg (2007), undertook a study that deals with the spatial understanding and the visuo-spatial memory of visually impaired people. She pointed out that the "literature of geometry" apparently is connected to the spatial perception of blind people which is connected to the concept of "Mobility and Orientation" (M&O). M&O helps a blind or visually impaired student to know where he/she is in space (orientation) and where he/she wants to go(mobility) by helping them to construct a plan to get there.

How to teach geometry to blind students and how they should learn is an area of research that is spread between the areas of disability research – visual impairment in this case – and mathematical education. The contribution to the latter comes primarily from education and that of disability research comes primarily from psychology and medicine.

The use of technology in the education of children has shown positive and beneficial effects. The emergence of haptic technology has raised human computer interaction to the next level and has opened up new, more promising avenues for assisting learning and teaching among people who are blind (McGee, 2003). Haptics along with audio feedback have the potential of creating interfaces for non-visual audio-haptic interaction which may form a step towards "reading" digital graphics and pictures. However, besides the teaching benefits blind students may have from this, it may also promote collaboration and team work since sighted and non-sighted students will have a common starting point of communication and understanding (Klingenberg, 2007).

2.2 The Importance of Haptics

One of the major elements of this current research is the use of haptics and tactile cues which a haptic interface can provide to users to enable them to interact successfully with a Virtual Learning Environment (VLE). Haptics refers to the sense of touch and the term is derived from the ancient Greek word *άπτω*. Haptics is the ability of a person to sense, feel, recognise and interact with real or virtual objects in a real or virtual environment through the sense of touch. Haptics is used to define *"a number of different concepts related* to human perception and understanding through touch" (Khatib et al., 2003). In "Touching for Knowing", (Hatwell & Martinez-Sarrochi, 2003) and (Hatwell et al., 2003) describe the close relationship between perception and haptic functioning. Haptic exploration with no visual feedback means to understand and explore an object or a space haptically which requires users to move actively. Haptic sense in the context of computer interaction is enabled when users either move the mouse or simply press keys on the keyboard. Virtual haptic displays can be provided by either tactile – e.g. Braille display – or kinaesthetic – force feedback – devices.

Haptic interfaces make use of the sense of touch and kinaesthetics in human interaction. Using haptic interfaces a blind person is able to actually sense digital objects or shapes.

Nowadays, there are a limited number of available computer programs that allow users to interact with graphical information in a graphical user interface (GUI) through the use of haptic devices (Sjöström et al., 2003). These computer aided software approaches will be discussed further in Section 3.5 'Force Feedback Devices and the Novint Falcon'

Because there is an increasing quantity and diversity of information available to interact with, there is a consequent need to introduce new ways to interact with that information. According to (Kataria and Tapudum 2010), haptic systems combined with, tactile, kinaesthetic and motor capabilities when used in conjunction with cognitive processes present a 'uniquely bi-directional information channel to the brain'. Also research study presented in Immersion's "The Value of Haptics" (Immersion, 2011) shows that tactile feedback can make users more efficient and effective while at the same time reducing their error rate and stress levels. Touch is a highly effective secondary communication channel that leaves the visual sense able to better attend to other control issues (Van et al., 2005). In general it can be said that tactile feedback adds satisfaction and quality to a user's experience by making him/her more efficient. In Immersion's point of view tactile feedback is *"a tremendous and underused source of productivity gain for many applications within modern society"*. In general the importance of haptics in daily procedures can be grouped in the following way:

- <u>Quantitative Task Performance</u>: Through a series of experiments based on Fitt's Law, Hasser (1998) managed to show that the sense of touch provides the highest degree of performance for people who are blind compared to other senses feedback (Hasser et al., 1998).
- <u>Multimodal Feedback</u>*:* Work by (Delus et al., 2001) *&* (Akamatsu et al., 1994)*,* report the increase of users' performance when haptics are combined with audio feedback and sight.
- <u>User Satisfaction:</u> Another finding that comes exactly to support the view of Immersion's book "The Value of Haptics" (Immersion, 2011) that users perform more efficiently and effectively with haptic interfaces over non-haptic ones, are studies carried out by (Serafin et al., 2007) & (Brewster et al., 2007) & (Chang & O'Sullivan, 2005). Serafin et al (2007), performed two studies on how participants interact with touch screens on a desktop setting and integrated in a vehicle. In both studies, participants assessed 4 different types of feedback conditions; (a) visual feedback, (b) visual and auditory feedback, (c) visual and haptic feedback and (d) auditory, visual and haptic feedback. Results have shown that participants strongly prefer touch screen implementations that incorporate haptic elements and also provide insights on regional differences in their perception.

- Non-visual Interaction: *"Research findings support that haptic interfaces allow users to effectively communicate with a computer without the need of visual feedback"* (O'Modhrain & Gillespie, 1997). This is a very important advantage that can be used to effectively design mechanisms for users with limited or no vision.

2.3 Haptic Recognition

Reed et al (2006) showed that haptic object recognition and localisation *"activated inferior and superior parietal areas, respectively, suggesting a correlation with the distinction between dorsal and ventral visual streams made earlier by Ungerleider and Mishkin"* (1982). The haptic system has its own specific pathways for encoding objects and *"the ease of encoding is a strong influence on the salience of objects attributes"* (Klatzky et al., 1987). Performance of constrained discrimination and free-sorting tasks indicated that the availability and salience of object properties differ under haptic exploration with and without vision. Klantzky et al. (1987), supported that the representation of an object which is naturally encoded by haptics appears to be significantly different from a visual image. Haptic identification is essentially biased towards the way objects feel and not toward how they might look.

Based on a series of experiments, Klantzky et al. (1987), supported that material information would have been important for haptic exploration of an object whereas structure exploration would be more significant when vision was also allowed. During haptic exploration without visual or imagery bias, hardness and texture were found to be encoded readily and particularly salient. On the other hand, when both vision and haptics were available, shape and to some extent size were more easily encoded and salient (Klatzky et al., 1987). They concluded by saying that *"visual imagery instructions led to an overwhelming emphasis on shape to the exclusion of virtually every other property of the objects explored".*

Also, contour information seemed to be particularly important when participants were asked to name an object they hadn't previously seen. Therefore, it can be said that the process of following contour is necessary to acquire the exact shape haptically (Klatzky et al., 1987) [See also Section 2.5 Blind People and Perception & (Kennedy, 1997)].

According to Lederman and Klantzy (2009), touch scientists have been debating whether, like vision, the somato-sensory system is served by two subsystems, a *"what"* system that deals with perceptual (and memory) functions, and a *"where"* system that deals with the perceptual guidance of action. The "what" system in touch processes the many different properties of surfaces and objects. This can be justified by the fact that familiar objects are recognised quickly and with high accuracy by using only the sense of touch (Klatzky et al., 1985). Whereas, the "where" system in touch provides a description of the layout of points, surfaces and objects in the world, likewise the counterpart in vision.

According Normal et al (2004), touch and vision can be similar in that they are both sensitive to an object's global or overall shape (Lakatos & Marks, 1999) & (Norman et al., 2000). However, the human ability to measure the differences in "local metric structure" between objects such as depth and curvature is not accurate (Norman et al., 2004). Therefore, it can be argued that there are some very important similarities between vision and haptics, which may suggest that the visual and haptic systems may be interconnected (Amedi et al., 2001). In one of their studies Ittyerah and Marks (2007), supported that performance was better in haptic exploration than visual conditions and furthermore that the intervening activities exerted greater effects with haptic than visual representation.

In one of Klatzky et al (1985), systematic studies about haptic object recognition, it was found that people are highly accurate and fast in recognising objects. These findings come in contrast with previous findings which support that both empirically and theoretically, haptic system is inadequate for object recognition, especially when compared to vision (Klatzky et al., 1985) & (Gipson, 1966). A more recent study by (Lawson &

Bracken, 2011), supports that haptically explored 3D objects are usually recognised more efficiently, albeit more slowly and less accurately than with vision and also that raised-line drawings of familiar objects are very difficult to identify with active touch only. One of the reasons why this is the case is that 3D objects have more depth information than outline drawings so as extra information about identity for example texture, hardness, weight temperature can be added. Lawson and Bracken (2011) concluded that depth information is very important in the haptic exploration of read 3D objects, as it provides additional cues to the user that make them more quick and accurate.

"Haptic perception of surface and object properties is tightly bound to the nature of contact (i.e., whether an object is pressed against the finger or explored over time, and how it is explored)" (Lederman & Klatzky, 2009). Lederman and Klatzky (1987), have defined a set of exploratory procedures (EP) of which the most intensively investigated to explain the systematic relationship between exploration and object properties [See Figure 2-1: Depictions of six manual "exploratory procedures"
Adopted from Lederman and Klatzky]. EP is a stereotypical process that is followed to haptically explore a surface or an object with or without vision. EP can take a number of patterns, like "static contact" which is associated with queries about warmth/coolness.

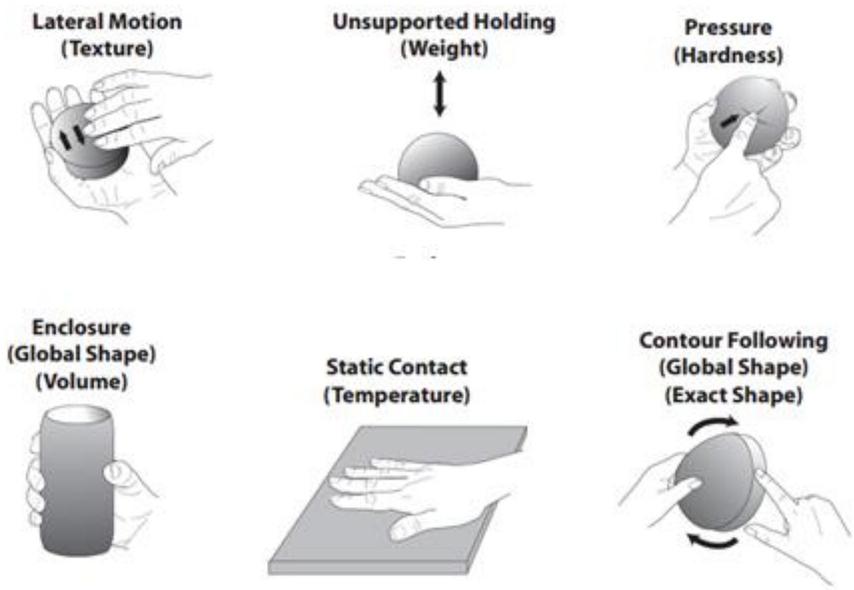


Figure 2-1: Depictions of six manual "exploratory procedures" Adopted from Lederman and Klatzky (1987)

A very interesting set of two experiments were conducted by Lederman and Klatzky (1987), where they tried to establish and explain the links between desired knowledge about objects and hand movements during a haptic exploration of an object. During Experiment 1, match-to-sample was used, where blindfolded participants were directed to match objects on a particular dimension e.g. texture. Throughout the experiment hand movements were classified as exploratory procedures. Experiment 2 tried to address the links between exploratory procedure and knowledge goals. Hand movements this time were constrained and performance on various matching tasks was assessed. The main conclusion that emerged from these experiments was that in free exploration a procedure is generally used to *"acquire information about an object property, not because it is merely sufficient but because it is optimal or even necessary"* (Lederman & Klatzky, 1987). The authors characterised hand movements as "windows" through which it is possible to learn about the *"underlying representation of objects in memory and the processes by which such representations are derived and utilised".*

2.4 Blind People's Understanding of shapes in VE

Currently, most VE make use of visual displays with some use of auditory and very little haptic feedback. VE applications can be used in many ways to simulate aspects of the real world which are not physically available to people, like simulation of buildings or interior designs of ancient monuments (Veltman, 1997). Some of the most important applications of VE can be found in helping people with disabilities, especially in education, training, communication and rehabilitation (Plant, 1995). Colwell et al (1998), through a series of studies using the Impulse Engine 3000 (IE3000) haptic device, investigated the perception of three object dimensions in VR: texture, size and angularity. Penn et al (2000), presented an extension of the work reported by Colwell et al (1998), by using the same methodology but having PHANToM as the haptic interface device.

2.4.1 Haptic Perception of Texture in a VR

Roughness is one of the primary perceptual properties of objects and physical properties that define the roughness have been of interest and investigation among the psychophysical society (Kornbrot et al., 2007). Furthermore, today it is possible to develop virtual stimuli with properties that parallel those of the physical world and provide the potential to create meaningful tactile interfaces for visually impaired people. Interfaces that replace visual information with auditory and haptic information are of great importance for visually impaired people and their interaction with these interfaces (Petrie et al., 2002).

The goal of Colwell et al (1998) study was to examine whether previous results from experiments using real textures could be replicated using virtual textures. Both sighted and blind participants were asked to examine a number of different virtual objects i.e. cubes very similar to the ones Lederman (Lederman, 1981), used in her own studies with the only difference being that those textures involved grooves with a rectangular waveform whereas the textures used in the current study involved sinusoidal shaped grooves. Results have shown that blind participants were more discriminating in their assessment of the roughness of the textures rather than the sighted participants.

Penn et al (2000) used PHANToM with two end points – stylus and a thimble – and participants made magnitude estimates on the 10 virtual textures which were randomly ordered by the computer. The stimuli consisted of 10 different virtual textures that were placed on plates covering an area of “sinusoidal shaped parallel grooves” along the entire length of the plate with a 4 cm in width.

One of the first observations of their study (Penn et al., 2000) was that sighted people found difficulties to distinguish the same virtual textures with the IE3000 device than with PHANToM, which led to the conclusion that *“the same increment between virtual textures might not be sufficient for all users to distinguish between them across different devices”* Penn et al (2000). Moreover, they observed that the majority of the participants perceived the roughness of the virtual textures and the geometry of those textures, the opposite of that found for the real textures used by Lederman (Lederman & Taylor, 1972). According to the latter, *“the perceived roughness increased as a function of increasing groove width (positive exponent)”* whereas in Penn et al (2000) virtual reality studies *“perceived roughness increased as a function of decreasing groove width (negative exponent)”.*

2.4.2 Haptic Perception of Size/Angularity in VR

The goal of Colwell et al (1998) study was to examine whether participants perceived virtual objects to have the intended size and angle. The Impulse Engine 3OOO allows users to examine a virtual object from both inside and outside and therefore for some of the virtual objects used, both inside and outside presentation were given to investigate any differences this factor produced. The virtual objects used in this study were cubes and spheres – both inside and outside presentation, rotate cubes – outside presentation and sheared cubes (inside presentation). Each type of virtual object was presented three times, with a range of different sizes and angles of rotation and shear. Participants were asked to feel the object and then they had to choose between 4 possible answers the object the thought they had felt. Sighted participants were shown scale drawings and blind participants were shown scale tactile 2D representations. Sighted participants judged the sheared cubes more accurately than the blind participants but other than this there was no significant difference between perceptions of sighted and blind participants. Both groups were significantly more accurate in regards to the appreciation of larger objects than smaller objects. Finally the participants showed some difficulty in the judgment of the angles of the rotate cubes but possibly this had been the lack of a reference point for judging the rotation.

Penn et al. (2000), in a study on perception of size and angularity of 3D virtual objects, asked blindfolded and blind participants to examine 15 virtual objects and to perform estimations of size and angularity. The methodology used for this experiment was novel as research on the perception of object properties, like size, concentrated on the exploratory procedures (EP). It is very difficult to replicate the movements of hands in virtual environments as they are in real time. Moreover, PHANToM and IE3000 only offer a single point of interaction and the most analogous interaction in reality would be to explore an object using either a single finger or a pen. In order for the participants to respond to the questions they used an occluding sleeves ruler to measure object size and an angular ruler to make degrees of shear estimations. Tests were run for both the thimble and stylus endpoints. Results showed that in the experiments involving the PHANToM participants underestimated the spheres than cubes; however that was not the case with IE3000. In the experiment involving IE3000 accuracy decreased as a function of increasing size. This was also the case for the spheres and the PHANToM, but not the cubes in which the accuracy was similarly good for the smallest and largest cubes but relatively poor with intermediate sizes. Penn et al. (2000), also continued by advising designers to have in mind that in haptic VR when there is an increase in the groove width of which a texture is composed is *"predominantly associated with reductions in perceived roughness".* They concluded by saying that future designs should allow users to adjust the range of groove widths to reflect *"their discrimination ability".*

2.4.3 Haptic Perception of Complex Objects in VR

Colwell et al. (1998), investigated the understanding of haptically explored virtual complex objects. The goal of this study was to examine whether simulated real objects could be recognized. Participants were asked to feel and explore complex objects like a sofa, an armchair and a kitchen chair. An initial study showed that participants could recognize the object by just feeling it. Therefore they were informed about the object to "feel". This helped them to understand the several parts of the objects – except the kitchen chair which they found challenging – but they said that it wouldn't necessarily be able to work out what they represented when putting together all the different parts.

Overall results have shown that it cannot be assumed that virtual textures and objects will feel to the user as the designer intends. But it is difficult for the IE3000 to allow users to feel the virtual objects in the same way in which real objects are felt. However, they do show that a haptic interface has potential to blind computer users.

2.4.4 Haptic Object Recognition in relation to Visual Processing of Objects

In mid 80s, Klatzky et al (1985), showed that people are very good at identifying common objects by just exploring them with their bare hand. Results from their experiments showed that blindfolded participants manually identified 100 common objects with very high accuracy (close to 100%) within 2-3 seconds per object. In a more recent study Klatzky and Lederman (2000), tried to address the nature of processing during haptic object recognition in relation to visual processing of objects. Through this study they found the already widely accepted fact, that the earliest features the visual system extracts in object recognition is spatial information in the form of oriented edges (Klatzky & Lederman, 2003) & (Hatwell et al., 2003) & (Klatzky et al., 1985), which are combined to produce a low-level object primitives or features, but the haptic system processes the orientation of edges in space rather ineffectively. Lederman and Klatzky (1997), showed that although participants were able to detect the presence/absence of an edge of an object very quickly (only a few milliseconds of contact), it took them considerably longer to spatially process these edges in terms of orientation (Kurze, 1996). Analysing results from performing haptic exploration suggested that the haptic system can appreciate edges relatively quickly and accurately if processed intensively in terms of magnitude (Lederman & Klatzky, 1997). However, when edges are processed spatially, in terms of a spatial reference system, the performance is considerably poorer and slower.

It can be said, then, that the haptic system is compromised – slow and prone to error – when processing edges contained in fingertip-sized 2D patterns (Lederman & Klatzky, 1997) & (Loomis, 1990) and in larger raised 2D spatial displays (Lederman et al., 1990) & (Magee & Kennedy, 1980).

Haptic exploration and recognition of 3D objects by following only the edges is relatively poor as well. To evaluate the use of spatial information for haptically explored 3D objects, Klatzky et al. (1993), asked participants to explore 3D fixing rigid objects to a supporting surface by only following the edges. Participants were required to wear a compliant glove that further deprived them of texture and thermal cues. Results showed an accuracy of up to 74% in 45 seconds for gloved single-finger and 93% in 16 seconds in gloved whole-hand manual exploration.

Lederman and Klatzky (2004), tried to approach the question *why people show poor performance in haptic apprehension of edge information.* And they proposed the following two reasons:
(a) processing local edges with the fingertip as compared with the eye, is *"limited by the fingertip's relatively coarse spatial resolving capacity"*.
(b) the method people follow to explore 2D patterns and 3D objects "further constrains haptic spatial processing". Lederman and Klatzky (1987) have shown that people typically extract edges by using variants of two hand-movement patterns or exploratory procedures.

2.5 Blind People and Perception

"We typically think of sight as the perceptual system by which shapes and surfaces speak to the mind"
(Kennedy, 1997)

Based on some evidence discussed in previous sections, touch can be seen to relay much of the same information as sight. When a person sees an object he/she knows roughly how it will feel if he/she touches it with the same applying when a person explores an object haptically. Here a question arises: since touch and sight are two completely dissimilar senses - the former receives input in the form of pressure and the latter responds to changes of light – *how* can they both interpret a line in the same way? One theory can be that lines in drawings represent the physical boundaries of the object, so they can be interpreted in the same way by both touch and sight.

Kennedy argues on this, because he believes that a line, no matter how thin, has two sides: an inside and an outside border. Consequently, thick lines are perceived fairly differently from thin ones. For example if a contour line of a profile is too thick it may represent two profiles, one per edge [see Figure 2-2: Thin/Thick Contours]. Similarly, if a line is too thin it is perceived as a single line and cannot be used to distinguish the inside or outside.

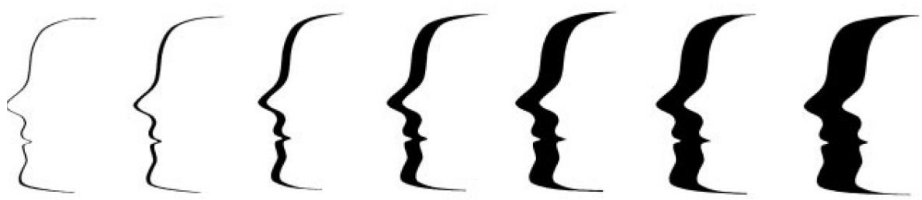


Figure 2-2: Thin/Thick Contours
(Adopted from Kennedy, 1997)

In order to investigate his theory, Kennedy prepared another set of experiments. He showed contours (see Figure 2-2: Thin/Thick Contours) to blind users and asked them to determine how many faces are present. When edges were only 0.1 cm apart, users said that it was one face, but when edges were 0.8 cm apart they said that there were two faces. Another theory says that lines can represent any “perspective boundary”, including those that are not tangible like shadows (Liu & Kennedy, 1993).

Shadows and other intangible boundaries are not recognised in outline which somehow explains why blind people can appreciate most line drawings made by sighted people (Kennedy, 1997). In Figure 2-3: Shadow Patterns, *“a single contour separates light and dark areas of the face”* Kennedy and his team explained in their paper ‘How the blind draw’ (Kennedy, 1997). Picture on the right, a line has two contours which makes the same division. This example shows that the visual system, like the tactile system, does not perceive 2 contours of a line likewise as it perceive a single contour.

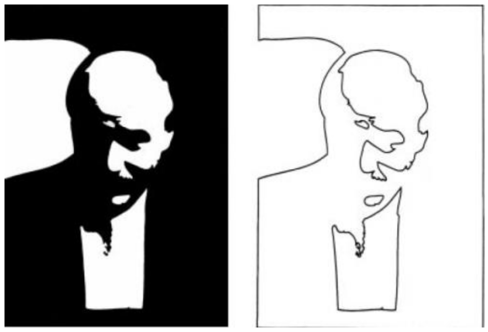


Figure 2-3: Shadow Patterns
(Adopted from Kennedy, 1997)

Blind people canno ... hat they try to interpret in such drawings are the contours, which for them is an indicator of the location of a single edge of a surface. Sighted participants interpret brightness borders as pointers of surface edges and blind people interpret pressure borders in the same way (Shimizu et al., 1993).

This can be seen to justify the ability to interpret surface edge functions even in the absence of any visual signals. This is the reason why blind people so readily appreciate line drawings and other graphic symbols. Having this evidence in hand, teachers should be encouraged to prepare materials for blind users that make vital use of pictures (Kennedy, 1993).

Since blind people can easily understand and correctly interpret lines as the physical contours of an object, then this can be of great importance in teaching basic geometrical objects. It could be particularly helpful to illustrate to blind users the different properties of a geometrical object, e.g. the distance between two ridges is one single side of the object. Based on this explanation, teachers can build on more advance tasks, like calculating the volume of a cube, which is *side times side times side* (x^3).

The research carried out at Certec is of great interest. (http://www.english.certec.lth.se/haptics/), Lund University in Sweden. Certec has been investigating haptic interfaces since 1995 by exploring the possibilities they can offer to people with different kinds of disabilities. In one of its studies, they used a PHANToM (See Chapter 3.3.1.1 Opposing Type) based program to enable blind users to paint. They called this "Paint with Your Fingers". Using the PHANToM, users were able to choose a colour from the palette which was associated with a texture for the blind users to feel. Changing to a different program mode the user could feel the entire painting and, moreover, what other people had painted. This raises a possible solution in the attempt to haptically represent colours by assigning a distinctive texture to each one. This of course requires an in-depth analysis of all the parameters involved, taking into consideration the psychological aspect of what emotions/feelings each colour is linked to and which texture style better fits these emotions.

Testing the appropriate prototype with 20 late and early blind users, the most interesting outcome of this session was that it is possible for blind people to create an "inner picture of rather complex environments" through the sense of touch (Sjöström, 2000). Another important finding was that some late blind people were able to confirm that what they felt through the PHANToM was similar to previous experiences in life (when they had had their sight) (Sjöström, 1997) & (Sjöström & Jönsson, 1997).

2.6 Education, Geometry and Technology

Although mathematics is one of the major subjects in the school curriculum and the one that students cannot avoid throughout their student lives, a significant proportion of them dislike it. This is due to its nature which requires critical thinking and reasoning skills which are intrinsically difficult.

Teaching not only mathematics but other scientific modules depends significantly on visual instructions since they are modules that are rich in visual representations. Since visually impaired students have little or no vision, it makes it extremely difficult for them to learn or be taught these concepts.

When a blind student is asked what he/she hates most in the school curriculum, the most common answer is, Mathematics! Within mathematics, especially at school level, geometry is the major theory of space (Erwin et al., 2001). Spatial sense is very important in the children's development of a number of different skills and understanding in many topics, even from the early stages of elementary schools. Shape, distance, orientation, size, positive and negative numbers on a number line, relative location and reading maps refer to spatial properties and relations (Klingenberg, 2007). Studies of human problem solving and language understanding have pointed out the importance of spatial representation and reasoning (Kennedy & Tipps, 1994). The process of manipulation of different objects in space along with the required spatial thinking, provide a strong background for other more advance mathematical and scientific subjects like trigonometry, calculus, algebra and physics (Klatzky & Lederman, 2003). These are some of the important reasons why mathematical sciences and geometry are not an isolated part of the curriculum and teachers' weakness as to how to teach these subjects efficiently and effectively to students with visual impairment should be taken into deep and serious consideration and investigation. School policy must create an environment with equally shared opportunities for all students, despite any disability they may have.

Unfortunately, as studies have shown throughout the years most science teachers and college science educators have very limited or no direct experience in teaching students with special needs and therefore the may hold "stereotype views" of their capabilities (Ballesteros et al., 2005).

This is very significant for blind students who want to be included in today's society and share equal opportunities with their sighted peers. Elementary geometry and mathematical pedagogy is not an isolated part of the curriculum and educators should acquire the appropriate knowledge to teach blind students, or the corresponding government department may train and employ educators with the appropriate background and experience in teaching students with special needs.

Schools similar to the ones this research has been conducted at should introduce the use of assistive technology to students. Also, teachers should be able to gain the appropriate training on new assistive technology and decide which better suits their students' needs and which should be integrated into their teaching. It could be argued that schools should have the appropriate funding to achieve this. It all comes down to the school policy and the corresponding governmental department. All stakeholders – school administration, government and teachers – should aim for what is best for students with special needs. After all, they are in a position to serve a purpose: to ensure students in general receive the highest level of training and coaching. The stakeholders form a unit, at the centre of which is the main focus – the students.

Introducing something new needs the appropriate study and support, to eliminate any rejections and maximise, on the other hand, the possibilities of it being successfully accepted and adopted by the end users. However, studies have shown that both students and teachers perceive assistive technology as too expensive and difficult to use, and a source of many other problems such as its compatibility with other similar technologies. Gentaz stresses that to upgrade these assistive technologies costs an appreciable amount of money, so blind users tend not to upgrade as often as they would like to, and therefore they are forced to use outdated systems which may not meet all their requirements (Gentaz & Hatwell, 2003). This very important fact is another major obstacle that prevents schools from adopting new technology. There are a number of ways that schools can deal with this matter, like paying annual membership payments so that all students can have access to information within their school's network and/or offer lower prices on new programs or updates, similar to the way in this is done in universities. This may form a gateway to today's technology with all the benefits learners may have from it.

2.6.1 Geometry: Impact on educational

"Knowledge of geometry enhances sighted students' understanding of mathematics and connects mathematics to the real world"

(Bouaziz et al., 2005)

"The earliest features that the visual system extracts from objects are spatial in the form of oriented edges" (Klatzky & Lederman, 2003) & (Hatwell, et al., 2003) & (Klatzky et al., 1985). Haptic perception depends upon the complementary information that is gathered by touch, the active movement of the body or parts of the body (e.g. hands) and spatial cues as well as stimulus size and awareness (Paterson, 2006). As mentioned earlier, the haptic system is not very good at extracting information about the spatial layout of edges.

To illustrate the importance of the above, Olive G. Klingenberg a researcher and a teacher for blind students, describes an event in her own experience as a teacher that shows clearly how blind students use edges to orient an object in a 3D space. Within a class there were a number of sighted students as well as a girl who was blind. The girl was sitting in front of her bookshelf where she kept her books and the process of fetching and putting the books back was a daily procedure for her (Klingenberg, 2007). The teacher instructed the students to go and get the sleds that were placed in a box at the end of the blind student's shelf [See Figure 2-4: A sketch of the classroom. Blind student is sitting to the right in the first row. The bookshelf in this sketch is brown
(Adopted from Olive G.Klingenberg from Geometry: Educational Implications for Children with Visual Impairment)]. As teacher was delivering the specific message, she was looking at the box. The students looked in the same direction - the box which was on the shelf. They could see the box and the shelf and *"they didn't seem to care or take into consideration the landmark*

that was given (at the end)" (Klingenberg, 2007). In addition, teacher was looking in the direction of the shelf while she was giving out instructions. Teacher's attitude provided sighted students with the ability to "*draw inferences about this topological concept"*. Blind student's body language showed that she did not understand this message and she simply stated that: *"There are so many edges."*

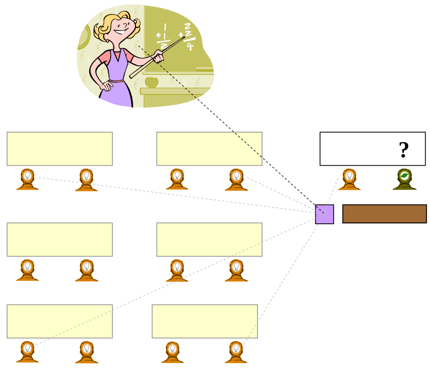


Figure 2-4: A sketch of the classroom. Blind student is sitting to the right in the first row. The bookshelf in this sketch is brown
(Adopted from Olive G.Klingenberg from Geometry: Educational Implications for Children with Visual Impairment)

Based on the above illustration, it seems that the girl used 'edge' and 'at the edge' as synonyms. The edges of the shelf were present and certainly important to her in the orientation but they probably did not *"reproduce a geometrical body of 2D rectangle or a 3D prism,"* thus the spatial location instruction was meaningless to her (Klingenberg, 2007). A blind person is aware of edges because they are quickly available through touch, but it is critical to conceptualise the edges as a global shape and therefore be able to accurately position the object within the relative space e.g. the classroom.

This example stresses the importance of having *"rich knowledge and use of it will make it possible for visually impaired students to grasp the sighted world"* (Klingenberg, 2007) . Also, verbal instruction should be as rich and meaningful as possible and avoid relying on body language and/or facial expressions. Sighted people may use gestures to communicate with other people but it is important to realise that this method of communication means nothing to people with low or no vision.

Teaching geometry to elementary schools is very challenging because of the differences in the concept of space. Based on Barthelot and Salin, there are three different levels of space in regard to teaching geometry to blind students (Barthelot & Salin, 1998):

1. Microspace: any object that can be held in students' hands – e.g. a book, a pencil.
2. Mesospace: any area that is explored and therefore known by the student. It's not a huge area that normally refers to a school campus or a neighbourhood.
3. Macrospace: this last category refers to areas that are bigger than the two previous ones and they are usually unknown – a city, a new country - and in order to become familiarised with them, one should use the appropriate knowledge and be able to read maps - "transfer big spaces into maps" and the other way around.

According to Barthelot and Salin (1998), the difference in space-levels is a parameter that is not taken into serious consideration by the teachers, whereas researchers consider it to be one of the main sources of learning difficulties for sighted students. Does, however, the research literature about blind students learning geometry need to look into the same problem?

Thompson and Chronicle (2006) in one of their case studies try to illustrate that the pre-defined material an object is made of, is the leading information that enables object recognition by a blind child. For example, if all cubes are made of velvet then the visually impaired person would be able to identify the object as soon as he/she touches it, without the need to further explore it to determine its type. A similar study was conducted in two different countries, in Germany and the UK, and both showed that textures can be recognisable by PHANToM and Impulse Engine 3000 (Jansson et al., 1999).The way of analysing an object's information by the sighted and blind students is very different. For sighted students the material attribute is something that is completely independent and irrelevant of the geometric structure. For this idea to be successful and globally approved and therefore used as a secure method of geometric object, identification would require the establishment of specific norms for each object type; for instance specific textures cannot on their own enable blind people to successfully recognise the type of the object. An attempt to exemplify this has to do with the establishment of a new object literature in a way similar to the Braille taxonomy or the written Alphabet. This would require extensive and careful research that would look into the psychological aspects and the haptic system in detail. Gentaz and Hatwell in 2003 showed that this might be a possible solution by demonstrating how two geometrical forms with similar shape but different texture can be judged less similar by touch than by vision (Gentaz & Hatwell, 2003). This raises the question whether it is better to use only a small range of 'well-known tangible figures' in the learning process or if it is fewer 'tangible assortments' that cause these judgment difficulties. Bouaziz et al in 2005 argued for establishing specific norms in the use of tangible graphics that would be simple cues that are easy to extract and recognize haptically (Bouaziz et al., 2005).

2D Meaning and Reproduction

A blind student may identify a drawing or draw an object using *"a small-scale object to provide immediate perceptual support since it can be held in her/his hand"* (D'Angiulli & Maggi, 2003). Two-dimensional (2D) reproduction of real objects lacks meaning for blind students as tangible illustrations do not physically resemble the haptic object (Thompson & Chronicle, 2006). Experimental research and pedagogical practice show, however, that blind people can be beneficial by the study of 'representation-conversions' and also can benefit from the use of illustrations and drawings to build a meaningful mental models (Hatwell & Martinez-Sarrochi, 2003) & (Ostad, 1989) & (Thompson & Chronicle, 2006).

2.7 Educational Games

Computer based games is a mature medium that has attracted many scholars from a number of different disciplines. Computer video games have been largely ignored by educators and the introduction to schools and learning have been rather slow. Squire K. argues that educators have discussed and paid more attention to overbid *"the social consequences of game play, ignoring important educational potentials of gaming"* (Squire, 2002) . Furthermore, Squire pointed out that video game playing occurs in *"rich socio-cultural contexts"* by bringing friends and family together and acting as an *"outlet for adolescents and providing the 'raw material' for youth Culture"* (Dickey, 2005) & (Squire, 2002). From a very brief comparison of childhood in the last two decades, it can be said that digital games have not only dominated the 'growing up' period of children but they also direct their needs and their wants. Another important factor is the integration of video games with the internet and this pair has become dominant not only in the entertainment area but in communication as well. If we combine computer games with online social networks like Facebook, it is noticed that children are growing up in a "digital society" or in a "digital globalization", since distance does not any more constitute an obstacle for socialising.

Video games consoles and computer games have become one of the most *"pervasive, profitable and influential forms of entertainment"* around the world (Squire, 2003) & (Habgood et al., 2003). The Sony PlayStation is currently the best-selling home console, selling over 154 million units worldwide (Sony Corporate website). Video games are a powerful force not only in the entertainment and economic sector but also in culture. Based on figures that justify the power video games have especially with young people, some educators have expressed the interest to investigate the influence these games have on users and how they can take advantage of this and introduce game-based-leaning in schools (de Aguilera & Mendiz, 2003). Many educators do see much potential in this and they see this new medium as *"powerfully motivating digital environments*" (Toro-Troconis et al., 2010) and they move on to determine what are the motivational components that make users engage with games and investigate their integration into "instructional design" (Bowman, 1982).

There are lots of parameters that an instructional technologist and/or a game designer should study in order to understand why games are such a popular and influential medium. Primarily there is the need to understand how game designers create emotions such as joy, happiness, anger, anxiety and so on in the players. This can be achieved by balancing a number of game characteristics such as character behaviour, game rewards, the number and level of obstacles, competition with other players and lastly and very importantly how they can achieve collaboration with other gamers (Squire, 2003).

Recently there has been some debate over whether integrating educational games into schools from the very early stages will help students form a better understanding of crucial subjects in the curriculum that require primarily vision and reasoning. Yet there is still a big group of people who are very sceptical and believe that video games might *"foster violence, aggression, negative imagery of women, or social isolation"* (Provenzo, 1992). But there is one thing that all agree with: that computer-assisted instruction (CAI) and multimedia integration in education have significantly changed children's learning and cognitive processes (Tsung-Yen & Wei-Fan, 2007) and can make learning a more enjoyable experience. Furthermore, research indicates that educational computer software can be motivating for children with learning difficulties and/or students with a cognitive handicap (Millen et al., 2011). Moreover, the use of technology in the education of blind children has also shown positive and beneficial effects. The emergence of haptic technology and the opportunity of creating interfaces for non-visual haptic interaction may form the footstep to digital graphics and 3D models by blind users (Petridou et al., 2011).

Combining today's technology and the tremendous advancements it has made in the last two decades, designers are able to create digital scenes that are rich in visual representation with good quality graphics. Video games may offer users different kinds of emotions through a number of different types of games such as action games, simulations, strategy and tactics, role playing, sports, puzzles, adventure and discovery. However, this application mainly applies to sighted people, leaving people who cannot use the ordinary graphical interface with no alternative way of interaction. Taking into account the tremendous advances computer technology has made over the last couple of decades it is disappointing to observe a declining trend in the design of technology for an inclusive digital society.

Over the past 25 years a substantial body of psychological, educational and development literature has been able to highlight the potential of educational games (Habgood et al., 2003) & (Gee, 2004) & (Kafai, 2001) & (Prensky, 2001) & (Reiber & Matzko, 2001) & (Loftus & Loftus, 1983). Some software companies, market software with educational potential under the name of "edutainment", but findings have tempered the enthusiasm as they do not agree that edutainment products may illustrate an effective educational medium (Habgood et al., 2003).

Some educators and researchers have studied what made Pac-Man so popular soon after its release in the 1980s, and they wondered if the *"magic of Pac-Man cannot be bottled and unleashed in the classroom to enhance student involvement, enjoyment and commitment"* (Bowman, 1982).

Even though experimental research hasn't justified the view that 'educational games are more fun than traditional teaching method' there is a significant number of researchers who strongly believe that computer games are fun if they are designed to offer a set of intrinsic and extrinsic characteristics, like fantasy (Habgood et al., 2003) & (Malone, 1980). Games may motivate children to engage with learning even if the games themselves are not the most efficient way to learn.

Malone, (1981), through a series of observations, surveys and interviews generated three main elements that "Make video games fun" and attempted to adjust these three elements into creating enjoyable educational programs (Malone, 1981):

- **Challenge**: to have clear goals, a score and immediate feedback on their progress given to participants. To have a multiple difficulty levels to adjust the game difficulty to learner skills. Challenging problems and levels of difficulty can engage users in a learning environment – a digital game or at school. Personal experience of the writer tutoring young children with specific learning difficulties (ADHS and ADD) have shown that they engage more in educational games that offer an increase in challenge.
- **Fantasy:** having random elements of surprise an emotionally appealing fantasy and metaphor that is related to game skills. This can be represented by happy and playful sounds to achieve surprise for young users. This last characteristic can be proved to be particularly useful for low or no vision children who primarily rely on audio feedback to interact with such environments. However, studies have shown that learners may quickly lose interest and motivation when they have too many sounds whose meaning they have to memorise (Gee, 2007). Intrinsic and extrinsic fantasy is the most frequently cited explanation given to distinguish between effective and ineffective educational games (Malone, 1980). Malone defined intrinsic (later endogenous) as *"one in which there is an integral and continuing relationship between the fantasy context and the instructional content being presented".* However, Habgood et al, argue against this as they believe that the specific *"concept appears to have a confused standing within literature"* (Habgood et al., 2003). They tried to address this confusion by providing an in-depth review and critique on Malone's statement regarding intrinsic and extrinsic fantasy and they concluded that *"it cannot be justified as a critical means of improving the educational effectiveness of digital learning games"* (Habgood et al., 2003). The role of representations, flow and game mechanics have been pointed out as parameters that are more likely to affect the *"integration of intrinsic motivation and learning"* aspect to computer games. However, this does not detract from the motivational power of fantasy towards making

effective educational games; it rather attempts to explain that it is not the major parameter.

- **Curiosity**: unknown elements that will trigger a user's curiosity to find out and continue playing. Similarly with agency and risk taking, users in a game need to dominate the game and to take any risk to accomplish their goal.

Six years later the theory of this set of characteristics was expanded to add:

- **Control** as an additional individual motivation and cooperation.
- **Competition** and recognition as an interpersonal motivation (Malone & Lepper, 1987) & (Lepper & Malone, 1987).

Malone's work on computer games was carried out in the late 70's and 80's and was primarily focussing on what makes game fun instead of what makes them educational (Habgood et al., 2003) & (Malone, 1981). However, it is important to take into account that this research along with its findings were carried out in a period where personal computers and games were entering the scene. Therefore, at that time any new technological introduction encompassed feelings of excitement and satisfaction to users. However, Malone's finding and proposals may fail to apply to today's applications as many things have been changed and invented ever since. Users and researchers today have a variety of games and technological advancements available to contrast with. Hence these findings are safe to be re-evaluated and re-adjusted to today's facts.

Bowman contrasts video gamers with students in traditional school environments. He says that students in class are led by their teachers and they act as passive recipients who have little or no control over what they learn. Contrasting characteristics of video game playing and traditional schooling, Bowman made the following observations (Bowman, 1982):

- In games players fully control how much they play and when they play. Whereas students in class learn at one pace and are given very little freedom and control to manage the content of their learning. Therefore one positive outcome can be the fact that students study and learn when they feel like it!

- Players have the *"feeling of mastering the environment therefore becoming more powerful, knowledgeable and skilful in the environment".* Whereas, students in class *"learn knowledge abstracted"* (Bowman, 1982) by teachers and practise this knowledge during homework and paper tests and exams. On the other hand students in class wish to compete with other students to achieve higher performance and to be highly ranked in class overall performance book.
- Video gamers work together - they share knowledge, tips, ideas and secrets. This enables collaborating learning and the exchange of thoughts on the same area/subject. Comparing this to student's wise learning, it is performed in isolation and cannot use each one as a resource. On very few occasions students do tend to work with their peers but again competition may master the joint learning.
- Finally games are played for the reward of playing them, of becoming a professional gamer and for the emotional state they produce (Herz, 1997). On the other hand, schools are structured around a different nature of rewards such as good grades or the fear of failing.

Adding to the above, games are by their nature of an entertainment-type and they have to remain that way if they are going to be used for educational purposes. If a game changes its basic characteristic then it falls into another category and will therefore lose the pleasure it offers to the users; something that can be combined effectively with education and form the "edutainment" – a word that from the writer's point of view means a balanced combination of high quality software, engaging games and effective educational character.

Throughout the years computers have been used in education primarily as tools for supporting *"drill and practice for factual recall"* (Jonassen, 1988). Drill and practice games such as Alga-Blaster, Reader Rabbit or Knowledge Munchers have been popular because they can easily be adapted and used in a long-established and didactic curriculum as "enrichment exercises" during independent study. Good drill and practice games use action as the primary genre to engage users (Fenn et al., 2009) & (Bowman, 1982) & (Malone, 1980). Very little if any research has been conducted in order to study and determine the effectiveness of these games. But there is little evidence to show that a well-designed video game may *"produce results which are substantially different from non-computer based games"* (Squire, 2003) & (Clark, 1983). Although drill and practice may play an important role in student-centred learning environment such as problem-based learning, it still lacks some important characteristics to support students in a number of different needs, such as student exploration of micro-worlds (Sarama & Douglas, 2002) & (Savery & Duffy, 1995).

According to Gee, good video games incorporate good learning principles if they manage to attract and maintain the learners' attention (Gee, 2004) & (Gee, 2005). He explains that, if a game was too difficult to learn how to play, then learners/gamers will quickly lose interest and abandon it or not buy it (Gee, 2004). Players will not accept easy and dumped down games, therefore, challenge and learning are a large part of what makes a *"good video game motivating and entertaining"* (Gee, 2007). Based on his experiments he concluded what some of the learning principles a good video game must incorporate are. (Gee, 2004) & (Gee, 2004) & (Gee, 2005):

1. **Identity:** Good video games attract users through identity. Players should spend time and become committed to the new virtual world of the game where their character will live, learn and act. In contrast, why is the identity of being a good student less appealing?
2. **Interaction:** Plato in *Phaedrus* argued that books do not speak back to the reader and therefore reading a book is very passive. The positive thing with video games is that they do speak back to the player by giving back feedback or force back feedback or a new task to complete. Words and activities in well-designed games are placed in the context of and *"interactive relationship between the player and the world".* Likewise school books and notes need to be placed in the context of interaction where the world and people talk back.
3. **Production:** Players do produce - they do not just consume; they write and not just passively read. There are games where players create different virtual careers based on their own choices, like the multi-player

game of World of WarCraft. In a way, players produce or "write" the virtual world they choose to live in – in school, they should produce or "write" the domain and the curriculum they study.

4. **Risk Taking:** A well designed video game decreases the consequences of failure. Even if they fail they would be offered the opportunity to re-start their game from the last stage before the failure. Players, thereby, are encouraged to take risks, explore new patterns and try new things. In a way failure can be a good thing. Whereas in schools there isn't so much room to take risk and one learns from mistakes and pursues new things.
5. **Agency:** Players in games have a strong feeling of agency, controlling and ownership of what they are doing, something that unfortunately is very rare in schools.
6. **Well-Ordered Problems:** In good video games players face problems that begin with easy tasks, that will help users to build up a hypothesis – and proceed with more challenging ones later in the play. The way the problem is spaced and organised is very crucial in the design of effective games; this is the reason why games have levels. In the same way, attention needs to be paid to the way problems are ordered *"in a rich immersive space in a science classroom".*
7. **Challenge and Consolidation:** When players launch a good game for the first time, they have a clear set of challenging problems to solve. When players manage to solve the problems, the game presents them with a new set of challenging problems to solve with increased level of difficulty. Players need to re-think, re-evaluate, learn something new and integrate this new learning with their old mastery to dominate the game. In return, this *"new mastery is consolidated through repetition"* in order to keep players' attention and interest. Bereiter and Scardamalia named this cycle the "Cycle of Expertise" and illustrate the importance of totally mastering and dominating a game describing it like this: *"it is the way anyone becomes expert at anything worth being an expert in"* (Bereiter & Scardamalia, 1993). In schools there are two dimensions to this; there are the poorer students who do not receive enough opportunity to consolidate

and on the other hand good students who don't face enough challenges to their school-based mastery.

8. **System Thinking:** Games encourage players to think about relationships and not just focus on isolated facts and events. In multi-player games like the *World of WarCraft,* it is very important to think what the opponent will do. Such system thinking is very crucial in the real complex world.
9. **Explore, Think Laterally, Rethink Goals:** Schooling has taught students that being smart is a safe, fast and efficient way of achieving personal goals. Games however, work differently! They encourage players to explore thoroughly and collect as much information as needed before moving on fast. It requires players to *"think laterally and not just linearly and to use such exploration and lateral thinking to re-conceive one's goals"* (Gee et al., 1996).

Through his views on effective learning, Gee tries to explain that learning in games and in school has very much in common and it can be said that they follow a parallel flow. He focuses more on characteristics that may engage learners rather than on the characteristics a game should have to be fun. In a way humans enjoy learning, though sometimes in schools it is very difficult to understand it (Gee, 2007).

2.8 Audio-Haptic Interaction

So far in practice (2013), there are no end-users who rely on audio-haptic devices to access graphics and models. What seemed to be a natural way of accessing this information when haptic technology first entered the scene in the first half of 1990's has not in fact materialised. It would have been expected that this new technology would have brought about a whole new way of interaction for people with visual impairment since it had introduced a new modality to the existing ones (Grohn, 2008). There can be many reasons why technology failed to meet these expectations: firstly, the fact that haptic devices are very expensive and secondly, the lack of useful audio-haptic software that would offer a reliable solution which blind people could rely on to have access to graphics. It is important that the design and development of audio-haptic technology move from *"research vehicles to tools designed for practical use"* if it is to reach a larger audience (Grohn, 2008).

Slow progress and advancements of haptic technology in conjunction with the constant increase in interest in multimodal interfaces, research and development joined efforts to combine visual, haptic and auditory displays (Grohn, 2008). An annual workshop on Haptic Audio Virtual Environments (HAVE) has been organised since 2002 but unfortunately, much of the work is of very little or no interest and benefit for people with low or no vision. Most of the work presented includes, and relies heavily on, the visual modality (Grohn, 2008). Another annual workshop which is more focused on haptics and audio without the need for visual feedback is the Haptic Audio Interaction Design (HAID), started in 2006 with the hope of introducing new methods of interaction without the primary need of vision. Vanderheiden et al (1996) stated that audio-haptic applications that combine haptics and digitiser tablet are also an area where blind people or those with low vision may benefit (Winberg & Hellstrom, 2003) & (Vanderheiden, 1996).

- **Haptic Interaction**

Haptic interaction refers to hardware that is designed in such a way as to enable users to "feel" digital models. It has emerged from the robot industry in an attempt to control the robot from a distance and also be able to "feel" what the robot "felt" (Burdea, 1996). Force feedback and haptic desktop technology entered the scene in the mid-1990s and was firstly developed and used by big companies in specific areas, like the Immersion Corp. (2006) and Sensable Technologies (2006). Although available for more than a decade it still has not spread widely.

- **Audio interaction**

The sound that a computer reproduces is a more common way of interpreting information than force-feedback haptics. When sound was first introduced in computer interfaces it was limited to very simple and plain beeps mainly to attract a user's attention rather than give meaningful messages. However, to

this day audio output in computer interfaces serves as the medium to capture attention and enhance visual output.
Therefore information provided to blind or low vision users through the audio output still gives few basic informative clues.

Sound in computer games resembles sound effects from movies and in some cases is used to convey information that is not visible on the screen. If used in combination with force-feedback, people with visual impairment may benefit. Voice cues, as mentioned in 3.3.2 Existing Auditory displays, should be designed carefully so as to give straightforward meaningful cues to users in order to avoid misunderstandings and/or require users to spend additional time memorising different sounds and their meanings.

2.9 Audio-Haptic Games & Games for Visually Impaired Users

Games or game-like environments may be used to test and evaluate the different parameters of *"multimodal designs for interacting with audio-haptic environment"* (Grohn, 2008). Many games have been developed aiming to test and exercise the cognitive ability of users, like the memory games with haptic objects. These games have been designed to primarily assess and practise the ability to remember the positions of objects that are randomly placed in haptic environments (Magnusson et al., 2002).
Some games that are accessible to visually impaired people are Terraformers, AudioQuake or the audio game Sarah and the castle of witchcraft and wizardry make excellent use of audio cues to support navigation. However, audio-haptic games are still less mainstream (Szymkiewicz et al., 2008). Some of these games are presented below:

- **Memory House by Sjöström**

Sjöström at Lund University conducted a series of tests with "The Memory House" game to find out if it is possible to understand and control a system like Windows with only haptic and audio information (Sjöström, 2000). The game consists of 25 buttons and every time they are pressed they produce a sound. There are 12 pairs with the same sound and one with non-paired sound [See Figure 2-5: The Memory House].

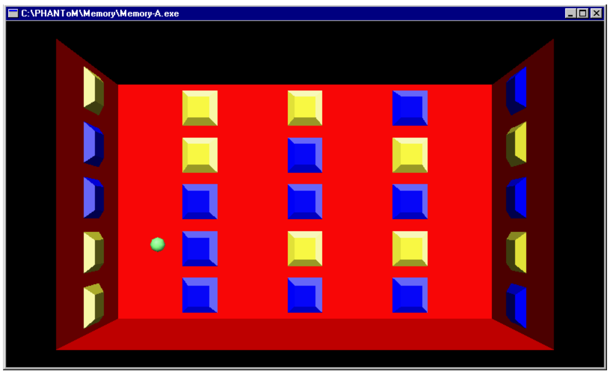


Figure 2-5: The Memory House
(Adopted from Sjöström C.)

The buttons are placed in 5 different rows and between them there is a thin line barrier which helps blind users to feel it using the PHANToM and therefore stay within one set of buttons. To help users navigate in the game environment and among the different rows there is a voice that reads out the number floor when a user moves from one row to another. This game has been tested by both blind and sighted people and comparisons have been extracted. The main outcome of these tests indicates that it is possible for almost any blind user to navigate among the sound buttons in the game. Blind users did almost as well as their sighted peers with the latter needing less time (Sjöström, 1997).

Therefore, it can be said that blind and sighted people do have the same perceptual and memory capabilities and that performance does not necessarily rely on vision. Vision in this experiment acts as a complementary aid, which contributes only to improving the time needed to complete the game. This helps explain the fact that sighted people needed less time to finish the tasks.

- **GRAB Haptic Audio Virtual Environment**

Wood et al. (2003), developed and evaluated a computer game for blind and visually impaired people using a new haptic audio virtual environment (HAVE). The GRAB HAVE consists of a new two-finger haptic interface and

Haptic Geometric Modeller which enables people to locate and interact with 3D computer-generated objects using their sense of touch and audio feedback. The primary questions they tried to approach were whether users can locate and successfully identify virtual objects and how they can effect changes to the game environment and if they can perceive such changes when they occur. Results have primarily shown that players mastered the game in a very short time which might indicate that tasks were not very challenging, something players confirmed with their feedback given in the questionnaire. Wood et al. (2003), commented that future improvements of the game should include a complex environment to create a sufficiently challenging game and a rewarding experience to successfully engage players. There were also a number of participants who found the game an immersive experience, despite its simplicity which may indicate that they had enjoyed the game. Overall, the testing had shown that the GRAB environment is suitable for gaming and that it has the potential to further be developed and improve some of the drawbacks identified during this testing.

- **Memory Game by Magnusson & Gröhn**

A very similar application to the Memory House is the Memory Game developed by (Magnusson & Gröhn, 2005). The virtual space of the game consists of 10 touchable spheres randomly distributed in the workspace. Each sphere is assigned a sound and users need to match the pairs [See Figure 2-6: The layout of the memory game
(Adopted from]. The haptic device blind users used to explore the VE was PHANToM. Having in mind the previous game results, the research group tried the drawbacks and improve the game. One such change was to divide the tool designs into sound designs and designs based on haptic feedback.

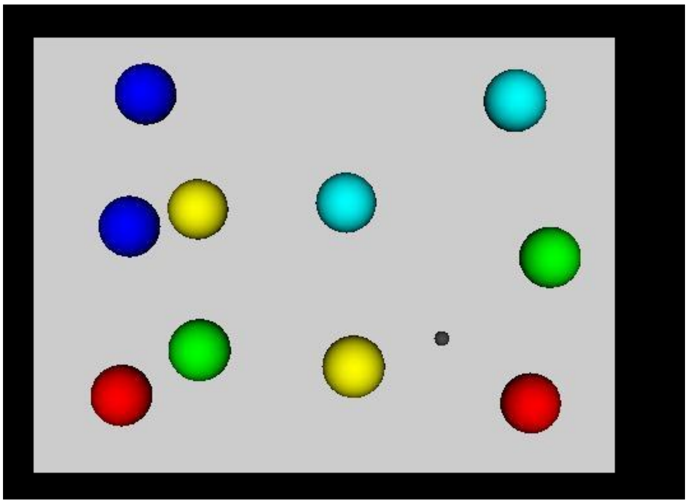


Figure 2-6: The layout of the memory game
(Adopted from **(Magnusson & Gröhn, 2005)**

Results have shown that the presence of a haptic search tool reduced the completion time. Moreover, findings supported that the combination of audio and haptic feedback makes it possible for blind users to use tools like attractive force and fixture effectively.

- **VITennis – Visual Impaired Tennis**

A very interesting application was built by the Human Computer Interaction Research Group at the University of Nevada, USA (Morelli, 2010). Using the Nintendo WiiMote they developed a software called VITennis [See Figure 2-7: VITennis Screenshot
(Adopted from http://www.slideshare.net/eelkefolmer/vitennis-a-vibrotactileaudio-exergame-for-players-who-are-visually-impaired)] to enable visually impaired users to play virtual tennis. They have taken into consideration the popularity and expansion of the game industry in the last decade and noted that most of these games strongly rely on graphics, something which is essentially impossible for visually impaired players. They also believe that *"traditionally, video games have done very little to increase activity amongst the players".* Studies have shown that traditional video games sometimes promote unhealthy behaviour even more than watching TV (Sinclair et al., 2007). The emerge of video games' new trend the exergames (Vandewater et al., 2004) has received some very positive comments mainly because of its nature, that

requires physical activity instead of the traditional button pressing. VITennis improves the audio and haptic cues in order to help the player to formulate a correct representation of the VE. The game has spatial audio cues in such a way that players know where the ball is and where it is heading, to the left/right of the screen. Visually impaired players receive haptic feedback through the WiiMote rumble capability which helps them to understand when to swing.

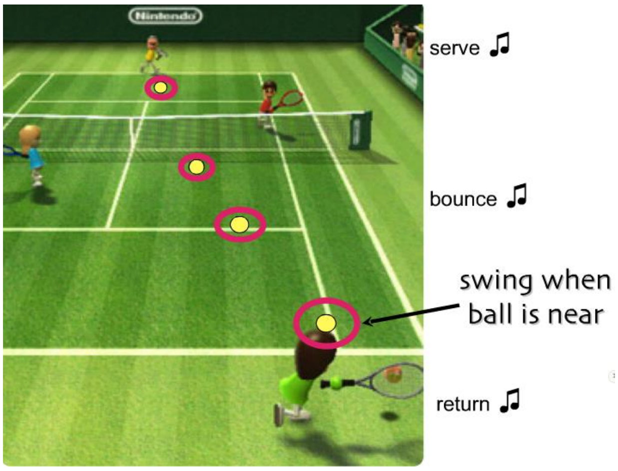


Figure 2-7: VITennis Screenshot
(Adopted from http://www.slideshare.net/eelkefolmer/vitennis-a-vibrotactileaudio-exergame-for-players-who-are-visually-impaired)

Preliminary investigation with 13 totally blind students focused primarily on monitoring energy expenditure by using wearable accelerometers. Results showed that levels of energy expenditure are higher than in regular video game playing. These levels were high enough to contribute to the daily recommended dose of exercise for children (Morelli, 2010).

- **Terraformers**

Terraformers is the first 3D game for both sighted and visually impaired people and it has been developed by the Swedish team Pin Interactive (http://pininteractive.com/). The developing team tried to create an environment that takes place in the future by creating an audio 3D environment that is created both with realistic and complete graphics but at the same time a full sound interface gives complete access to the same information in audio [See

Figure 2-8: Print Screen of Terraformers
(Adopted from http://pininteractive.com/)].

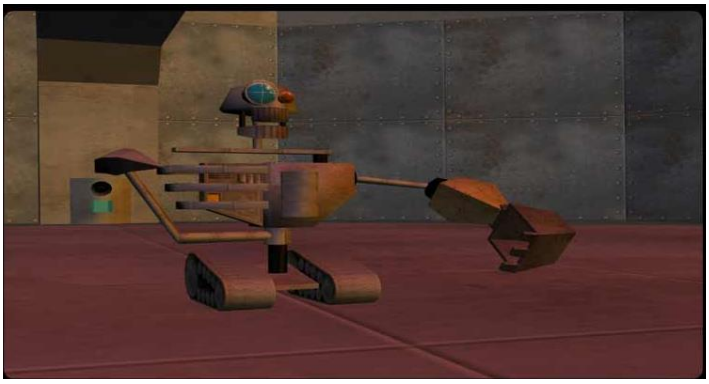


Figure 2-8: Print Screen of Terraformers
(Adopted from http://pininteractive.com/)

- **AudioQuake**

AudioQuake is the new generation of Quake of AGRIP Audiogame (http://agrip.org.uk/). Its main aim is to make it accessible to visually impaired people and furthermore promote game collaboration/competition between sighted and non-sighted people. It is an active development and developers aim to make it (http://audiogames.net/db.php?id=audioquake):

a) An internet multiplayer game.
b) Accessible mapping tools, based on the LevML standard
c) Implicit Accessibility by 3D audio and special effects.

2.10 Rendering Drawings for Interactive Haptic Perception

Foley describes rendering as the process of creating images from models (Foley et al., 1990). Kurze (1997) describes vision as " *the primary sense of perception the majority of images are created for visual perception"*. This unfortunately excludes the people with low or no vision who attempt to perceive images as a source of information. However, tactile images are available to visually impaired people in order to give them access to 2D represented information like diagrams, pictures and maps (Edman, 1992).

Up to date 2013, there is no systematic approach of how tangible images of 3D objects can be designed. There is not a particular method or an algorithm that can actually render haptic images of spatial real world objects . There have been a number of different experimental approaches so far, that blind people are asked to draw different motifs or study haptic scenes and then explore them in real time (Kurze, 1997).

In 1996 Kurze conducted a series of experiments using a specially designed tactile drawing tool (Kurze, 1996) where blind people were asked to render images of tactile models. Figure 2-9: A drawing by a blind student (Adopted from Kurze, 1997), shows how a blind student rendered an image of a table, a bottle and a car.

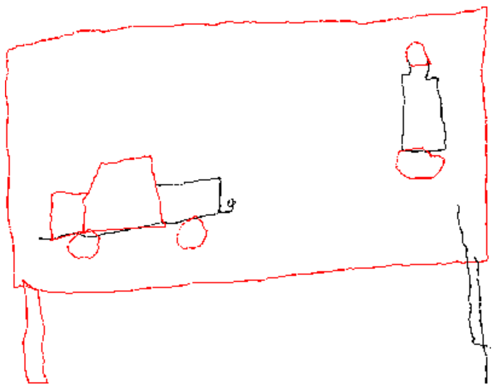


Figure 2-9: A drawing by a blind student

(Adopted from Kurze, 1997)

Based on a series of similar experiments three general conclusions were drawn (Kurze, 1997):

1. The "look and feel" of the drawings is completely different from visual drawings. While no perspective distortion was used, all the properties that were available haptically were represented in the drawing. The rectangles have been drawn as rectangles but parts that are not visible have also been drawn, for example circles of the top and bottom of the bottle (Kurze, 1997).

2. The process of drawing is mainly determined by the process of perception. Starting at a prominent part of the object and the scene all the connected parts are firstly explored and then presented on a paper, leading to a drawing where all parts that are available haptically have been drawn.
3. Some depth cues are also used. An object located at the background is drawn first by using thin lines and the foreground is added later with thicker lines. This means that the foreground overlaps the background.
Taking into consideration all the above and based on what related research has shown, there are a number of issues that should be taken into consideration in achieving useful design of haptic drawings:

a) In general, all touchable surfaces, objects and edges should be presented. *"This raises a question of how to determine tangible surfaces and edges"* (Kurze, 1997) & (Kurze, 1996).
b) Another important question is how depth can be achieved in drawings. Since there isn't any visual feedback, haptic properties must be used. One possible solution is the use of thin and thicker contour lines representing background and foreground respectively.
c) What sort of other types of media can be used and how? Since the level of resolution of haptic sense is low, additional inputs, like speech, should be used where appropriate and also since blind people have different needs there should be other methods available for one to choose and customise the working environment. This finding was enhanced during the series of tests conducted for the current research. Students' preferences on audio outputs and instructions vary, as some of them felt more confident when having audio instructions throughout the trial; whereas some others felt it could be disruptive and misleading.

The Haptic Rendering Pipeline

A haptic rendering pipeline is a series of sequential operations performed by the renderer that may lead to significant alterations in the model and in the resulting drawing. Figure 2-10: The haptic rendering pipeline (Adopted from Kurze, 1997) shows the traditional haptic rendering pipeline as presented by Martin Kurze (1997).

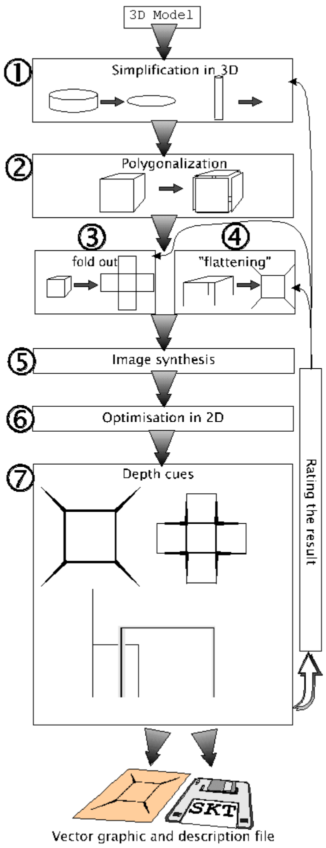


Figure 2-10: The haptic rendering pipeline
(Adopted from Kurze, 1997)

The primary input for the haptic renderer is a description of the scene with the geometric model of the objects that appeared in it, their positions and properties. If there is any text information associated with a single object, this is managed as well. The steps of the rendering pipeline are:

1. *3D Simplification*: The whole scene is explored object by object. Relatively flat objects are closest to 2D equivalents and are then transformed into the equivalent 3D objects. For example flat cubes are distorted into single square illustrations and vice versa.
2. *Polygonalization*: The process of splitting a 3D object into a set or polygons. In other words to be able to fold-out the objects' faces e.g. a cube is disassembled into a set of squares.
3. *Fold-out Faces:* Each object's faces are folded out in order to be arranged in a single plane.
4. *"Flattening" linear parts:* To flatness of an object depends on the point of view from which one sees the object. The other parameters have to do with rotation and while faces are being rotated around a single edge the rotation axis of lines is not predetermined (Kurze, 1996). An example of flattening of a table is shown in Figure 2-11: Flattening
(Adopted from Kurze, 1997). The first version is chosen if the table is surrounded by other objects whereas the second when objects stand on table-top.

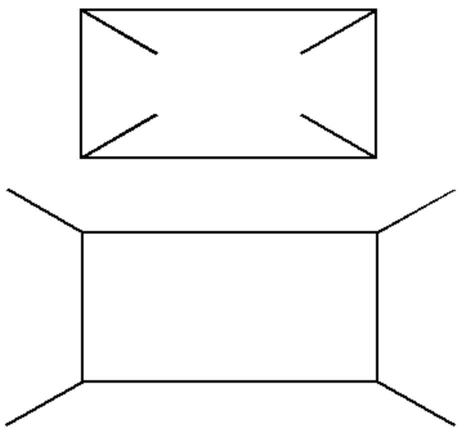


Figure 2-11: Flattening
(Adopted from Kurze, 1997)

5. Image Synthesis: Since the first steps deal with object manipulation in 3D, during this stage the 2D mapping is carried out. Image synthesis is described as *"the process of creating new images from some form of image description"* (Fisher et al., 2003).

6. *Optimization in 2D*: In some cases, where a draft image contains lines that are very close to each other and therefore very difficult to be haptically distinguished, objects are moved away from each other to resolve the issue.
7. Depth Cues: Now all information regarding depth have been removed, users can either rely on the context of information or on their general knowledge, for example table legs reach from the table top-down to the floor.

Up to this point all manipulations of 3D objects were made in order to match the needs of haptic perception as much as possible. The goal is to get to a level where the minimum possible manipulations are needed to achieve the understanding of the image. Kurze argues that *"the more mental rotations and manipulations are needed the more difficult is the process of understanding an image"* (Kurze, 1997). This can be expected as information overload may lead to misunderstanding results and the inability to optimally evaluate the collected information/cues.

Kurze (1997), based on the haptic perception that was explored and discussed in the haptic rendering pipeline, performed an experiment to justify the specific theory involving both early and late blind subjects. The steps are listed below along with the findings of each level and the conclusions drawn:

1. Single objects' drawings were presented with no added information and text support added. His intention was to find out whether drawings can be recognised without any technical or personal support and only by exploring the hard copy.
2. After going through the set of drawings users were asked to assign the drawings to the corresponding real objects [See Figure 2-12: A pot. Note the difference between the two circles representing the opening and the bottom]. To make it even more challenging, the objects available were similar to each other but yet only a single object was the 3D corresponds to each drawing example.

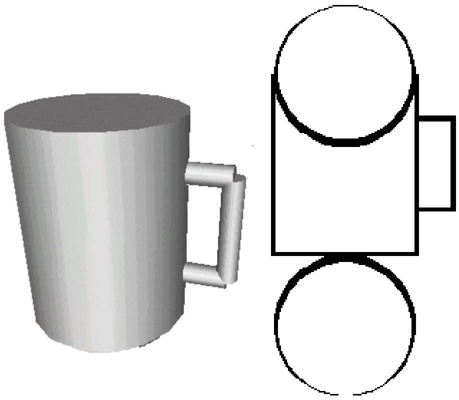


Figure 2-12: A pot. Note the difference between the two circles representing the opening and the bottom
(Adopted from Kurze, 1997)

3. Drawings of compound scenes were given with a presentation system, similar to Nomad or Audio Touch (Lotzsch, 1994), which is based on a touch pad and a speech synthesizer. The Speech synthesizer was only used to provide users with only objects' names and no spatial information was given. Participants were asked to set up the scene using toy models by comparing the scene with the original 3D model.
4. The final and most challenging task was a drawing of a kitchen that was completely unknown to the participants. There were all things that can be found in real kitchens, like closets, appliances and dishes [See Figure 2-13: A kitchen for a real world task,
rendered visually (left) and haptically (right). Their task was to prepare a coffee-brewing task. Participants first explored the image and then they entered the real kitchen to complete the task with materials and objects they had previously explored in the image. A very similar series of experiments based on the same philosophy, let blind people explore a meso-space environment haptically e.g. a school building and then asked them to navigate in real time in the real buildings. In a more extended use of this test, blind users may benefit as they will be able to learn about unknown environments by exploring them either through haptic images (for small scale areas) or by virtual haptic exploration (for larger scale areas).

Figure 2-13: A kitchen for a real world task, rendered visually (left) and haptically (right).
(Adopted from Kurze, 1997)

2.11 The importance of spatial information in haptic exploration

As mentioned in the previous section, the earliest features that the visual system extracts from objects are spatial in the form of oriented edges in order to place the object in space (Klatzky & Lederman, 2003) & (Klatzky et al., 1985). Blind students are aware of edges e.g. the edges of the blind girl' shelf in the experiments of Klingenberg, but it is difficult for them to conceptualize edges as a global shape lying beyond the reach of the hand (Klingenberg, 2007).

Klatzky & Lederman (Klatzky & Lederman, 2003), distinguish between "spatial information" and "intensive information". Spatial information describes the physical location of an object and the relationship between objects (http://www.crcsi.com.au/About/What-is-Spatial-Information). On the other hand, intensive information is the human intention of extracting more information about something in a closed space. Sighted people accomplish this task through sight while blind people rely heavily on their touch to acquire the needed information. There are three different types of tactile/haptic edge layout (Klingenberg, 2007):

2. The edges may form a 2D pattern within the scale of a fingerprint.
3. The edges may form a 2D pattern that extends beyond the scale of a fingerprint.
4. The edges may form the contours of a fully 3D object, e.g. a book, desk or a vase.

A small object which can be held in one or two hands can be easily manipulated and users may extract the necessary information to recognise it. If an object is beyond this scale and needs freestanding exploration e.g. a book shelf, it is a much more difficult and slow process for tactile and haptic exploration.

Three issues arise that suggest that attention must be paid to the understanding of the properties of 2D and 3D figures:

1. Firstly, visually impaired students have more to learn and consequently must spend much more time studying than their sighted peers. This is because they need to receive specific education and training to gain understanding on reading and making tactile drawings. *"This eventually leads to a big dilemma as to whether more attention should be paid to and priority focused on these extra educational inputs and assistance"* (Klingenberg, 2007). Another dilemma which arises here is whether it is reasonably fair for blind students to receive more teaching time than their sighted classmates? Or should blind students receive excemption from classes that require spatial awareness and pay attention to modules that come more readily to them?
2. Secondly and equally important is the way lessons in classrooms are carried out. Blind students should be offered the opportunity to express their tactile/haptic exploration and discuss with their teachers to receive appropriate and immediate feedback. Furthermore, sighted students should receive education on how to treat their visually impaired classmates and what they are capable of doing. It is important for them

to understand the special needs their blind peers have in a class and on particular activities and how they perceive the spatial environment. Teachers in schools say that blind students are often isolated by their sighted peers in primary schools. This is mainly because the sighted students see visually impaired students as "disabled people" who cannot compete in today's society, people that need special treatment and people that it is impossible to socialize with. Others fear getting involved (becoming friends) with a blind classmate because they do not feel in any way that they have the same interests. There are others who feel afraid of responsibilities they might have to guide a visually impaired person around. There is of course the group of students and parents who believe that visually impaired students should attend special schools in order to receive appropriate training and education from specialized teachers. This last approach is not as bad as it might sound but what happens when psychological research insists on an inclusive society? Again there is the issue that every human being has the right to be included in society and receive equal opportunities and assistance.

3. Finally, there is the issue of the learning material. *"Should the tactile illustrations be presented in a multiple-choice framework and should there be a text explaining the illustration specifically?"* (Klingenberg, 2007). It has been shown that tactile illustrations associated with text are more easily read and understood by blind students (Kennedy, 1993) & (Tanti, 2007). In the first case, it means that the tasks in the Braille books have to be transformed in a different way than the original tasks in the books in ordinary reading. Both solutions are "more to do" results: more text or more illustrations for the blind students to be taught (Bouaziz et al., 2005).

Klingenberg (2007) proposes that geometrical materials presented with specific norms in the case of surfaces might be the avenue to help blind students to build up an understanding on these objects. By using 2D material in school may make students' activities more manageable by teachers since it is less complicated and less difficult to organise a group of students working on known tasks from their books rather than using 3D objects. But this might not be the best possible solution since blind students find it challenging to identify real objects based on tactile 2D figures. However different approaches that can be used, like *"models with specific weight and some sort of resistant surface that is nice to touch may form a possible solution to replace tasks in the schoolbooks",* Klingenberg pointed out (Klingenberg, 2007). Nevertheless, students with visual impairment need to work with both 2D and 3D objects, because substituting 3D material is important in helping students to develop a "functional understanding".

In Norway (Klingenberg, 2007), blind students may get exemptions from geometry and instead have another module of the curriculum that it is easier to master and which does not rely heavily on spatial awareness and thinking and reasoning skills. This very often influences education throughout all school years in the way that geometrical literature is downgraded. The question is whether downgrading the level of teaching geometry is a good solution.

2.12 Visuospatial cognition

"Visuospatial mental images" refer to specific types of mental representations that result from a complex cognitive process that depends on different information sources e.g. visual, spatial, tactile and conceptual (Cornoldi et al., 2003). Then, collected information is processed within the "Visuospatial working memory system" (Klingenberg, 2007), which extracts specific information of the object that is not fully identical to the original one. This specific information works as a reference to objects' mental models that are easily retrieved when needed to present or identify the particular object. Born-blind people are able to develop mental images but they are organised in a different way from that of sighted people's mental images and they are heavily dependent on the person's perceptual experience and haptic cues collected (Bouaziz et al., 2005) & (Cornoldi et al., 2003).

Many comparisons have been made between blind and sighted people and their ability in a variety of spatial tasks, like rotation, pathway memory and word imagery. Every single study results in two fundamental outcomes: blind people’s group performs either less accurately or more slowly than the sighted control group (Fleming et al., 2010). What is interesting is the findings of some researchers who propose that blind and sighted users use the same patterns of performance, which shows that both groups utilise similar mental representations (Heller et al., 2005). According to Fleming (2010) and his findings, most perceptual data used by blind people is received and processed consecutively (e.g. haptic and audio information) whereas visual data is received and processed in parallel. It has therefore been concluded that these shortages may appear due to the serial processing of sound and touch that can be slower and more vulnerable to errors than the parallel processing of vision (Aleman et al., 2001).

CHAPTER 3

State of the Art:
Technology

3.1 Introduction

Haptic technology attempts to add the sensation of touch to computer interfaces so that it is possible to "touch" virtual objects. Haptics are gaining widespread acceptance as a key part of virtual reality systems, adding the sense of touch to previously visual-only solutions. Most of these solutions use stylus-based haptic rendering, where the user interfaces with the virtual world via a tool or stylus. This technology is described in detail in Chapter3.2 A taxonomy of current Haptic Technologies. Researchers from the University of Tokyo have developed 3D holograms that can be "touched" through haptic feedback using "acoustic radiation" to create a pressure sensation on a user's hands. This technology was presented in SIGGRAPH 2009 in New Orleans (Zyga, 2009). Ruspini (2003) says that the term haptics *"is used to describe different concepts related to human perception and understanding through touch"*. In Touching for Knowing (Hatwell & Martinez-Sarrochi, 2003), describe the *"close link between perception and action in haptic functioning".* In order for blind people to perceive haptically they are required to actively move their hands. In human computer interaction (HCI) the haptic sense is enabled when a user moves the mouse or strikes a key on the keyboard. Virtual haptic interfaces can provide either tactile – Braille display – or kinaesthetic – force feedback displays. Therefore, Haptics can be grouped into the following categories:

1. ***Haptic technology:*** technology that users interact, through the sense of touch. Technology may assist in the creation of virtual objects and environments that will enable users to explore a virtual world and additionally to enhance the remote control of machines and devices (tele-operators). In recent years haptic technology has allowed users to get training in significant tasks, like doctors performing brain operations or dental operations. It can also offer the feeling of texture of clothing for sale on the Internet (Jessica, 2003). Another good example of what haptic technology can do and how powerful it can be to visually impaired people is the study by Dr. Orly Lahav at the University of Tel Aviv (Lahav, 2006). The main aim of her study was to give "*navigational sight to blind users*". She has developed a software tool to enable blind users to navigate around unknown places. This software tool has a connected joystick that interfaces haptically with the user.

Lahav explains that "people can feel tension beneath their fingertips as a physical sensation through the joystick as they navigate around a virtual environment that they only feel" (Lahav, 2006). The joystick offers a variety of force feedback to the user to inform him/her about obstacles they may find during the exploration. For example it stiffens when the user meets a virtual wall or barrier. Users can be also hear sounds like phones ringing when they walk by a reception desk! Dr Lahav (Lahav, 2006) had presented the specific project to a conference in the USA. At the conference, a partially blind woman first explored the VE of the centre as well as the campus. After only 3-4 sessions of practice the woman was able to effectively navigate and explore these sites while blindfolded. This discovery gives very positive hope of creating a virtual guide or a cane that will improve the way in which blind people can learn to navigate and thereby give them a higher degree of independence. Similar findings were obtained from another study which was conducted at the Nottingham Trent University (Evett et al., 2008) where blind people used a Wii controller as a virtual cane to navigate around a virtual campus. This study, which is described in more detail in Section 3.4, has "*made it possible to investigate in detail how the human sense of touch* *works by allowing the creation of carefully controlled haptic virtual objects*". These objects are used to *"systematically investigate human haptic capabilities, which would otherwise be difficult to achieve"* (Monkman, 1992). These new research tools may contribute towards the better understanding of how touch and its underlying brain functions work.

2. ***Haptic perception:*** the ability of a person to recognise objects through touch. To achieve this involves the combination of three parameters. These are "*somatosensory*" [1] perception cues or patterns like edges, curvature and texture, "*proprioception*"[2] tools that are the position of the hand and body with respect to the object and how comfortable the person feels (Klatzky et al., 1985). Haptic perception relies on forces applied to the user like vibration, motion and force-feedback (Stedmon et al., 2007). Haptic perception is particularly important to people with low or no vision. They rely heavily on the sense of touch to enable them to interact with objects, people and spaces (e.g. walking around the house).

Based on the above one can come to the conclusion that the sense of touch is very critical for both sighted and non-sighted people. Lack of the sense of touch can be catastrophic to a person, since she/he won't be able to grasp objects, feel heat or even be able to walk.

Some commercial computer games already benefit from early haptic devices, like the force-feedback joystick of Nintendo Wii and PS3 Move.

The rest of this chapter presents the state of the art in the domain of haptic technology. Several reports and articles have been published in the context of research projects which are publicly available. Therefore, the aim of this chapter is to present what has been done in this area.

[1] The somatosensory system is a diverse sensory system comprising the receptors and processing centres to produce the sensory modalities such as touch, temperature, proprioception (body position), andnociception (pain)
2 Proprioception is the sense of the relative position of neighbouring parts of the body.

3.2 A taxonomy of current Haptic Technologies

Current haptic technology is a varied field. Devices range in size from very small to very large and also from very simple to very complex. This section will provide a systematic taxonomy of all current types of haptic devices that have been considered as being potentially useful or relevant for the system being proposed.

3.2.1 Dimensions of the taxonomy

The common denominator of all haptic devices is that they seek to make an impression on the tactile or kinaesthetic senses of the user. These senses act on different dimensions, the smallest scale being perceived within the skin (tactile sense), and the larger scales mostly in tendons, joints and muscles (kinaesthetic senses) (Stedmon et al., 2007).

The level of detail in the haptic world could be termed as the *'spatial frequency content'* of the haptic experience (Miguel et al., 2004). Another distinguishing factor to consider is the frequency response, which can vary from very slow to very quick. According to Stedmon the various dimensions of this taxonomy can be grouped in (Stedmon et al., 2007):

<u>Size scales</u>

Humans can haptically perceive the world around them on a number of scales ranging from the reach of the human arm (order of 1 meter) through that of the spreading and grasping fingers of the hand, (order of 0.1 meter) via details felt by the skin on the finger tips and palm of the hand (order of 0.01 to 0.001 meter, i.e. down to 1 millimetre) all the way down to surface roughness or texture which may live at the micrometre level and which can only be explored by sliding the fingers over a surface.

The first scale is perceived by movements of the arm, with receptors in joints, tendons and muscles. It is usually referred to as the *kinaesthetic or haptic scale*. The second scale is felt by the exploring and grasping movement of the fingers, perceived through a combination of kinaesthetic clues and skin deformation indicating the orientation of the surface that is touched by the fingers. It is usually referred to as *tactile/haptic*. The third scale is explored by various receptors in the skin, and referred to as *tactile*. The fourth scale is perceived by high-frequency receptors in the skin, and is often referred to as *vibro-tactile*.

Degrees of freedom (DOF's)

The number of degrees of freedom indicates the level of detail that the device can render simultaneously at any given time. In mechanics, degrees of freedom (DOF) are the set of *"independent displacements and/or rotations that specify completely the displaced or deformed position and orientation of the body or system"* (Gould & Lewis, 1985). Degrees of freedom can be classified as follow:

- ***Six degrees of freedom (6DoF)*** refers to motion to the ability of a body to move forward/backward (Surging), up/down (Heaving), left/right (Swaying) in three perpendicular axes, combined with the rotation about it, pitch, yaw, roll in a three dimensional space [See Figure 3-1: Six Degrees of Freedom Illustration (6DOF)].

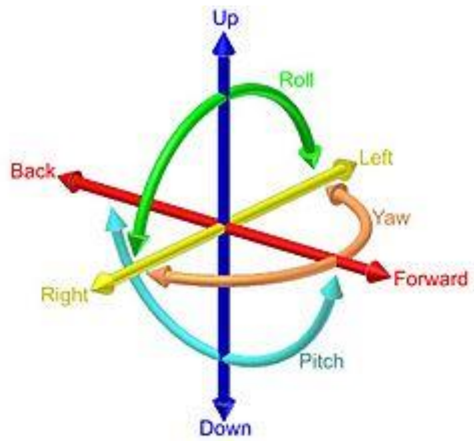


Figure 3-1: Six Degrees of Freedom Illustration (6DOF)
(Adopted from Wikipedia)

- ***Point-based force feedback interfaces*** – refer to haptic devices that give force feedback in only one single point. These devices are also called point-based and most commercialised haptic devices are of this type.
- ***Tilting (and curving) surfaces*** - some experimental devices add local degrees of freedom to the end-effector of point-based force feedback devices. These may take the shape of small plates tilting under the finger, or thimbles tilting on a movable roller. Sometimes these effects take the place of 'normal' degrees of freedom, substituting a haptic illusion for true '3D motion Morpheotron' (Stedmon et al., 2007). The cues that are generated to the user's finger could be very useful in the proposed project (initial thought See Appendix B) as blind users might be able to make use of such cues to interpret a geometrical object. These tilting interfaces may generate easier and more understandable cues to the users.
- ***Shape and contour interfaces*** - shape interfaces exist at various scales, from the larger contour devices to tactile 'pincushion' type devices. They are usually based on some form of grid. The number of degrees of freedom often equals the number of grid points but in some cases each grid point can do more than just rise vertically and the number of DOF's may be even larger as this was described by John M. Kennedy's studies (Kennedy, 1993) & (Kennedy, 1997) & (Kennedy & Tipps, 1994).

Grounding and Kinematics

There are two types of haptic devices, the ones that are wearable by the user, like the CyberGlove and the ones that are fixed (grounded), the "inertia world".

Contact Type

This describes the level of the contact between the user and the device. They may be organised into two categories: the ones where the user has a continuous contact with the device even if he/she touches nothing in the virtual environment or the "encountered" type, where the user is in contact with the device only when the latter is touched by the user. Most force feedback devices are of the first type and most shape and tactile devices are of the latter type. The classical VR application of a control stick or a steering wheel in a flight simulator is technically an encountered device, although the user stays in full contact with it during most of the simulation (Stedmon et al., 2007).

The contact type of the force feedback device of the initially proposed system [See Appendix B] is preferably to be of the encountered type that responds only when users touch something in the virtual environment.

Control type

There are two types of force feedback:

- *Impedance controlled*: The majority of the available devices today are of this type. They are mechanically designed in such a way as to be able to 'render' free air (i.e. low mass and low friction when passive) and to render virtual walls in virtual environments (VE) and inform the user of the existence of the first by sending resistance forces via the motors (Stedmon et al., 2007). This is particularly interesting and helpful for navigation software built for blind people.
- *Admittance controlled*: Their causality paradigm is exactly the opposite of the impedance controlled devices. Here the user inputs force to the device so that the latter responds with a displacement. Admittance controlled devices are usually built to be stiffer and more robust, (Stedmon et al., 2007).

The following table is based on the taxonomy presented above:

Taxonomy Dimensions	Description
Size scale	Human perception of the world according to scaling factors
Degrees of Freedom (DOF)	Level of detail that the device can render simultaneously at any given time
Control type	Impedance controlled devices & admittance controlled devices
Contact type	Continuous contact of the user with the device or 'encountered' type of device

Table 3-1: Taxonomy Dimensions
(Adopted from Stedmon, et al., November 2007)

3.3 Current Haptic Technologies

Following in this section there is a presentation of the current haptic technology along with some uses of this technology.

3.3.1 Existing haptic/force feedback displays

Today the majority of force feedback devices use linkages and motors to generate force and convey it to the users' finger, hand or arm at a single point. Single point of interaction in the context of non-visual interface allows users to dynamically create a mental model of the object by haptically exploring it and therefore receiving information in sequence (Grohn, 2008).

There are a number of different haptic technologies available in today's market. The majority of these devices have been developed by universities and research institutes and they are not commercial products. For those researchers that do not choose to develop their own haptic device, the PHANToM is among their first choices. There are also lots of experimental designs of haptic machines that offer a limited number of degrees of freedom, typically 1-DOF and 2-DOF. (Stedmon et al., 2007).

3.3.1.1 Opposing Type

Opposing type machines are those that either stand on the ground or sit on a table opposite the user e.g. the PHANToM Omni. They are stand-alone machines and they are not physically attached to the user's body or hand, like the wearable or exo-skeleton devices described in the next category.

Serial kinematics

Most 3-DOF and 6-DOF haptic robots are of the impedance controlled type (the classic example of this first category of 'opposing type' serial robots is Sensable's PHANToM) with serial kinematics. Some commercial products include the following:

- CEIT large workspace gantry robot
- Haption Virtuose 3D and 6D

✓ *VIRTUOSE 6D35-45:* this is the only product on the market today, which offers force-feedback on all 6 DOF (Stedmon et al., 2007).

Figure 3-2: Virtuose 6D35-45
(Adopted from http://www.inition.co.uk/3D-Technologies)

✓ *VIRTUOSE 3D15-25:* this is a 3D haptic interface (3 DOF with force-feedback and 3 DOF with position sensors). (http://www.inition.co.uk/inition/pdf/ffhaptic_haption_6d35-45.pdf).

Figure 3-3: Virtuose 3D15-25
(Adopted from http://www.inition.co.uk/3D-Technologies)

- SensAble Technology (http://www.sensable.com/) is one of the few companies that are explicitly focussing on the development of 3D touch-enabled force feedback solutions and technology that allows users to 'feel' what appears on screen. This technology offers users full interaction with the computer by enabling the sense of touch besides sound and vision. This gives the freedom to work in *"a more natural, intuitive way"* (Larsen, 2005) and also gives power to non-sighted users.

✓ *PHANToM Omni Haptic Device:* PHANToM Omni is one of the most reliable devices on the market and is generally considered to be the device that gives the most accurate haptic cues to the user. It is a haptic device which simulates a pen in 3D free space with the help of software called VTK Designer. It has been developed by SensAble Technologies in collaboration with research conducted at MIT in the 1990s by industry pioneers Thomas Massie and Dr. Kenneth Salisbury. It is used in a variety of applications starting from practising medical and dental operations in a suitably designed virtual environment, to virtual sculpting. It has also contributed dramatically to the improvement in many aspects of the life of visually impaired people. (Salisbury & Mandayam, 1997) in one of his studies states that he believes that the use of PHANToM Omni can help blind people or those with poor eye sight to learn the alphabet as easily as their sighted peers do by copy-writing. It can be used to guide the hands of a blind person to help them learn not only the alphabet but any drawing. When tested on 8 blind participants, within 20min of practice they could easily write. In the real world the users hold in their hand a pen attached to a mechanical arm placed on the top of the desk. The physical pen users hold in their hand is translated *"into its virtual counterpart rendered on the screen"* as is shown in Figure 3-4: PHANToM Omni Haptic Device. The virtual pen follows the movements of the physical one and when the virtual pen collides with virtual objects appropriate forces are sent to the physical pen that guides the user accordingly.

One of the PHANToM's advantages is that it is capable of providing haptic-force feedback to the users. On the other hand, one of its main drawbacks is considered to be when exploring small objects. Therefore, in order to overcome this barrier users usually use both their hands and all of their fingers. According to Jansson's findings, it is demonstrated that object identification with only one finger is difficult and not accurate (Jansson et al., 1998).

There are many research groups that study *"methods of texture and geometry refinement in order to improve the sense of touch for texture"*

(Green & Salisbury, 1997) & (Massie & Salisbury, 1994) & surface curvature (Yu et al., 2000) identification when using the PHANToM.

The PHANToM Omni is considered to be the most reliable tools to enable blind users to draw, pick and manipulate 3D objects in virtual environments. The integration with other haptic devices, like the CyberGrasp, can lead to a powerful workspace for learning about geometry for visually impaired users. One main drawback of this product is considered to be its market price which remains unaffordable for many (schools and individuals) to buy.

Figure 3-4: PHANToM Omni Haptic Device
(Adopted from www.sensable.com/haptic-phantom-omni.htm)

✓ *PHANToM Desktop:* This device has the same characteristics as the PHANToM Omni but the PHANToM Desktop delivers higher fidelity, stronger forces and lower friction (SensAble Technologies).

Figure 3-5: PHANToM Desktop
(Adopted from www.sensable.com/haptic-phantom-omni.htm)

Parallel Kinematics

Parallel haptic robots are not as popular as the serial type. They have certain advantages, mainly their higher mechanical stiffness-to-weight ratio. One of the major disadvantages is the more limited workspace, especially in the rotational degrees of freedom. Some of the commercial and scientific examples of the stiff link variety include (Stedmon et al., 2007):

- Stiff link parallel robots
- Force dimension Delta and Omega [See Figure 3-6: Delta & Omega]. They are commercial implementations of a 3-DOF parallel robot architecture called 'Delta Robot'.

Figure 3-6: Delta & Omega
(Adopted from http://www.inition.co.uk/3D-Technologies/)

- The University of British Columbia/Quanser Phantograph 3D, 5D. Hayward (Hayward, 2001) has suggested the use of the two-arm Phantograph principle in haptics and this has been extended by Qanser into a 5-DOF commercial device.

3.3.1.2 Wearable Technology

As its name indicates, it is technology that is attached to the body of the user. Wearable exo-skeletons usually are of the hand or finger type. Feedback forces are sent to the lower arm or sometimes to the shoulder of the user. Because of their design "high forces cannot be rendered realistically". Active wearable devices are almost always of the hand-interface type and are discussed in the following sections (Stedmon et al., 2007):

- *Passive and hybrid drive robots* - These devices typically display forces by braking, using either electrical brakes or magneto-rheological fluid brakes.

3.3.2 Existing Auditory displays

Auditory display is the use of sound to communicate information in human machine interfaces (Riener & Harders, 2012) & (Kramer, 1994). Auditory display can be simple informing sounds, like the error sound or the notification sound when an email is received, the screen readers that read out text to a blind person or the heartbeat sound that is produced by the ECG (Electrocardiography) machines in hospitals (Grohn, 2008).

There are two types of auditory displays, the *sonification* and the *auditory icons*. The main difference between the two is that the latter *"are every day sounds in interfaces that have an iconic resemblance to the object or action that they represent"* (Gaver, 1994). The sound of a crumbling paper when emptying the recycle bin on the desktop is a type of auditory icon. Very similar to auditory icons are the *earcons* which are synthesized and abstract auditory indications used to present events and interface components. Therefore, they can be generated automatically, which is the main difference and advantage over auditory types (Brewster, 1994). Stephen A. Brewster, along with his group, ran some experiments to see whether earcons could establish an effective and efficient way of communicating information (Brewster et al., 1993). Findings of their research showed that they *"were better than unstructured bursts of sound and that musical timbres were more effective than simple tones*". However, Ulfvengren, believes that users find auditory icons easier to learn and if they are well designed they can provide them with a direct association of the intended message. Ulfvengren also argues that a well-designed auditory icon saves users from the *"cognitive load of needing to learn and remember the meaning of the earcons"* (Ulfvengren, 2003).

Sonification on the other hand - a form of auditory display - is the use of non-speech audio to convey information, messages and/or perceptualize data to users. A recent study conducted by Alseid (2011) at the University of Amman, Jordan, investigated the impact non-speech sounds like earcons and auditory icons have when used alongside speaking avatars in e-learning interfaces. Results supported that these sounds can be effective in *"communicating supportive information that is related to the learning materials"* if they are presented alongside *"a full-body animated virtual lecture"* (Alseid, 2011). Furthermore, experimental results have revealed that users were able to memorise and understand the meaning of these sounds.

Screen readers and a *text-to-speech* (TTS) are mainly used by blind or low vision people to access written data. Users have options to modify their preferences, for example the synthetic voice to be used to match their desires. In addition there are interfaces that operate better without sound. In fact this is one of the reasons why the Moose was invented (Gillepse & O'Modhrain, 1995) and (O'Modhrain & Gillespie, 1997). Moose is a 2D haptic interface that reinterprets the Microsoft Windows with force feedback icons such as the scroll down arrow and other screen elements like the edges of the window which can be easily tracked haptically.

3.3.3 Existing grasping displays

Force feedback gloves and exoskeletons – wearable

Force feedback gloves have their origins in low power 'data gloves' which are only used for tracking hand gestures.

CyberGlove: It is a motion capture data glove that uses *"proprietary resistive bend-sensing technology to accurately transform hand and finger motions into real-time digital joint-angle data".* [See Figure 3-7: CyberGlove (Adopted from http://www.cyberglovesystems.com/)] (EST, 2009). CyberGlove has much potential if it is combined with other technology like PHANToM Omni. Together they can create a fully integrated virtual environment that will enable blind users to feel and be able to recognise an object. Other advantages of the data glove are its ergonomical design, portability and light weight.

Figure 3-7: CyberGlove
(Adopted from http://www.cyberglovesystems.com/)

- *CyberGrasp*: This is another haptic device that offers force feedback on each finger and the hand. It is worn on the lower arm above the CyberGlove data glove (EST, 2009). [See Figure 3-8: CyberGrasp (Adopted from http://www.inition.co.uk/3D-Technologies/)]. A research group in Salonica, Greece, managed to show through a series of tests, that the integration of CyberGrasp and PHANToM Desktop, actually had some very positive results when tested by blind users. Although CyberGrasp on its own cannot prevent a user from penetrating objects in the virtual environments, the use of PHANToM desktop can achieve this. The results of this specific research study showed that most *"participants were very positive about beginning with simple objects and then proceeding to more complex ones, though there were some users who would have liked to deal with more complex scenarios"* (Nikolakis et al., 2005). This shows that the participants felt comfortable in using the integrated system which gave them the power to deal with more complicated and demanding scenarios. The point is of great importance for the system being proposed in the current work since the future scenarios/tasks will have to deal with more advanced and demanding tasks, like splitting a complicated 3D geometrical object to 2D objects and performing the appropriate calculations.

A major drawback in using the CyberGrasp is the design of the device. Since the proposed study focuses on young students, making them wear this piece of technology might panic them and therefore they might show some resistance to it. Furthermore, the main goal is to design something financially affordable and easily transportable for potential users. A final conclusion to draw from Nikolakis study is that technology based on VE may eventually provide people with visual disabilities new training and job opportunities.

Figure 3-8: CyberGrasp
(Adopted from http://www.inition.co.uk/3D-Technologies/)

- *CyberForce*: The CyberForce [See Figure 3-9: CyberForce (Adopted from http://www.cyberglovesystems.com/)] was an option designed to work with the CyberGrasp. Using these two devices together (along with the CyberGlove), users can sense weight and inertia while picking up a heavy virtual object or feel the impassable resistance of a simulated wall. Again due to its hardware design it is difficult to be used as a mobile and portable solution.

Figure 3-9: CyberForce
(Adopted from http://www.cyberglovesystems.com/)

- *Novint Falcon*: This is a relatively new haptic device aimed primarily at the game market, with a price that is comparable to other gaming platforms. The maximum workspace is 10*10*10 cm^3, the resolution is 400 dpi and the maximum force is 8.9N. The Falcon has a ball grip with 4 buttons that users hold to interact with the VE. It uses both grasping and force-feedback technology [More for Novint Falcon 3.4.3. Novint Falcon: The medium].

3.3.4 Existing surface displays

Local surface on a full contact force feedback display

There is an interesting category of devices that become more realistic in giving the impression and feel of touching a familiar and understandable object with the use of one or more fingers (Stedmon et al., 2007). Below is a brief presentation of some of these displays:

- *McGill Morpheotron* – When a person explores or touches an object haptically a number of items of information are gathered from different sources which enable elementary cues to be constructed that are then used to obtain a perception of that object (Dostmohamed & Hayward, 2005). Hayward et al (2000) at McGill University have shown that on tilting a finger platform surface an illusion of gentle curvature and depth can be created even in flat plane motion. The Morpheotron device is just a passive psychophysical proof-of-concept device with a tilting surface attached to the wheels by a crank [see Figure 3-10: The Morpheotron Haptic Interface (Adopted from http://www.cim.mcgill.ca/~hanifa/Morph/index.html)]. It is not considered to belong to the family of virtual reality devices but it has shown that tilt does contribute to the perception of shape and that programmed tilt can actually simulate gentle curvature of motion even in straight line motion (Dostmohamed & Hayward, 2005).

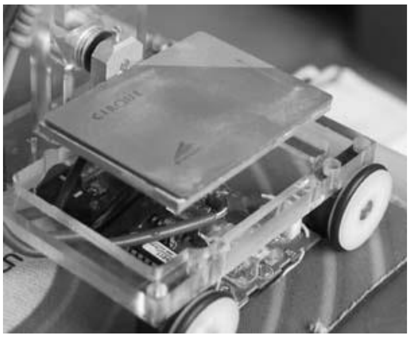


Figure 3-10: The Morpheotron Haptic Interface
(Adopted from http://www.cim.mcgill.ca/~hanifa/Morph/index.html)

- *Touch and Design Project – this EU project* (http://www.kaemart.it/touch-and-design) has created a prototype of a local surface interface which went a step beyond an oriented local flat surface. It displays not just the orientation but also the local curvature (in two dimensions) of the surface patch. The T'nD project tried to bridge the gap between traditional hand-made models and the computer aided system like computer aided design (CAD) and computer assisted surgery (CAS). T'nD's goal was to provide users with the functionality that informatics and mathematics can bring but via a manual interface that relies mainly on touch.

Local surface on an encountered display with tracking

Local surface displays are of the encountered type (Stedmon et al., 2007):

- *Johns Hopkins 'VisHap'* - this system uses a PHANToM as the platform to detect and interpret very small objects of a shape e.g. a push button. The user's hand is tracked by a camera based vision system and the device is attached to the user's hand. When contact is made, the force feedback is applied in the usual impedance controlled manner (Ye et al., 2003).
- *Tachi - Pen de Touch* – A very interesting system has been built by Tachi Lab (Tachi et al., 1994). 'Pen de Touch' provides the user with a pen-shaped handheld haptic display that allows haptic interactions with VE by generating kinaesthetic sensations on the user's fingers. Unlike conventional haptic displays that mainly provide users with vibrations, the 'Pen de Touch' device delivers *"kinaesthetic sensations to the muscles"* on a user's fingers (Kamuro et al., 2009). Although, due to its design, it can solve problems of mobility, it cannot be of any use for the proposed system since its interaction is heavily relied on vision feedback.

Full shape displays – encountered

A 'full shape display' is a device that can actually present to the user the shape of an object as touched by the human hand. These displays are of the encountered type.

- *Iwata 'Haptic Screen' – FEELEX -* has developed various haptic interfaces for many years (Iwata et al., 2001). They proposed a desktop force display which is combined with graphics and haptics and it provides force-feedback for finger-hand manipulation (Iwata, 1990).

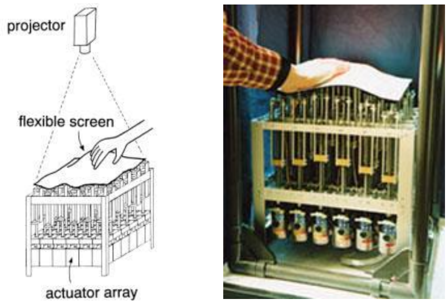


Figure 3-11: Basic idea of the FEELEX
(Adopted from **http://intron.kz.tsukuba.ac.jp/index_e.html**)

Curving mesh type

Most recently, a series of interesting attempts have been made to create surfaces which are more like an actively curving mesh, supported or grounded at only a few positions and free to take on more complex shapes of double curvature.

- *Georgia Tech 'Digital Clay'* - attempted to create a desktop-sized, fully controllable mesh surface using massive numbers of ultra-miniature fluidic actuators. Very interesting theoretical work has been done so far, but a working prototype remains to be made. *'Digital Clay'* is a term that *"signifies a computer-controlled physical surface, capable of taking any of a wide variety of possible shapes in response to changes in a digital 3D model or changes in the pressure exerted upon it by bare hand"* (Gargus et al., 2002). The project of 'Digital Clay' targets developing a medium that allows this sort of interaction. *"It is an instrumented, actuated, computer-controlled physical volume bounded by an actuatable surface that acts as a haptic interface"* (Allen et al., 2001) & (Haihong & Wayne, 2002). [See Figure 3-12: Digital Clay
(Adopted from Control Concepts For Digital Clay, Haihong Z., et al., 2002 (Gargus et al., 2002).

Figure 3-12: Digital Clay
(Adopted from Control Concepts For Digital Clay, Haihong Z., et al., 2002)

3.4 Force Feedback Devices and the Novint Falcon

Currently a number of different force feedback devices are currently available, some are marketed as assistive technology and others as games platforms. The Nintendo Wii joystick and Play Station controller are the most famous and commercially available games controllers that offer force feedback to the player. This new way of lively interaction with the user has dramatically changed the way the latter interact with the game environment and the high level of satisfaction they reach during play.

A recent use of the Nintendo Wii is for its joystick to be used as a virtual cane for blind people. The work that has been carried out at the Nottingham Trent University in the Interactive Systems Research Group (http://home.isrg.org.uk/) is significant. They looked into the different uses of Nintendo Wii to powerfully affect the life of blind people in many ways. Nintendo Wii's virtual cane uses the technology of the Wiimote which has the ability to define a body within a 3D space and provide an interface of 3D environments to visually impaired people. In order for the Wiimote to be used as a cane in the environment the Wii Cane System has to be used to map the real world position and orientation of the Wiimote to that of a "virtual counterpart within a simulated 3D environment" in order to provide the user with the necessary information. Necessary information and feedback in the verbal, auditory and vibratory forms is passed on to the blind and/or visually impaired user to help them navigate around virtual environments. (http://wiici.dyadica.net/pages/research/the-wii-cane). Using the system, people with visual impairment would be able to explore new spaces on their own and enhance their ability to move around the world independently while in the meantime this will contribute towards the improvement of their spatial cognitive awareness. One of the major advantages this technology has is the significant aid blind people would receive for supporting independent navigation.

It is very important for people with visual impairment to feel as independent as possible and take care of themselves. In order to achieve this, education along with technology should cooperate to produce specific changes to the curriculum and introduce assistive technology from the early years of education. Children with visual disabilities should be trained to cope with challenges in society and school's demanding modules from an early age.

Another new generation of force-feedback games console is the Falcon introduced by Novint Corporation. The Novint Falcon is considered to be the first consumer 3D device which allows users to "feel" what's happening in the game. It is believed not only to be a new generation of force-feedback games interface but the "realistic" interaction with virtual reality. Along with the new X-Box 360 Kinect project that allows users to interact with games, TV, music in a complete new and innovative way of body motion and voice recognition http://www.xbox.com/en-GB/kinect.

Novint Falcon [see Figure 3-14: Novint Falcon] is the first game console launched by the Novint Technologies Inc. Its main area of specialisation is the design and development of haptic or 3D haptic devices and software. Novint Falcon was intended to replace the mouse in gaming and other applications. The name comes from the fact that the falcon is a predator of the mouse.

Users grasp the ball-shaped grip – which is detachable and can be replaced by a pistol. The variety of joints on the arm allows the actual grip to move just like a mouse, though oriented vertically with an additional axis of in and out movement. An example to illustrate this freedom of movement is one of the Novint Falcon's technical demos which present users with a floating sphere of various substances and textures [See Figure 3-13: Novint Falcon Sphere Demo]. Users can control a floating hand in the 3D space plus and produce the in and out movement which is not allowed by mouse movements. Physically a user pushes the Falcon's grip forward and presses the virtual hand against the spheres. Through the process of some highly proprietary algorithms and computation, the motors inside the Falcon provide a sensitive resistance to give users the impression of actual touch [http://uk.ign.com/articles/2007/11/06/novint-falcon-review].

Figure 3-13: Novint Falcon Sphere Demo
(Adopted from CNET video)

When the hand is pressed into a virtual sphere the mechanical feedback goes from no resistance - when the hand is outside the ball - to a sudden resistance as the hand collides with the virtual ball. There are a number of different available sphere textures that offer an entirely different haptic sensation to users. For example, a virtual sphere made of sand offers an entirely different sensation of grit rather than stickiness and or slippery surfaces (Novint Technologies Inc).

Novint two main areas of research and focus are video games and professional use of its products. Therefore it expands beyond the game industry to more professional use, e.g. in Medicine, in Geological/Geophysical and Automotive applications [for more details go to 3.4.2 Novint Falcon Professional Application]. Furthermore Novint Falcon's advances have attracted many big companies worldwide such as Mobil Esso and research groups have funded many of Novint on-going 3D data interaction efforts.

Figure 3-14: Novint Falcon
(Adopted from www.novint.com)

3.4.1 Technical Review of the Novint Falcon

As mentioned above, the Novint Falcon controller was primarily built to replace the mouse and joysticks; it is on its own a small robot that lets users experience a true virtual touch. It allows users to control a game in three dimensions (3D), and also lets them feel hi-fidelity 3D force feedback. The Falcon comes with removable handles (a pistol and a ball grip) that the user holds to control it. As the user moves the grip in three dimensions (forwards-backwards and right-left similarly to a mouse, but also up-down, movements , which cannot be achieved with a mouse) the Falcon's software is programmed in such a way as to be able to keep track of where the grip's position is and creates force feedback to users (Novint Technologies Inc, 2008). The Falcon's sensors are capable of keeping track of the *"handle's position to sub-millimetre resolution and the motors are updated 1000 times per second (1 kHz) giving a more realistic sense of touch"* (Novint Technologies Inc, 2008) & (Wikipedia, 2011). The surfaces of virtual objects may have a solid or textured feel. The weight and dynamics of objects can be adjusted so that an object's inertia and momentum can be felt by users. Furthermore, all different actions and interactions of a virtual actor can be felt, such as the feel of recoil of a gun, hitting a tennis ball with a racket or a car’s acceleration. (Review article http://uk.gear.ign.com/articles/833/833067p1.html) & (Wikipedia, 2011).

The Novint Falcon comes with a grip that is connected via three arms to a roughly conical body with U-shaped base [See Figure 3-14: Novint Falcon]. Each of these three arms moves in and out of the Falcon’s body. The primary grip is a small spherical grip with four buttons. The buttons are:

- The Novint logo for the primary button (similar to an 'N')
- An upside down triangle on the left hand side(similar to a 'V')
- A lightning bolt just above primary button(similar to an 'N')
- And a plus sign on the right hand side(similar to a 'T')

All the letters together make up the word 'NVNT', the consonants in Novint name and its *“ticker symbol”* as a public company [See Figure 3-15: Novint Falcon's Grip].

Figure 3-15: Novint Falcon's Grip
(Adopted from www.novint.com)

At the front side of the Falcon's conical body, there is a Novint Falcon logo that lights up in different colours which indicates the different states the device is in Figure 3-16. Inside the body there are three different motors that are attached to each one of the arms. As each one of three arms moves there is an optical sensor which is attached to each motor to keep track of the movement of each arm. *“A mathematical function called a Jacobian is used to calculate the position of a 3D cursor in Cartesian coordinates based on the positions of the arms”* (Novint Technologies Inc) & (http://uk.gear.ign.com/articles/833/833067p1.html) & (Wikipedia, 2011).

Therefore, the position of the Falcon's haptic cursor is controlled by the Falcon's movement in the VE and which Falcon's software uses to determine and calculate the forces to be applied to the user. The appropriate currents are transmitted to the motors at the 1 kHz servo rate to offer the users a truthful and realistic haptic feedback. Therefore, a force can be applied to the grip in any direction, up to the maximum force (~10N), every 1/1000th of a second (Novint Technologies Inc).

Figure 3-16: Novint Falcon logo lights up in different colours to indicate the state of the device
(Adopted from www.novint.com)

Other than the primary spherical grip, Novint has developed another grip in the shape of a pistol. This was primarily built for users to play First Person Shooter (FPS) games but it can be also used for other applications too. There are three buttons on it accessed by left hand thumb. Although it offers more stability and control over the game, it cannot be used by left handed people [See Figure 3-17: Pistol grip] as all the buttons are on the left side and only accessible by the right hand thumb.

Figure 3-17: Pistol grip
(Adopted from www.novint.com)

Up until now the games industry has incorporated sophisticated graphics and sound design and development but none of them have added realistic touch to their games (Novint Technologies Inc). The main aim of the Novint Falcon is to fill this gap and along with high definition graphics and sound to add touch to make virtual items and experiences feel as real as possible.

Novint creates software for a number of different categories. It has originally created HDAL which stands for Haptic Device Abstraction Layer and is responsible to form the communication channel between the computer and the Falcon (Novint Technologies Inc, 2008). The software layer that is created above HDAL is called HFX (i.e. Haptics Effects) that is responsible for creating force feedback effects in games.

The Novint Falcon can work with any PC game or application. A number of different adjustments to the game can be made by end-users, to better fit their playing style such as changing the buttons on the grip to map different controls. Novint is currently working on a project to develop the gesture recognition system called the *"Gesture Cube or G-Cube"* in which a user has to learn 36 simple to memorise gestures to activate any key press or macro. For future use to the proposed system, gesture recognition will add more stability and enhancement to access digital information and interact with virtual environments for both sighted and non-sighted users.

3.4.2 Novint Falcon Professional Application

Novint advances do not only have a potential impact on games. Many companies have integrated Novint technology into their working process mostly as a training tool. Below there is the description of the two most well-known professional applications of Novint:

- **Medical and Dental**

The sense of touch is crucial for medical training. Many diagnostic, surgical and interventional training tasks depend upon on the training and utilization of the sense of touch. Until recently this kind of training was infeasible using computers. The introduction of VoxelNotepad (VNP) and Virtual Reality Dental Training System (VRDTS) by Novint technology and medical products, is aiming to form a new way of computer-based training through the simulation channel (Novint Technologies Inc, 2009). It allows users to interact with medical imagery including MRIs, CT scans and 3D Ultrasound scans [See Figure 3-18: Preparation by turbine handpiece].

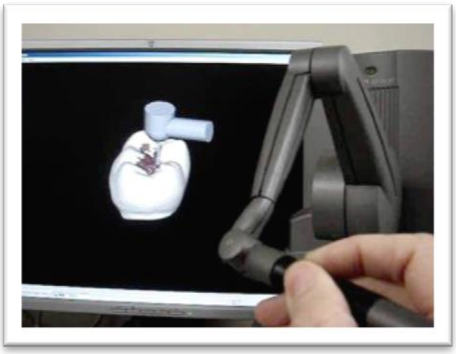


Figure 3-18: Preparation by turbine handpiece
(Adopted from www.novint.com)

- **Design and Architecture**

A new way of creating a prototype for 3D models was developed by Novint that was called the "Instant Prototyping". With Instant Prototype, architects are allowed to develop a virtual prototype from its digital models for design and analysis purposes. This speeds up the whole production cycle and furthermore saves money and time in manufacturing physical prototypes (Anderson, 2007). It can also be useful in large scale prototype development where a physical prototype is not a feasible solution.

Figure 3-19: Virtual Prototype
(Adopted from Sandia National Laboratories)

Figure 3-19: Virtual Prototype shows an architectural walkthrough application for Sandia National Laboratories (Anderson, 2007) . The specific application allows users to perform a virtual walkthrough of the different sections of the building, feel the texture of the walls and even be able to stop and read signs stick on the walls. Moreover, users can actually feel the weight and texture of virtual objects and movement of the digital objects can be constrained, like the motion of a door which can be constrained to pivot only around its hinges.

This experience of navigating around virtual buildings can be very helpful and powerful for users as it may allow them to 'feel' the digital models and gain a better understanding of their nature and extent. Furthermore users have the power to re-organise the interior design by re-allocating the virtual objects, something that can be organised much faster than when using a mouse and additionally the placement in the environment can be much more precise (Anderson, 2007). Coming down to blind people, this technology can be used to illustrate a virtual navigation guide for people with visual impairments.

3.4.3 Novint Falcon: The medium

Audio and force-feedback haptics applications with no visual display for use by people with visual impairments are in the centre of this research. Since the target group is people with low or no vision, visual feedback is not of great help from the user's perspective but a visual outcome will form a communication channel between teachers-sighted peers and visually impaired students.

- **Why the Novint Falcon?**

Going through and investigating in depth all the haptic technology that is currently available the Novint Falcon was chosen to be the platform on which to build and test the proposed educational game. The two main reasons that support this specific choice are:

1. *Novint Falcon's consumer affordablity*. Its price is much lower thanthat of other technology like the PHANToM Omni. Moreover, the advantages of the relatively low price is that the Novint Falcon is a platform that schools can afford to buy and place into classes and allow students to explore it without the need of supervisor-teachers. Furthermore, it is a tool that parents can more easily be convinced to buy for home use.
2. The other major advantage it has, in contrast to the other available haptic technology, is that *it is mobile and no additional equipment should be worn either on users' arms or fingers.* Since the research is dealing with primarily young blind participants the least that is expected is not to make them feel uncomfortable or scared.

3.5 Assistive Technology for people with visual disabilities

Since 1960 many assistive technology devices have been introduced in schools to help blind students towards learning. Initially these devices were only able to assist blind people in navigation around the environment and later the first voice synthesizer devices were introduced to help them with their studying (BANA, 2011) & (Presley & D'Andrea, 2008). During the 1980s, computer systems brought a major change in blind people's lives. The first personal computers (PCs) were brought into schools and students were able to work independently in both writing and reading. Many computer systems offer voice synthesis to enable blind people to read textual information but it can offer very little meaningful feedback when it's essentially mathematically or graphically oriented data. There have been a number of attempts to develop novel ideas of giving access to this particular data but as yet no comprehensive and solid solution has been widely used by people with visual impairment.

Some of the most commonly used assistive technology is listed below:

Talking Tactile Tablets

According to Landau and Gourgey (2003), educators and map-makers have determined that textured-diagrams and raised-line pictures may be efficiently used to demonstrate spatial concepts to visually impaired people. For this specific reason, the Baruch College Computer Centre for Visually Impaired People and Touch Graphics Company of Brooklyn, New York, came together to design and build a completely new approach to audio-tactile computing for the marketplace as a *"unified suite of hardware and software components"* with the primary goal of introducing innovative ways of interactive learning and entertainment for people with visual impairment (Landau & Gourgey, 2003).

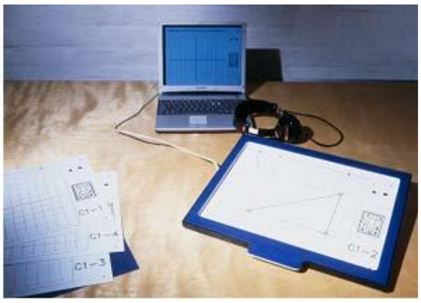


Figure 3-20: A student using the Talking Tactile Tablet. He is pressing the control buttons to navigate through the application (left) & The Talking Tactile Tablet connected to a laptop computer, shown with an assortment of tactile overlay sheets (right)
(Adopted from Landau & Gourgey, 2003)

The TTT serves as a pointing device and the tactile overlay as a static display. Every time the user touches any point on the tactile overlay, the pressure generated by his/her finger is transmitted to the touch pad below through the flexible PVC sheet. Then the computer interprets this touch as a set of *x,y* coordinates and compares them with a database of regions of any shape. In other words, its tangible surface produces touchable icons that provide an audio feedback every time they are pressed (Landau & Gourgey, 2003). One of Talking Tactile Tablet's advantages is the easy and understandable way of using it, which means users feel comfortable from the very beginning.

The importance of developing applications using the multi-media authoring system Macromedia Director (Landau & Gourgey, 2003) is to allow people with low or no vision to gain access to digital information and interact with data that some years ago was inaccessible. This is an important achievement because it opens new routes to the world of multimedia and interaction with digital information.

DESENVOX

Borges and Jansen (1999) in Brazil developed a program in tactile graphic computing the "Desenvox" (Borges & Jansen, 1999). With this first prototype, the developers' main aim was first to creat an interactive system for tactile graphic generation to be used efficiently by blind students. They have tested the system in teaching simple geometric concepts, evaluating the difficulties and comparing their results with other strategies that don't make use of computers (Borges & Jansen, 1999) e.g. experiments with real objects (Lego). According to Borges and Jansen (1999) one of the main challenges that a blind user has to face is *"related to the inherent difficulty that a blind person has in searching objects in two or three dimensions"*. Even if the process of reading a drawing or an object on a flat surface is performed through the tactile process, still it remains difficult and challenging for a blind person to conceptualize the corresponding 3D real object. To achieve this it is essential to use some *"mental positioning of the geometric figures"* to assemble a complete image of the drawing or the object (Borges & Jansen, 1999). What is unique with DESENVOX, is that it presents the objects to blind users as a list of basic geometry elements, e.g. rectangles, circumferences and ellipses, curved lines, bitmaps, texts etc. DESENVOX is very useful and valuable in bridging the gap between the way sighted and blind people collaborate towards learning. In this situation technology has provided blind and sighted people with the "tool" of an effective and meaningful dialogue. Although DESENVOX is very good at putting down the ‘mental figure’ of a blind person into a ‘visual image’ for a sighted person to view, it lacks the ability to give the cues needed for a blind person to identify real world objects.

Another system that allows blind users to explore both indoor maps and large-scale Open-Street-Map data on a tactile graphics display, is the Interactively Displaying Maps developed by (Schmitz & Ertl, 2012). With digital maps becoming widely available through smart phones, it is an important first step to explore and navigate around unknown areas. Visually impaired users have to rely on maps that are specifically provided for them, and are often only available for small areas. What is still missing is the link between those digital maps and blind users. Screen readers and Braille devices have adopted the role of this link for digital information in text format, but for spatial information such accessibility is still missing.

Screen Magnification Software

There are a number of different assistive screen magnification software tools available for use both in schools and by individuals. Below there is a list of the more popular ones:

- **ZoomText:** ZoomText, ZoomText Plus and ZoomText Xtra, all belong to a family of products that enlarges text and graphics. It can zoom the whole screen or a portion of it or a single line.
- **InLARGE**: It is a screen magnification software that is used by low vision and learning disabled Mac users. It is very similar to the ZoomText group of software, with some added extra features.
- **Lunar & LunarPlus:** Lunar and LunarPlus are considered to be the world's leading screen magnification program for visually impaired computer users. It has a number of advanced features to better help users to manage data and navigation like enlarged screen more efficiently by allowing important information to be permanently displayed.
- **Supernova:** Can be either used as reading software, as a screen magnifier or as a Braille display support. It is particularly used by low vision

students where residual sight and hearing are both required (http://www.schools.ac.cy/schoolfortheblind).

Speech Access

This is another assistive technology group that provides blind users with speech synthesizers. There are two categories of Speech Access Technology, the Talking Word Processors and Speech Synthesizing Screen Reader Software.

- **Talking Word Processors:** Intellitalk is a type of Talking Word Processors that allows blind students to hear anything they entered in Word processor (a letter, a word, a sentence or phrase).
- **Speech Synthesizers:** A screen reader is used to interpret what is being displayed on a computer screen. Blind people use speech synthesizers extensively when using the web. Having in mind the amount of information that can be found online and more generally the increasingly important role of the web in society, it is very important for people with disabilities to gain access to the Web. The Web Accessibility Initiative (WAI) (http://www.w3.org/WAI/) established some guidelines for making the Web an accessible medium.

Screen Reader Software

- **JAWS (**http://www.tsbvi.edu/technology/overview.htm**):** which stands for Job Access with Speech is the world's most popular reader. JAWS provide access to software applications and the Web for people who have low vision or how are blind. Its multilingual synthesizer 'Eloquence' speaks through the computer sound card.
- **Speech Synthesis and Screen Readers:** Allows visually impaired users to keep track of any commands given or texts written on a screen by listening to them. One of its advantages is that it supports and allows the integration of Braille display.
  - NonVisual Desktop Access (NVDA) software enables blind and visually impaired people to use a computer by communicating what is on the

screen using a synthetic voice or braille. It was created by NV Access founders Michael Curran and James Teh who are both blind computer programmers who have been developing software to enable blind users to have easy access to computers. NVDA is a free, open source and portable screen reader for Microsoft Windows and it is available in over 43 languages. NVDA is programmed in Python and it currently works exclusively with accessibility APIs such as Microsoft Active Accessibility, IAccessible2 and Java Access Bridge. It uses eSpeak as its integrated speech synthesizer and it supports output to Braille displays.

Braille Access

It is a tactile reading screen with 80 (or/and 70, 40 or 20) braille cells attached to a computer that capable of reproducing in Braille format what is on the line where the cursor appears on the screen. The user therefore, can read in Braille what is on the screen in a silent mode avoiding disturbing other people around them with the sound of synthetic voice or being isolated by using headphones. The Braille system is the most widely used system which allows people who are blind to read and write. It was invented in 1821 by Louis Braille. It was originally developed by Charles Barbier as an encrypted method of communication between the soldiers of Napoleon (Daniels, 1996). Blind mathematicians work primarily with Braille or computer-based linear textual representations – Latex (Knuth, 1984) & (Lamport, 1985). Braille has some major limitations that have to do with politics rather than technology. Even though mathematics is considered to be an *"international language"* there isn't an agreed international Braille code for mathematics. Therefore, if Braille mathematical documents are available, they may be in a code that is unknown to students (Stevens et al., 1996). The two main practical disadvantages and limitations of the Braille system with regard to mathematical representations are 1) many more cells are required therefore it is time-consuming to scan through and 2) Braille is linear.

- **The Nemeth Braille Code for Mathematics:** It is a Braille code for encoding mathematical and scientific notation linearly using standard six-dot Braille cells for tactile reading by the visually impaired. The code was developed by Abraham Nemeth in 1952 but revised in 1956, 1965, and 1972 (Navy, 1993), and at the beginning of 1992 was integrated into Unified English Braille. A visually impaired user can use Nemeth Code to render all mathematical and technical documents into six-dot Braille, including expressions in areas such as arithmetic, algebra, geometry only in 2D, trigonometry and calculus.

- **The Braille Cell as Symmetry:** The Braille cell consists of six dots arranged in two columns – 3 at each column. Labelling the dots in the left column from the top as 1, 2, 3 and from the top in the right column as 4, 5, 6, dot 1 is the letter a, while a combination of dots 1, 2, 3 and 5 is the letter r and dots 2, 4, 5 and 6 form the letter *w*.

Figure 3-21: The Braille cell with 6 dots; The letter a (dot 1); The letter r (dot 1,2,3,5); The letter w (dot 2,4,5,6); The letters r and w are vertical mirrors of each other
(adopted from Klingenberg, 2007)

Trying to see the dots as if they were representing a 2D illustration, may reflect and illustrate symmetry in letters *r* and *w* as is shown in Figure 2-8 The Braille cell with 6 dots. Although this is only a pattern within the scale of a fingertip, with *"the top and side of it regarded as a spatial frame, a Braille pattern is difficult to code as a global shape"* (Millar, 1997). In a concrete context, mirroring is a visual phenomenon, but working with symmetry it might be possible to allow people with visual impairment to understand the concept.

- **Braille2000:** This is quite new in the market and it is fully Internet-aware and it is very simple to send a braille document to a braille production centre (http://www.c-a-s.com/).

- **Braille N'Print:** It can be easily attached to the Perkins Brailler and a printer and can convert braille texts into normal print by *"transforming the*

Braillers key strokes into information compatible with the printers' software" (http://www.schools.ac.cy/schoolfortheblind/).

Scanned Material Access

- Open Book: Another interesting proposal is that of Open Book. It is used to scan text and also text which is embedded in pictures and converts it into electronic format. Eventually the text embedded in pictures is "spoken" to visually impaired users. Open Book is very useful and valuable tool to enable blind people to read pictures and graphics that come with embedded text.

Another interesting application that is used to display geometrical 2D figures to students is the integration of a Wingman Force Feedback Mouse with audio (Bussel, 2003). Rouzier in 2004 tried to investigate how the use of PHANToM and how haptics can help visually impaired people to learn geometrical concepts (Rouzier et al., 2004). The system is called SALOME and it combines haptics and sound to assist teaching planar geometry. It allows haptically reading, measuring and constructing geometrical figures. Moreover, it can help students who are blind to shape a mental representation of geometrical and topological concepts.

OPTACON (Optical to TActile CONverter): It is an electro-mechanical device which allows people with no vision to go through printed material that has not been transcribed into Braille. The Optacon reading device converts normal printed text into embossed ones on a special tactile screen and blind users can haptically read them [See Figure 3-22: OPTACON].

Figure 3-22: OPTACON
(Adopted from Wikipedia)

VersaBraille: This is a device that stores and retrieves information through sound and in Braille format.

CCTV (Closed Circuit TV): Gives access to documents, pictures and books to users with low vision. It uses a stand-mounted or hand-held video camera to display a magnified image onto a video monitor or a television (TV) screen. While CCTVs are still widely used today VersaBraille and Optacon are not.

Mimio: This is a relatively low cost device which can be attached easily to any whiteboard that can easily transfer everything that is written on the board to a blind student's personal computer. This gives immediate access to anything that is written on the whiteboard and students may use any accessibility software (Lunar, Zoomtext etc) to gain access to data or they can simply store it for later use.

3.5.1 Assistive Technology for Accessing Mathematical Literature by Blind People

Most assistive technology available to assist blind users to gain access to mathematical notations and paradigms rely heavily on audio feedback. The most notable applications of this technology are listed below:

The Mathtalk Program: This was developed by Robert Stevens at the University of York, UK (Stevens et al., 1996). Many of the ideas proposed in this application were expanded by the Maths project - (Mathematical Access for TecHnology and Science for visually disabled people). Since algebra notations rely heavily on the use of pencil and paper to be presented, the Mathtalk program aimed to speak standard algebra notation through a speech synthesizer. It targets to transform blind users from passive listeners into active readers.

Lambda Project: The structure and nature of mathematics is designed in such a way that it makes it very hard for blind students to study as it heavily relies on graphical and visual representations. Lambda project attempted to bridge this gap by developing *"a linear mathematical notation which can be* *manipulated by a multimodal mathematical editor"* (Edwards et al., 2006). This program gives visually impaired students access to mathematical notation through Braille notation, synthetic speech feedback and/or visual display for students with residual vision. Testing and evaluation of Lambda showed that it is well used by students who already feel comfortable in using computers. This finding supports observations and findings of i-HALE's testing and evaluation process, which showed that visually impaired students with good knowledge on using computers performed better than those with a poorer background in the area.

ChattyInfty and Audio Graphing Calculator: The ChattyInfty audio-accessible text and math editor can be used by blind users to create documents with mathematical formulas. The Audio Graphing Calculator provides blind students with a flexible tool for scientific computation and simple data analysis. The x-y graphs can be presented as audio tone plots and every time the graph becomes more positive, the pitch rises and every time it becomes more negative the pitch falls (Gardner et al., 2010).

3.6 Initial System's Design Constraints

Studying in depth all the technology and the research available today, the initial thought was to develop a solution that would use the PHANToM technology. Soon this idea was abandoned mainly because of three reasons:

1. The technology was far too expensive and therefore falls beyond the scope of this project. The main goal was to design and develop novel ideas that would be consumer affordable. For this specific reason the Novint Falcon was chosen to form the testing medium as its price was reasonably low compared to other commercialised haptic devices and the one that parents and schools may better afford to buy.
2. Since the proposed study was primarily designed to involve participants at school level the game-project should be as easy and uncomplicated as possible. If existing technology was going to be combined this would have required users to wear exo-skeleton devices.

3. Lastly, the specific technology is not mobile.

A brief presentation and discussion on the original ideal can be found in Appendix B.

CHAPTER 4

Methodology

4.1 Introduction

The hypothesis for this research is that a playful haptic virtual environment would engage blind users with learning about geometric shapes. As a result VE had to be designed, built and tested. There would be a number of steps in this process. The first was to determine what the limitations of the equipment that was planned to be used were. Would it be possible to use – have sufficient resolution and so on? Thus the process began with an evaluation step or feasibility study. The approach taken in the design was to be user centric, so it was important to start with user opinions of the device and this was the first stage. After this a different level for the game was designed, based on the ideas gained from the feasibility study. These levels were designed to be extensions of one another. The design was then evaluated by user trials. The evaluation methodology was designed to collect both quantitative and qualitative data. The quantitative data was required to measure the degree of participant improvement over time in terms of the average time taken to locate new objects in the VE and the number of objects correctly identified at each level. The qualitative data was used to ascertain the success of the application as an engaging, rewarding experience and to identify sources of difficulties or frustrations and possibilities for improvement.

Interaction with visually impaired students had been limited prior to the visits to the two institutions – The School for Blind in Cyprus and the NCN

Nottingham. One of the fundamental principles of successfully obtaining all the necessary information to proceed with the current research was to learn about the potential end users and how they behave in a specific environment – the school. Moreover, equally important was to collect as much information as possible on their daily procedures and how they interact with other people and the environment. For this specific reason, students were observed in less academic activities, like cooking. A set of questions were established before each meeting to maintain control over the collected information. Questions like: How do blind students navigate around the school premises or unknown spaces? How do they take care of themselves? What is the interaction they have with technology and the use of computers? The level of maths awareness and many other questions needed to be answered from the initial steps. The closed collaboration with all stakeholders – students, parents and teachers – shaped the game to meet the expectations of those involved. Meetings were set on a basis of every 3 months at the beginning and more often towards the end of the game completion.

Following, in this chapter, is the step-by-step presentation of all the steps that have been taken to produce the final outcome. Starting with a blindfolded users' study was the very first attempt to test the Novint Falcon's robustness; next was the presentation of observing blind students on extracurricular activities. After this was the presentation of the Feasibility Study which helped to shape the rest of the levels. A tutorial session is discussed in detail and explains the reason why it was crucial for the end users to receive training prior to testing and evaluating the final outcome. Finally, the 4 levels of the game are explained in detail.

4.2 User-Centred Design (UCD)

Users were in the centre of attention in this project and were approached with the maximum sensitivity, having in mind the differences in perception needs they have when compared to sighted people. Working and spending time with the end-users was the first step to develop a bridge of understanding and honesty; primary characteristics for the research that was conducted [See Appendix A which describes the data collected from observing blind students at their school environment]. User involvement in the design activities was very crucial and a parameter that may eliminate the possibilities of future problems and failures and at the same time help to maximize the possibility of getting meaningful results. User involvement both in the design process and in the evaluation is one of the principles of the multidisciplinary research area of Human-Computer Interaction (HCI). Human-computer interaction has its roots in the "*human-machine interaction and ergonomics and spawned many branches of methods and traditions"* (Grohn, 2008). Computer science, psychology, pedagogy, social sciences and design sciences fall under the scope of human-computer interaction (Dix et al., 2003) & (Sharp et al., 2002).

According to ACM (Association for Computing Machinery) HCI is defined as:

> *"Human-computer interaction is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them"*

However, today the concept of HCI has a somewhat conservative approach to it and new and more flexible concepts like interaction design are used. It may be that the use of a new word can eventually lead to a concept that is independent of the *"historical ballast of instrumental usability tests and the treatment of users as secondary"* (Grohn, 2008). Modern HCI treats the end-users as the primary and most important aspect of the whole project and builds solutions that are based on their recommendations and preferences. This should be the main focus of every development team: blend technological science with innovative ideas and adjust the outcome to the users' will! After all, these are the future users of the system. This is exactly the fundamental basis from which the current project's idea was born, designed and developed. Users were in the centre of attention throughout the entire development process and evaluation.

The importance of involving users in the design process of interactive systems has been noted since mid-80's when Gould and Lewis (1985) described the three principles of UCD (Gould & Lewis, 1985):

- *Early focus on users and tasks*
  As Gould and Lewis originally pointed out the *"active involvement of the actual end users in the design process"* is very crucial. They also pointed out the need to regularly meet with end users, performing interviews and exchanging views and opinions on possible designs. The proposed prototype was not to be completed without the active participation and recommendation of the end users.
- *Empirical measurements*
  The objective measurable quantities target to get out of the testing level, for example task completion times and learning time well as the users' thoughts and attitudes about their experience in trying out the software.
- *Iterative design*
  In software engineering the process of building software that is based on the traditional systems development life cycle (SDLC) which is a process of repeating prototyping, assessing, analysing and redesigning until a "good-enough" product is developed. However, HCI gives emphasis to the involvement of end-users in the evaluation phase which is split into the conceptual design, interaction design and detailed design (Grohn, 2008).

The author, along with the teachers of the school and college, formed a group which ran all the tests. Every time a meeting was over, they discussed the data collected and along with participants' comments and feedback they decided on the characteristics the newer version of the application should have. Parents were also involved in some of the discussions by brainstorming on the existing design and the areas of improvement. Each meeting was associated with a 'list of action' which described the aims of each meeting, its goals and measurements on the data collected. At the end of each meeting the specific list was updated with comments of all the stakeholders.

In the following chapter of Feasibility Study, the principles of participatory design and development are applied involving the end-users – the participants. The importance of involving end-users in the process from the initial steps is presented through the analysis of the data collected in every meeting. Along with this, every meeting with the end-users is analysed in detail as well as how these findings shaped the game.

4.3 Introduction to i-HALE

Since the initial meetings with the potential end-users, a serious discussion was made and attention paid on games. The initial thought was for the final outcome to have the characteristics of a game but this had to be explicitly decided based on the participants' views and preferences. All participants at school level were fascinated by the idea of having games *"teaching them mathematics"* and furthermore compete with other classmates for the final trophy. Teachers and parents also pointed out the strengths a game oriented application would have on students' approach to learning. Teachers commended that very often they use game oriented teaching and have students working on tasks under specific instructions that lead to some kind of reward. Teachers' experience showed that this approach attracts students' interest and helps them maintain their concentration throughout the session. Parents also expressed the idea of using a game to engage students to go through all the levels of the application. After deciding that the final application will have the characteristics of a game, naming it was equally important. The name aimed to include all the aims and objectives of this study targets. i-HALE stands for (interactive) Haptic-Audio Learning Environment. Haptic-Audio feedback would form a well-designed Learning Environment for participants with visual impairment.

i-HALE Aims

The main aim of i-HALE is to create a playful and exciting multimodal learning environment for low vision or blind participants to enable them to learn, practise and test their knowledge on 3D objects through the haptic and audio channel. Furthermore, it aims to give users the appropriate and necessary stimulus to understand 2D illustrations and their reproduction to 3D objects. This may, as a result lead to the enrichment of participants' understanding of more complex objects.

To provide a meaningful experience, the game has to have an objective for players to pursue, decisions the players could make, sufficient information to make these decisions, resources they must manage and take into account possible obstacles to their success. Audio and practical tutorials are offered at the start of the game, presenting some of the key points of geometry that cover the contents of the game. Participants are given enough time to practise with the environment, to familiarize themselves with the haptic learning environment and revise basic geometry concepts.

4.4 Tutorials

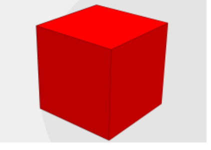
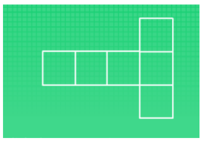
It was very important for the participants to receive the appropriate step-by-step training, an approach that allows them to try out the haptic device and interaction with the VE. If participants have problems solving test tasks, it may be possible to discern whether the problem originates in the handling of the device or whether the problem is that of solving the task. Therefore the tutorial session was carefully designed and planned. The participants were allowed to spend as much time as needed with the pre-test tasks as well as playing games that come with the Novint Falcon. This gave them the ability to familiarise themselves with the machine itself, how it works and furthermore to develop an idea of what exactly is asked from them. The tutorial session consisted of three parts:

1. ***Geometric Literature Awareness***

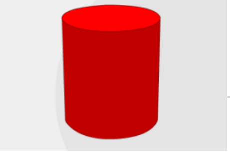
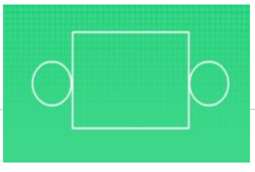
End-users received a verbal presentation of the objects to be used in the task tests. The presentation was in .*doc* format and with NVDA (NonVisual Desktop Access – see section 3.4.3) - a free and open source screen reader for the Microsoft Windows operating system- participants could listen to the presentation. While they were listening, the author, along with the teacher, offered them the corresponding real geometrical objects to explore haptically. The following step was to show them how these 3D objects can be transformed into 2D illustrations. For this specific part of the training, raised line paper was used showing the different levels the object was made up of. Participants were able to make an immediate match with a real object and its 2D transformation. The author believed that this would help participants to develop a precise mental model of the object. This method had been adapted by mathematical teachers' suggestions and ways they use in class.

These objects were extracted from the geometry curriculum for beginners and they form the basis for the future development and understanding of geometrical skills. They were also informed of the nature of the game and they were tested against their knowledge, memory and performance, using the grip. End-users were also informed of the length of the game, the levels and the points earned for every correct, every wrong answer and the bonus points.

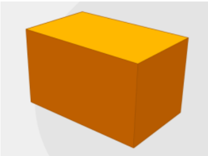
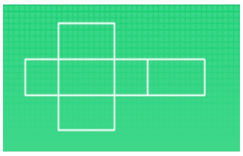
Cube – it is a solid object with 6 square sides of the same size. Its 6 equal sides meet at right angles. It has 8 vertices and 12 edges.

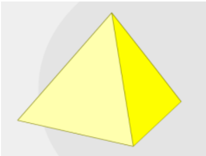
Cylinder – it is a solid tube with long straight sides and two equal-sized circular ends.

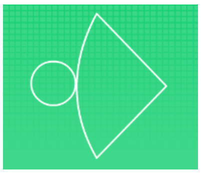
Rectangular Prism – it is a solid object with 6 rectangular sides. A closed box composed of three pairs of rectangular faces placed opposite each other and joined at right angles to each other.

Pyramid – it is a solid object with flat and most often square base and four flat triangular sides which slope inwards and meet to form a point at the top.



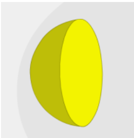

Cone – It is a solid shape with a round or oval base which narrows to a point. A cone is a pyramid with circular cross section, and a right cone is a cone with its vertex above the centre of its base.

Sphere – An object shaped like a rounded ball.

Hemi-sphere – An object that is half of the sphere.

Torus: An object shaped like a ring.


2. ***Static Environment***

The next step was to present the virtual versions of the 3D objects to the users. Every single object was placed in the virtual scene in a limiting box in order to restrict users to the optimal working space and to prevent them from having to scan the whole workspace. The restricted workspace would also provide users with a non-changing reference. Only haptic feedback was available during exploration but the user was also provided with a verbal description of their position with respect to the object.

3. ***Dynamic Environment***

The following three different environments consisted of dynamic objects with vibration and magnet effect on, that were placed in different positions in the VE. The workspace was not restricted to a box as in previous tutorials. Participants had to scan the virtual environment to locate the object and manipulate it in free space. The virtual scenes were designed with a stepwise increase in complexity:

1. A cube with vibration with dimensions 5*5*5 cm.
2. A cylinder with vibration and magnetic effect. Added on that was placed in the far left hand side of the environment.
3. Three spheres placed at the same horizontal level, of the same size, with one and three having the vibration effect and number 2 only having the magnetic effect.

4. ***Complex Environments***

The last level of training was very similar to the tasks to be solved in the real game with time restriction.

1. Locate an object
2. Identify it

A detailed presentation of the pre-test applications can be found in Appendix C. This specific application was also used in the feasibility level.

4.5 The Participants

Since there are a limited number of blind, research persons to contact, some of the evaluating participants took part throughout the feasibility and the actual studies. As a side effect, some of these persons have learned to use the Novint Falcon quite well and thus need little or no training to test new prototypes. This is an advantage that saves time both for the research person and for the researcher. The research participants for the whole study were from 2 educational institutions, the NCN Nottingham and the St Barnabas School for the Blind, in England and Cyprus respectively. Participants from the college only participated during the feasibility study, whereas users from the school participated throughout all the levels of the study. The participant group consisted of both congenitally blind and low vision persons. Also, apart from participants at school level, 4 mature participants expressed the interest to participate in the experiments. They were allowed to take part with the potential to bring a new dimension to the study as to whether mature learners would be interested and benefit from such technology. Their results would form a very interesting basis of discussion and contradiction with participants at school level.

The following table presents all the participants:

Participant	Age	Gender	Blind Low Vision	Occupation
A	14	M	Blind	Student
B	14	M	Blind	Student
C	17	M	Blind	Student
D	15	F	Low Vision	Student
E*	20	F	Low Vision	Student
F*	21	F	Low Vision	Student
G*	22	F	Low Vision	Student
I	14	M	Blind	Student
J	28	M	Blind	Student
K	15	M	Low Vision	Student
L	16	F	Blind	Student
M	66	F	Low Vision	Housewife
N	55	M	Low Vision	Accountant-retired
O**	57	M	Low Vision	Mechanical Eng.-retired
P	51	F	Blind	Secretary

Table 4-1: Users who participated in the research

*Participants at college level

**User is blind at left eye and 6/20 vision at his right.

People describes as of "low vision" are those whose sight is <20/200 to 20/400 when corrected by spectacles or contact lenses. Participants D and O became visually impaired after brain cancer at the age of 9 and 47 respectively. The remaining visually impaired users were born with low vision and their sight gradually reduced over the years. All participants described as "blind" were congenitally blind and therefore had no visual experiences. Participants A, G and L have mobility problems with their hands and fingers. Lastly, user G suffers from Guillain–Barré syndrome (GBS). Finally, participant I suffers from 'Attention Deficit Hyperactivity Disorder (ADHD)'.

He may be characterised as an introverted, lonely, reactive, hyperactive person with intentional problems.

4.6 Studies

Blindfolded Investigation

Before continuing with the design and development of any application it is very important to test the robustness of the medium. The lack of literature on studies with blind users using the Novint Falcon, made this issue a first priority. The aim was set at three dimensions:

1) Test robustness
2) User friendliness of the medium
3) Accuracy on virtual touch.

This question needs to be answered very quick therefore blindfolded participants were selected to test some demo applications that come with the platform.

Feasibility Study

In order to collect the necessary information and data to conclude on the final design, an iterative method of determining requirements is established which follows a loop of re-design until a functional piece of prototype met the requirements and expectations set by the end users. Feasibility study has been split into three independent meetings, each of which focuses on approaching specific questions.

The First Round Meeting targets exploring the way blind participants manipulate real object in free space. It is important to understand how they extract/collect the necessary characteristics to determine the object's nature. Information collected from this first meeting will enrich the designer's understanding of how the 3D virtual objects should be designed and what characteristics (the edge, the face etc.) of an object must be distinct and in what degree.

The Second Round Meeting tries to evaluate the importance of textures in virtual haptic identification of 3D objects. Participants will test different

objects with different textures and qualitative (participants feedback) and quantitative (time to explore an object) measurements will be collected.
The Third Round Meeting evaluates all data collected from previous meetings, by developing small prototypes. This meeting finalises the haptic characteristics the VLE should have for it to be in accordance with the end-users' expectations.

During all these meetings with participants there was an on-going observation on their school activities and on other extracurricular activities. This information provided the author with a deep understanding of blind students' life.

4.7 i-HALE Levels

Participants initially run the Tutorials which guides them through the basic literature needed to complete the different levels. Participants are given a clear set of instructions on what they are expected to do during each level. At the end of each level they are asked to give immediate feedback of what they think/feel about the level they have just completed. They have to choose between positive, negative, good and average. Having completed all the levels, participants have to fill out a questionnaire of 20 questions [See Appendix D] to rate the different components of each level on a scale of 1 to 5. Questions like, how they managed each level or how they rate the interaction with object manipulation are asked. They also have to answer a different set of questions measuring perceived VLE performance. Data collected from this questionnaire along with observations collected throughout the whole project will form the basis of an in-depth analysis of i-HALE.

There are four different chapters, one for each level, and they are organised into three sub-sections: a) Introduction, b) Design and c) Results and Discussion.

i-HALE Level One: Identification of 3D Objects

The goal of this level is to allow participants to practise the interaction with virtual objects and the way they explore virtual scenes. Participants have practically experienced similar situations during the tutorials, therefore they are expected to find it easy during this task. However, knowledge transfer is measured in more depth during the next levels. Therefore, this level's goals are set in two dimensions: 1) to rate the level of understanding of what participants have to do and how they collect necessary information, and 2) to evaluate the level of successful interaction with the VLE.

i-HALE Level Two: Reproduction of 2D illustrations to 3D objects

The goal of this level is to evaluate the participants' ability to firstly identify a 3D object and to match it with its corresponding 2D illustration. In addition this level aims to identify the degree of knowledge transfer and how comfortably they scan the virtual scene and how quickly they extract necessary information to identify a virtual object.

i-HALE Level THREE: Size Order

The goal of this level is to enhance the participants' ability to evaluate objects with respect to their size. It also requires users to remember the position of objects and their size. This level doesn't aim to evaluate how participants scan the virtual scene, - this has been explicitly tested during the previous two levels. They are informed of the number of objects present in the scene and the workspace is narrowed down. Therefore, this level's goals are set in two dimensions: 1) How accurately they evaluate sizes, and 2) the level of knowledge transfer.

i-HALE Level FOUR: Complex Environments

The goal of this level is to examine whether participants' personal opinion is consistent with their performance. After the completion of the testing of the first three levels, participants were asked to evaluate another piece of software very similar with i-HALE with the distinction of having virtual objects with haptic effects – vibration and magnetic. Since a significant number of participants (8/12) supported this view, a new set of exercises were developed to evaluate this hypothesis. Therefore, this level's goals are set into two dimensions: 1) to examine whether personal opinions are reflected in their performance, 2) evaluate the knowledge transfer having in mind that this set of tests run 2 weeks after the last meeting.

Collaboration with sighted participants

The aim is to have sighted and non-sighted participants collaborating on similar tasks. Sighted participants need to enrich their knowledge on how they can optimally communicate with blind participants, for example what set of instructions are meaningful. This interaction will eventually enable them to collaborate on similar tasks with blind participants. The main goal is to bring in young participants (<17 yrs old) and have them work together. It is important for both parties to learn to trust each other. They might at some point need to do so in a school environment.

Results and Analysis of each level is as follow:

1) Participants are grouped into 3 different Performance Groups. This applies to all levels. Each group is measured, based on the average time each participant needed to locate a new object. With the completion of all levels, data collected would provide a quantitative analysis that shows:
    i. Increase/decrease of the number of participants in each group throughout the levels.
    ii. Individual participant's performance
    iii. Indication of knowledge transfer.
2) All details associated with this level are presented in a table:
    i. Average time needed to locate a new object
    ii. The number of located objects
    iii. Points + bonus earned – it also indicates the number of correctly identified objects
    iv. Participants who meet conditions from the first attempt
    v. Computer and Mathematical knowledge
    vi. Feedback ONLY for the level just completed.

3) Feedback against Computer and Mathematical knowledge is graphically presented. The chart can help to examine the relationship between good knowledge in these two subjects and the feedback participants left at the end of this level.
4) Evaluation of each Level and Tasks. This information was collected from the questionnaire participants have to fill in at the end of ALL levels. Interesting patterns can be extracted as to whether evaluation is associated with participants' performance on completing the several tasks within each level.
5) Exploration Patterns – A Virtual Traffic Environment. In addition to the above observations and collected data, the program also logged the way participants interact with the program. These log files show some interesting patterns, in that they reflect some of the explorative behaviours of the participants.
6) Compare the number of objects located during level One and Two. This graph shows graphically whether there is any improvement in the specific task (locate objects) and therefore if it can justify knowledge transfer. Scientific Analysis using statistical software is also presented.
7) At the end of all levels a graph is generated showing the total points collected by each participant. This shows the overall performance and it may also confirm observations and conclusions made earlier in the analysis.
8) Graphical representation of how participants see the experience with i-HALE. This may confirm the performance groups.

CHAPTER 5

Feasibility Study

5.1 Introduction

One of the fundamental initial steps was to perform a comprehensive feasibility study to ensure primarily users acceptance regarding the use of Novint Falcon grip. This investigation was conducted with blindfolded participants. Secondly, it was important to understand what are the movements a single finger follows to explore a real 3D object. This observation will give a set of guidance instructions to researchers of how to design the virtual 3D objects. Furthermore, it was essential to investigate how blind participants react to different textures and which one better helps them to explore and identify a virtual object. Analysing the data collected from the two previous meetings, the third and last meeting of the feasibility study will be conducted. During this, participants will be offered to practise small prototypes that have been designed and developed based on the feedback they have given during the previous two interactions.
Below, the participants who took part in the feasibility study are described (except the blindfolded participants).

Participants
A table of all participants can be found in 4.5 The Participants; not the same participants took part in all the feasibility meetings. All participants were allowed some time to familiarize themselves with the use of the grip and understand what the researcher wanted from them. Participants had different backgrounds in mathematics and in the use of computers. The participants at

school level were trained in more high level mathematical concepts and felt much more comfortable in the use computers. This is because the educational system, in which they are studying, is formed in such a way that students receive extra assistance on their modules during afternoon coaching at St Barnabas School for the Blind. Furthermore, there are teaching assistants during school times offering support and help when needed. This system enables them to be competitive in class exercises and promotes the shared understanding of school material. On the other hand the NCN Nottingham participants have received less training on subjects that require spatial thinking and reasoning and the level of computer knowledge was narrowed down to basic use. Educators and supporting staff described *"participants' only interaction with computers as being the use of assistive software".*

Records of the participants' academic performance in Computer and Mathematics are also presented. They are based on academic reports of the last semester marks performance and classification is as follows:

- Mark: 10-12/20 = Poor
- Mark: 13-14/20 = Average
- Mark: 15-17/20 = Good
- Mark: 18-20/20 = Excellent

The reason for adding this extra dimension is to investigate the hypothesis that participants with a strong academic background in either (or both) of these two modules perform better during the studies. To observe whether performance is linear with academic knowledge and expertise. "Use of the Novint Falcon before the test" indicates the time participants spent with the device right before the actual testing.

5.2 Tests with Blindfolded Participants

The Novint Falcon was primarily tested against its robustness, user friendliness and accuracy to feel true virtual touch. Since it was very difficult to get blind users to test and evaluate the Novint Falcon as a game console (due to Ethics Issues and Authorisation Approvals), blindfolded people who had never seen the platform before, were asked to first test the sphere demo and then play some of the small games prototype which come along with the console. Five people in total participated – three female aged 10, 13 and 28 and two males, 20 and 23 years old. They were explained what it is and what they had to do; all the information and details given to them were very similar to the ones given to blind users.

All but the 10-year old girl felt comfortable from the beginning giving the impression they enjoyed the experience. The little girl hadn't shown any excitement from the beginning and she kept asking *"what is it?".* After spending 7 minutes experiencing the interaction, she started to get along with the use of the grip and showed a more exciting and playful mood. The rest of the volunteers showed increasing excitement as time went by. These very initial results clearly showed that users need to spend some time playing with the Novint Falcon to familiarise themselves with a wholly new experience of human computer interaction. Moreover, they should have a complete, clear and comprehensive description of the things they have to do.

Figure 5-1: Novint's Tutorial & Game Screenshot
(Adopted from Novint Falcon)

As far as the accuracy force-feedback Novint Falcon gives, all participants identify correctly the sphere and the different texture applied to it. With eyes unfolded they all play a number of different games, from Virtual Pool to the Table Tennis, and they all concluded that the "feel" is very realistic and that it allows users a greater degree of freedom compared to traditional game joysticks. (See Figure 5-1: Novint's Tutorial & Game Screenshot).

5.2.1 Results and Discussion

The Novint Falcon was primarily tested for robustness, user friendliness and accuracy to feel true virtual touch. Since it was very difficult to get blind users to test and evaluate the Novint Falcon as a game console (due to Ethics Issues and Authorisation Approvals), blindfolded people who had never seen the platform before were asked to first test the sphere demo and then play some of the small games prototype which come along with the console. Five people in total participated – three female, aged 10, 13 and 28 and two males aged 20 and 23. What they had to do was explained to them and all the information and details given to them were very similar to the ones given to blind users.

All but the 10 year old girl felt comfortable from the beginning showing that they enjoyed the experience. The little girl had not shown excitement from the beginning and she kept asking "what is it?" After spending 7 minutes experiencing the interaction she started to get along with the use of the grip and showed a more excited and playful mood. The rest of the volunteers showed an increasing trend in excitement whilst time was passing.

These initial results clearly showed that users need to spend some time playing with the Novint Falcon to familiarise themselves to a whole new experience of human computer interaction. Moreover, they should have a complete, clear and comprehensive description of what they have to do.

As far as the accuracy force-feedback Novint Falcon gives, all participants correctly identified the sphere and the different textures applied to it. With eyes un blindfolded they all played a number of different games, from Virtual Pool to Table Tennis, and they all concluded that the "feel" is very realistic and that it allows users more degrees-of-freedom compared to traditional game's joysticks. (See Figure 5-1: Novint's Tutorial & Game Screenshot).

5.3 First Round Meeting: Real Object Manipulation

5.3.1 Design

It was very important to study how blind users manipulate real objects in free space to understand what the things they examine first in order to identify an object; what does an edge mean to them and how they perceive vertices and surfaces. Each participant entered the class on his/her own so that they had no knowledge of what they would be asked. Different 3D objects (a cube, a cylinder, a pyramid, a cone, a rectangular prism, a sphere and a hemi-sphere) were given to them to explore using only one hand, preferably the one they write with. While participants were manipulating objects the observer focused on the movements of their fingers and in which direction they rotated the object. Participants were encouraged to discuss the aspects of the objects as they were moving on. Time was not an important aspect of this experiment so it was not taken into consideration. After observing all participants a framework of movements was generated for each of one of them.

Participants

The participants who took part in this meeting were students from the school in Cyprus. A group of 6 participants aged between 14 and 22 (Participants A, B, C, D, K and P) participated during this meeting. Teachers and teaching assistants participated in the testing and evaluation session. Three out of the six participants (A, B and C) (50%) were born blind and had tested and evaluated the Novint Falcon for the first this meeting. The other participants had residual vision and the characteristics of each one can be found in Appendix H

Part.	Age	Residual Vision	Use of the Novint Falcon before the test	Computer Knowledge	Mathematics Knowledge
A	14	No	N/A	Excellent	Excellent
B	14	No	N/A	Excellent	Average
C	17	No	N/A	Excellent	Excellent
D*	15	Not Used	15 minutes	Average	Average
K	15	Used	15 minutes	Excellent	Excellent
P	51	No	15 minutes	Excellent	Poor

*Participant D lost her sight (<20) after brain cancer 5 years ago.

Table 5-1: Participants in First & Second Round Meeting

5.3.2 Results

Primarily the research was looking to answer the question what edges mean to blind users when it comes to exploring haptically a real object. There was the need of creating a framework of fingers' movement and how this can help in the game development. Below, there is a list of some of the objects users manipulated and their fingers' movements.

Cube: Because the object was small, just by placing it in their palm it was easy to understand the shape of the object. To make it more challenging and close to the Novint Falcon feedback, that is a single point interaction at a time, participant's index finger was placed randomly on a face of the cube. The finger was moving downwards along the face until the first edge was reached. Every time the edge was found the users immediately rotated the object in such a way as to be able to continue moving along the cube's faces. They were asked what the 'edge' means to them, they all said that *"it's the ending point and I have to rotate to continue".* Having done a full rotation of the cube they grasp the object in their palm and, positioning their thumb on one face and the index and middle fingers on the opposite face, they continue to explore the base using the ring finger. All four participants successfully identified the cube within 40 to 70 seconds. The observer asked which of the two mechanisms – moving along or grasping – was more helpful and accurate. Most of them responded that the they did the latter did unconsciously to double check that it was indeed a cube.

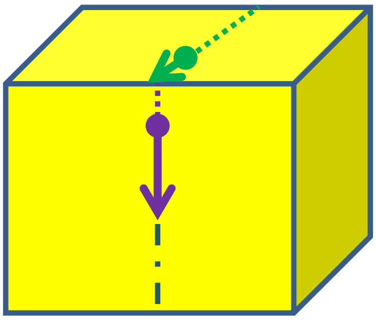


Figure 5-2: Real Cube Exploration

Cylinder: It was correctly recognized by all the participants. As soon as they realized that the face was circular they immediately explored the two bases positioning this time the thumb on the one and the index finger on the other. One of the participants commented that if the base is circular then there are no edges therefore that eliminated the possible answers.

Pyramid & Cone: The pyramid was more challenging than the other two. The user's index finger this time was positioned on the vertex of the pyramid. The two 14 year old participants this time followed the edges vertically to recognise the object with no need to explore the base but exploring the faces as well. Interestingly, when the user's finger was positioned on the face of the pyramid, the same process of exploration was followed as in the cube and the cylinder. A similar avenue was followed by the other two participants, with the only exception that both of them searched to explore the base more systematically than the other two did. The same exploration tactic was used with the cone, with the starting point to the vertex and participants moving along to reach an edge. As soon they realized that there was no edge they examined the base, stating that when *"there is no edge then the base is rounded"*.

This clearly shows that participants do have a good knowledge of the geometry literature that helps them identify the 3D objects effectively and efficiently. A rectangular prism, a sphere and hemi-sphere were also explored with the same mechanisms applied.

5.3.3 Discussion

Results from the feasibility stage support the findings of Olive G. Klingenberg (Klingenberg, 2007), that unlike with the visual system, the haptic system does not immediately extract the spatial features of an object in the form of oriented edges. In an attempt to develop a framework of finger movements during haptic exploration of real geometrical objects, it had been observed that users seemed to pay less attention to using the edges to orient the object. Blind people primarily moved along the faces of objects to identify an object and perceived edges as the limits and boundaries to move in. They also needed to be aware of the shape of the base and they seemed to pay less attention to vertices. In more challenging objects like the cone and the pyramid, blind participants examined the gradient of the face to help construct a successful model.

Since the intention was to develop a game that would imitate the real fingers' movements, the construction of this framework was of high importance. A general framework could be erected based on the feasibility stage's investigation:

1. Move along the faces of objects until reaching an edge
2. Perceive edges as the limits and boundaries to move in
3. Continue on a new face
4. Become aware of the shape of the base
5. Pay little attention to vertices

6. Examine gradients of faces – cone & pyramid

Therefore, in order of importance, the following framework may be derived:

1. faces
2. edges
3. gradient of faces
4. vertices & base as supplementary pieces of info.

5.4 Second Round Meeting: Feeling Textures

5.4.1 Design

A very important question to be answered during this meeting was the robustness of the Novint Falcon and how easily users with visual impairments could successfully interact and adapt to the use of the grip. Furthermore, another interesting and valuable trial was the textures and how helpful they can be towards the more accurate identification of an object in the VE. Participants were asked to locate the object and brainstorm on which texture gives them the most accurate tactile cues. They had to answer the question 'which texture better helps them keep track of their movements on the virtual object?' They had to choose between eight different textures: honey, rubber, magnetic, sandpaper, ice, molasses and rocky. One of the Novint Falcon's tutorials involves exploring a surface (a sphere) with different textures. Therefore, this meeting had the following dimensions:

1. The level of interaction and how accurate it was. Within the VE there was a sphere that participants were asked to locate and then determine its shape.
2. Determine which texture helps them better to detect the object's location in the VE and help them keep track of their movements on the virtual object.

Participants

The participants who took part in this meeting were participants from the school in Cyprus. A group of 6 participants aged between 14 and 22 (Participants A, B, C, D, K and P) [See 4.5, The Participants] participated during this meeting. Teachers and teaching assistants participated in the testing and evaluation session. Three out of the six participants (A, B and C) (50%) were born blind and had tested and evaluated the Novint Falcon before. The other participants had residual vision. It is exactly the same group of participants who took part in the first round meeting, therefore they can be found in Table 5-1: Participants in First & Second Round Meeting.

5.4.2 Results

Participants explored all textures available with the Novint Falcon tutorial and their preferences along with prevalent comments are presented in the following table.

Texture	Participant Preferences	Comment
Honey	Negative	-Sticky = grip stays on the object -moves through the ball, -not helpful to identify object
Rubber	Negative	-Shape changes every time user pushes it - not helpful to identify object
Magnetic	Positive	-Holds user close to the object -No slipping and loss of scene -Particularly helpful
Sandpaper	Negative	-Good in resembling object -Easy to lose control
Ice	Negative	-Tough surface -Helpful to resemble object -Easy to lose control
Molasses	Negative	-move through the ball, -not helpful to identify object
Rocky	Positive	-Very tough surface -User has constant control of his movements -No slip -Particularly helpful

Table 5-2: A list of all the different textures along with participants' preferences and comments

5.4.3 Discussion

Participants showed a preference for surfaces that were distinct and consequently very helpful in having control over their virtual movements on the object. The magnetic surface type was the one that better helped them remain on the virtual object. This, as a result, enabled participants to pay more attention to collecting the necessary tactile cues to identify object rather than control and stabilize the grip on the virtual object. The honey texture also helped users to remain on the object but the fact that it was too sticky made the exploration harder. Magnetic and rocky textures were selected to be the favourite ones and the ones recording the best results during exploration. Rocky was the most haptically distinct texture and participants were immediately aware every time they were losing the target. In addition, the magnetic effect keeps the grip constantly on the object and allowed the users to feel more relaxed and comfortable.

Based on participants' views, objects need to have:

i) A distinct surface, easily and quickly recognisable haptically

ii) To have bigger objects.

5.5 Third Round Meeting: Testing Pieces of Prototype

5.5.1 Design

The third round of meetings was about testing small prototypes of primitive shapes with haptic effects turned on and off. This testing involved more dynamic environments similar to the final game and participants had a clear set of tasks to complete. This work is published in the paper "The Development of Educational Interactive Virtual Environments for Children with Low or No Vision" (Petridou et al., 2011).

The tasks for this experiment were designed and developed by the researcher in collaboration with the teachers who gave an insight of what participants need to take into consideration, their preferences and comments that were derived from the first two meetings. The teachers were invited to try the prototype and to discuss possible adjustments that would better fit both the participants and the curriculum. In a previous visit to schools one of the questions that needed to be answered was whether the different texture will better help in the identification of objects. Results showed some trend of what is considered "helpful" in haptic exploration. Due to the fact that only a sphere was tested in different textures, secure conclusions couldn't be extracted, therefore this time the research team targeted testing a variety of objects with different haptic effects.

Participants

A group of 6 participants aged between 14 and 22 (Participants A, B, C, D, E and F) participated during this meeting. Teachers and teaching assistants (at school and college) participated in the testing and evaluation session. In one of the evaluation cases a participant collaborated with a class mate. Three out of six participants (A, B and C) (50%) were born blind and had tested and evaluated the Novint Falcon before. The other participants had residual vision and the characteristics of each one can be found in Appendix H

Part.	Age	Residual Vision	Use of the Novint Falcon before the test	Computer Knowledge	Mathematics Knowledge
A	14	No	N/A	Excellent	Excellent
B	14	No	N/A	Excellent	Average
C	17	No	N/A	Excellent	Excellent
D*	15	Not Used	15 minutes	Average	Average
E	20	Used	10 minutes	Poor	Poor
F	22	Used	10 minutes	Poor	Poor

*Participant D lost her sight (<20) after brain cancer 5 years ago.

Table 5-3: Participants in Third Round Meeting

Third Round Meeting was split into 5 different tasks and these are presented below:

Task 1: One sphere with solid texture and no haptic effect appeared in the VLE and participants were asked to first locate the object and then identify it. Time taken to complete the task was recorded and participants were allowed to brainstorm while exploring Figure 5-3: Tasks from left to right 1, 2, 3 – Picture 1.

Task 2: A cube was presented in the VLE and every time the user moved the grip onto the object the vibration effect was set off. The questions were the same as in Task 1 but this time participants were also encouraged to express their views on haptic effects and whether this simplifies the haptic exploration. They were also prompted to report their position on the object (e.g. at the base, at the back, left side etc.) Figure 5-3: Tasks from left to right 1, 2, 3 –Picture 2.

Task 3: Users were asked to find the number of objects in the VLE. They were not aware of the nature or the number of the objects. Objects were built to have vibration and magnetic effect. Figure 5-3: Tasks from left to right 1, 2, 3 – Picture 3.

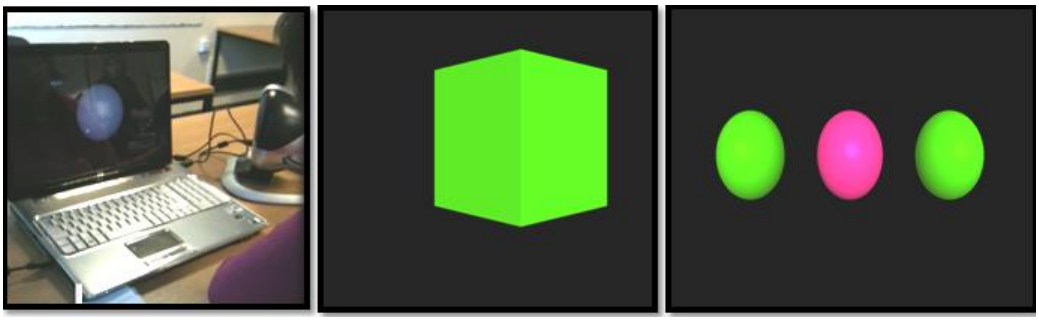


Figure 5-3: Tasks from left to right 1, 2, 3

Task 4: This task was the most challenging. Participants were given the object in Figure 5-4: – Picture 4 and were asked to name it. Also, they had to tell on which surface they were. Vibration was on.

Task 5: A similar scene to that presented in task 3 was given to users but this time spheres were of different size and had different haptic effects. The first one had a rocky texture, the second one had no effect and the third one had vibration and magnetic effects Figure 5-4: –Picture 5. Primarily the intension was to combine all the effects into one single scene and users were expected to give immediate feedback on their preferences. Since it was very similar to task 3, participants again used very similar exploration methods as they did before.

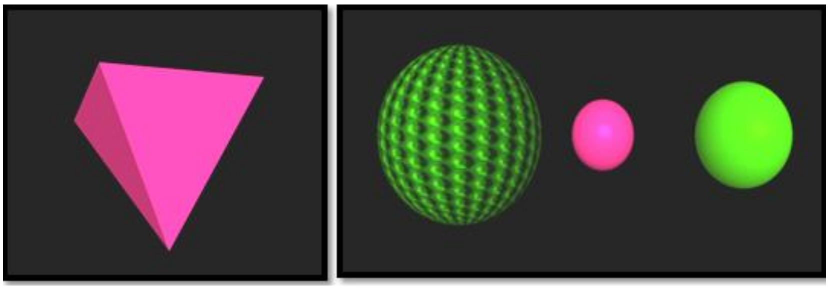


Figure 5-4: Tasks from left to right 4, 5

5.5.2 Results

At the very first interaction all participants were confused and concerned as to how stable the grip was. Their movements with the grip could be characterised as clumsy, causing the whole console to move. This was expected since they were not very familiar with the use of the grip. As time was passing by they showed a linear trend of better managing their movements.

The researcher along with the teachers advised the participants that they needed to make small movements each time. They all were allowed a period of 5 to 10 minutes to familiarize themselves with the use of the grip. Third Round Meeting was conducted 3 months after the initial two meetings; therefore participants' reaction had been expected.

Initially all users found it difficult to control the grip within the VE and therefore a) tracing the object and b) stabilizing the grip on it, seemed to be impossible as they constantly needed to know the position of the grip in the space and how close they were to the object. After two trial attempts with instructions given by the team all participants could detect the location of the sphere. The challenging thing was to manage to hold the grip on the top of the sphere. Only the 17-year- old participant achieved this and by making small movements he identified the object to be a sphere in less than 90 seconds. The other users recognized it correctly but it took them more than 2 minutes. One of the reasons users found some obstacles in the exploration process was the grip's speed that needed to be adjusted to reflect more realistic movements. Also the boundaries of the screen were not present in haptic examination leading the subjects making the unrealistic conclusion that the environment was endless, so using instructions like "the centre" or "at the centre" meant very little to them. The main reason of this ineffective first approach is considered to be the lack of audio feedback with sets of instructions as to where they were in the VE, no present boundaries and the unrealistic movements of the grip. Another observation suggested that tough surface was preferred by the majority of the participants. They all agreed that vibration was the least helpful and that with texture it would be difficult to spot edges and vertices.

Participants' detailed description of their performance can be found in Appendix H.

5.5.3 Discussion

During these meetings and based on the series of trials, participants showed an increasing success in correctly managing the grip and in understanding the tasks they were required to do. This supported the idea that spending time with interactive systems had positive and significant benefits and justify to some extent the knowledge transfer. Setting boundaries to the virtual scene and adjusting the grip's speed to resemble more realistic movements helped users to have more control over their virtual exploration.

Task 1: All participants managed to locate and identify the object successfully but their performance varied. The first 3 participants showed increased comfort in navigating and controlling the grip and this was mainly because they had spent some time practising with the platform during their spare time at school. Another reason can be the fact that their computer awareness and mathematical knowledge is stronger compared to participants E and F. The latter faced some problems to name the object even when they had successfully managed to isolate all the characteristics of the object (sphere). The performance of participant D is interesting in that compared with the rest of the participants she did better. This may be because that participant had undertaken the tutorial trial immediately before the evaluation of task 1. Participants E and F followed the same process as the previous participant but their performance remained at a very low level. These results support the belief that computer and mathematical knowledge play an important part in the adaptation to and engagement in the game as this was the main difference between participants D and Participants E and F. In addition, it can be said that success was not only based upon the well-designed VE and the tactile cues participants received but on the users' background knowledge and experience.

Task 2: Even though vibration was added to the objects with the aim of helping users identify collision and be aware when they slipped off the object, it was causing issues for the users in controlling the grip and exploring the scene. This was especially the case for participant E who had kinesis problems and found it extremely difficult to control the grip. Even though the majority of the participants managed to locate the object (<30 secs) fairly quickly, they spent much more time in gaining control over the grip before they could continue focussing once more on the haptic exploration of the object. In general only one in six participants said that they preferred vibration to be on. The rest of the participants admitted that the collision was immediately perceptible but vibration made it difficult to sense the edges.

Task 3: This specific task revealed some weaknesses of the system. Despite the fact that there were haptic effects on each sphere this was found not to be particularly helpful to participants. Collision was immediately noticeable but the fact that objects had the same haptic effects on one hand and the same size on the other hand made it extremely difficult for participants to identify the existence of three different objects in the VLE. Furthermore, the lack of audio instructions made the exploration process even harder.

Task 4: Despite the initial predictions and estimates that it would have been the most challenging task, 4 out of 6 participants managed to identify the object and at the same time were able to recognise the position they were at on the virtual object.

Task 5: Having all tactile textures combined into one single scene helped participants express their views and preferences. All participants agreed that vibration might cause additional problems in controlling the grip and moreover, objects with different texture would be difficult with details like edges and vertices. Their performance on the tasks supported their opinions.

Participants agreed that having solid haptic effect added to the exploration and that manipulation was better and would certainly be less tiring for them, something they believe *"would promote the playful and challenging aspects of the game".*

To conclude, the system's requirements were:

1) Bigger objects with bigger surfaces to explore
2) Audio Feedback as to where they are in the VLE
3) Audio Feedback on Time Left
4) Workplace boundaries
5) No vibration
6) No magnet
7) No haptic effect
8) Audio feedback on performance (Correct/Wrong input).

Based on these requirements along with all the data and observations collected with the interaction with participants, Levels One, Two and Three were designed and built.

CHAPTER 6

Software Design

6.1 Software Design introduction

Part of this research was to design and develop a haptic force feedback game that will enable visually impaired users to gain access to computer-based 3D geometrical objects in order to learn and practise mathematical concepts. The application was built using C++, the Chai3D3 (CHAI 3D is an open source set of C++ libraries for computer haptics, visualization and interactive real-time simulation), OpenGL4 (cross-platform API for writing applications that produce 2D and 3D computer graphics) and Autodesk 3DMax5 for designing primitive shapes. For this specific project Microsoft Visual Studio C++ (msvc9) was used. Further on in this chapter there is an in-depth analysis of the system and the design methodology followed. There is also a diagrammatic presentation of the main aspects of the game. To address the aspects of giving a realistic haptic interaction to the users in the most efficient and effective way a user centre design approach was followed. This process has been described in the previous chapter so this chapter concentrates on the technical aspects of the design.

[3] http://www.chai3d.org/
[4] http://www.opengl.org/
[5] http://usa.autodesk.com/3ds-max/

6.2 Development Tools

The haptic device used in this research was the Novint Falcon [See Section 3.4 Force Feedback Devices and the Novint Falcon].

Developing the software – which has been called i-HALE - was primarily done using CHAID3D which is an open source C++ based Application Programming Interface (API) that allows both high and low level programming of interactive real-time haptic simulation. The organisation of Chai3D is as follow:

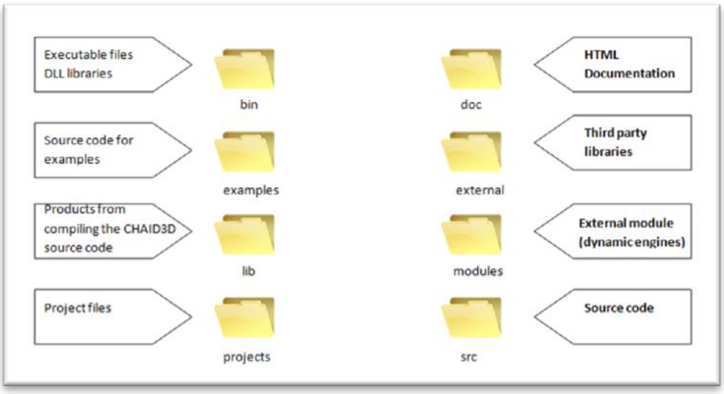


Figure 6-1: Organisation of CHAI3D
(Adopted from http://www.stanford.edu/class/cs277)

Chai3D comes with a number of examples along with their source code. Screenshots of some of the examples' output are shown in Figure 6-2: CHAI3D Examples:

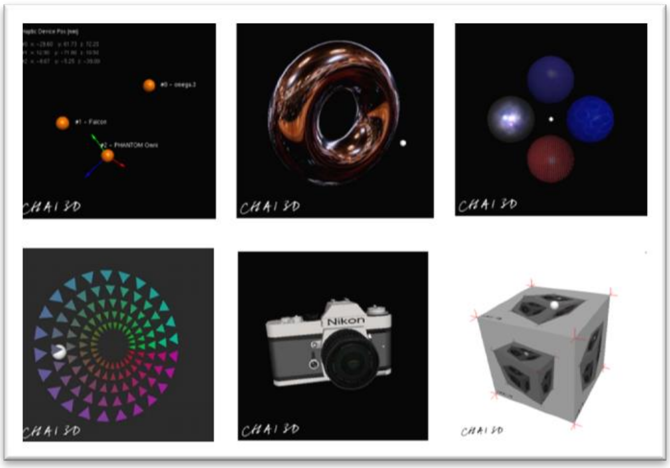


Figure 6-2: CHAI3D examples
(Adopted from Chai3D.com)

OpenGL based graphic rendering of objects and tools is automatically included by the CHAI engine. Objects with haptic effects were built in OpenGL whereas the ones with no effects were designed in 3DMAX studio and loaded into the system. The coding command for loading the .3ds object can be seen in Appendix L (a).

Virtual World

The steps to set up the scene properties were as follows. First the display window is initialised then the virtual world is created and lighting and a camera (viewpoint) are attached. Finally all the remaining objects are added. All variables were inherited from CHAI3D predefined classes e.g. variable world is an instance of class cWorld (cWorld* world;). The following image [See Figure 6-3: Virtual World] shows the role of each of the variables. However, for the purpose of this software, visually 3D parameters were not considered a primary focus.

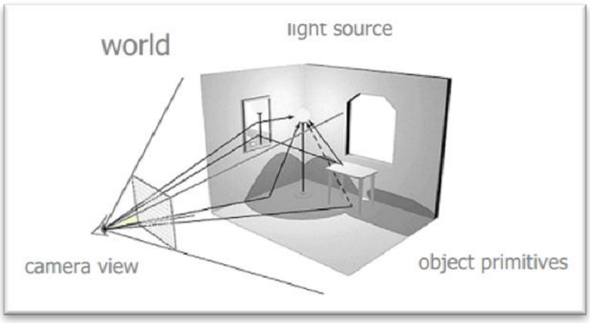


Figure 6-3: Virtual World
(Adopted from http://www.stanford.edu/class/cs277)

The next immediate step was to create the haptic device interface and connect it to the Novint Falcon.

3D objects in 3DMax and OpenGL

Two methods were used to develop the 3D primitives used in this study, (1) 3DMax Studio and (2) OpenGL. The following description concerns the design and load process of the objects developed in 3DMax Studio. The specific objects had no haptic effects. The first step was to declare these objects as variables as instances of a class called cMesh and add them to the virtual world by stating its 3D position. Following this, these objects were loaded into the code by specifying the path of the installed *.3ds* objects. Some basic characteristics and features of the objects may also be adjusted. An example of the software needed for this is given in Appendix L (b).

Objects built with OpenGL followed a slightly different process as these objects were constructed within the program and have haptic effects added. A callback function named createCube was developed that receives two parameters.

OpenGL splits all faces into triangles, therefore if a designer needs to design a 3D object they need to treat it as an assembly of 2D triangles. Therefore, to develop a 3D cube, the following steps are followed:

1) A cube called a quad is made up of 6 squares each consisting of two triangles with a common side forming the diagonal
2) All of the squares are drawn in a counter clockwise order, meaning the first point is the top right (Point 2 in the figure below), the second point is the top left (Point 1), the third point is at the bottom left (Point 4), and the final point is at the bottom right (Point 3) [See Figure 6-4: Quad vertices].

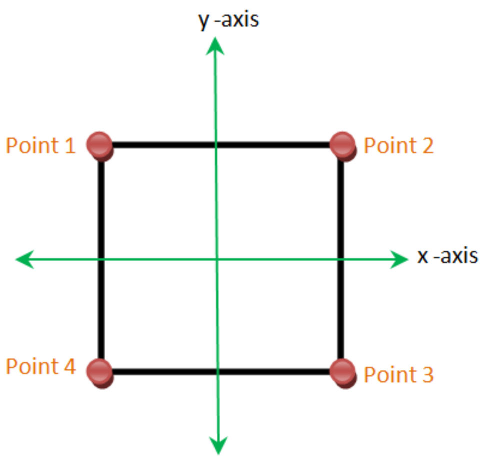


Figure 6-4: Quad vertices

3) Therefore the coordinates (x,y,z) each point has are as follows [See Figure 6-5: Cube construction in OpenGL]:
   Point1(-1.0 1.0 0.0)
   Point2(1.0 1.0 0.0)
   Point3(1.0 -1.0 0.0)
   Point4(-1.0 -1.0 0.0)

4) Then Points 1,2,3 are connected to create a triangle (a).
5) Points1,3,4 are also connected to create another triangle(b).
6) Now a 2D square is built.

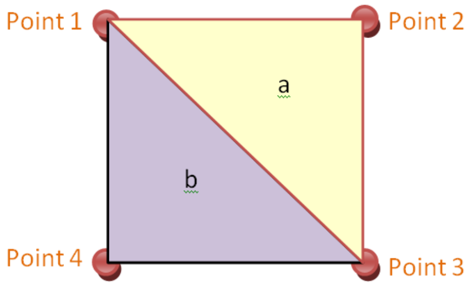


Figure 6-5: Cube construction in OpenGL

7) All vertices have been stored into 2d array

```
int vertices [6][6];
```

8) then a loop has been used to draw the triangles

```
    // create triangles
    for (int i = 0; i < 6; i++)
    {
      mesh->
newTriangle(vertices[i][0],vertices[i][2],vertices[i][3]);
    }

    // set material properties to light gray
    mesh->m_material.m_ambient.set(0.5f, 0.5f, 0.5f, 1.0f);
    mesh->m_material.m_diffuse.set(0.7f, 0.7f, 0.7f, 1.0f);
    mesh->m_material.m_specular.set(1.0f, 1.0f, 1.0f, 1.0f);
    mesh->m_material.m_emission.set(0.0f, 0.0f, 0.0f, 1.0f);
```

In the VLE the objects are placed randomly within the scene so as to make it more of a challenge for the users to find the object. For this purpose a callback function was also created to randomise the order of objects' appearance.

Labels Setup

Three different labels were created, the timeLabel, scoreLabel and the titleLabel. The function setupLabels was created that set up the properties of the labels, such as position, font, colour etc.

The Time label represents a countdown timer for each level. The Title label for Level One is a dynamic label that is used to display the written question (e.g. Find the cube) on the screen in a random order. Every time the user presses the space bar on the keyboard a new object is loaded and so a new question. This label is also associated with an appropriate set of audio instructions. The title label for Level Two-3 is a static label showing the only question associated with each level. Examples showing the code for setting up the labels and associated audio are given in Appendix L (c).

6.2.1 Software Structure

As explained above the game software was written in C++ the different stages of the game made use of pre-existing classes defined in the set of dynamically linked libraries (DLLs) provided in a system development kit (SDK) called CHAI3D provided with the haptic device. The class diagram for the software is given below [See Figure 6.6: Class Diagram 1].

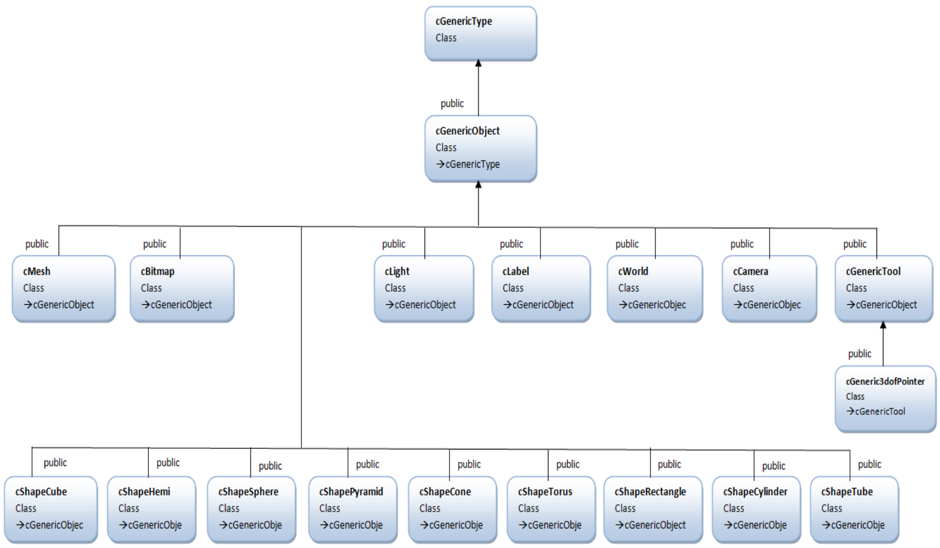


Figure 6-6: Class Diagram 1

All classes used to set up an i-HALE virtual scene derive from the abstract type of **cGenericType**. **cGenericObject** is an abstract class at the root of every renderable object in CHAI3D and defines a reference frame and the virtual methods for rendering which are overloaded by sub-classes. This class also defines basic methods for maintaining a scene graph. **cMesh** represents a collection of vertices, triangles, materials, and texture properties that can be rendered graphically and haptically where **cBitmap** provides functionalities to display a bitmap image. **cWorld** defines the typical root of the CHAI3D scene graph to which every aspect of the scene is attached. **cCamera** describes a virtual camera located inside the virtual world and it is responsible for setting up the OpenGL projection matrix for the current OpenGL rendering context. The default camera looks down the negative x-axis. The camera is first initialised and then it is attached to the environment of the virtual world.

```
  // create a new world
  world = new cWorld();
(...)

  // create a camera and insert it into the virtual world
  camera = new cCamera(world);
  world->addChild(camera);
```

cLight describes a light source of the OpenGL library which is rendered by a **cWorld** object. **cLabel** is used to display a line of text and **cGenericTool** describes a generic class that is used to create virtual tools inside the VE and connects them to the haptic tool. **cGeneric3dofPointer** which is a subclass of **cGenericTool** is used to represent haptic tools that can apply forces in 3 DOF and it provides i/o feedback with the haptic device. Classes **cShapeCube, cShapeHemi, cShapeSphere, cShapePyramid, cShapeCone, cShapeTorus, cShapeRectangle, cShapeCylinder and cShapeTube** are classes used to implement all the virtual shapes.

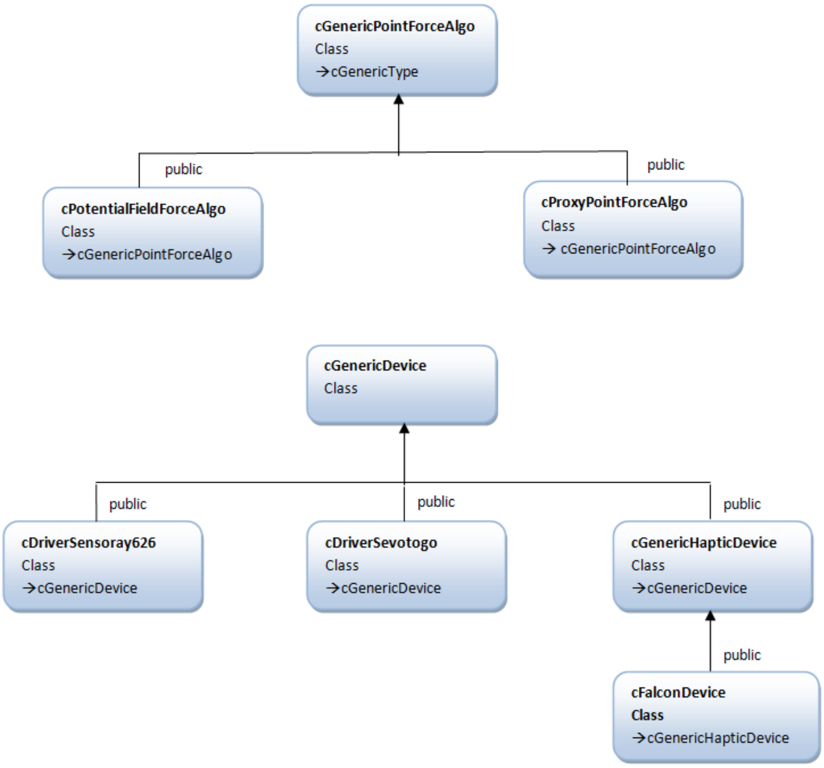


Figure 6-7: Class Diagram 2

cGenericPointForceAlgo is an abstract class for algorithms that compute single point force contacts and has two sub-classes: **cPotentialFieldForceAlgo** which is an abstract class for algorithms that compute single point force contacts and **ProxyPointForceAlgo** that implements the finger-proxy algorithm for computing interaction forces between a point force device and meshes.

cGenericDevice provides a general interface to communicate with hardware devices. **cGenericHapticDevice** is a virtual class from where all 2D and 3D point contact haptic devices are derived, for the specific research Novint Falcon.

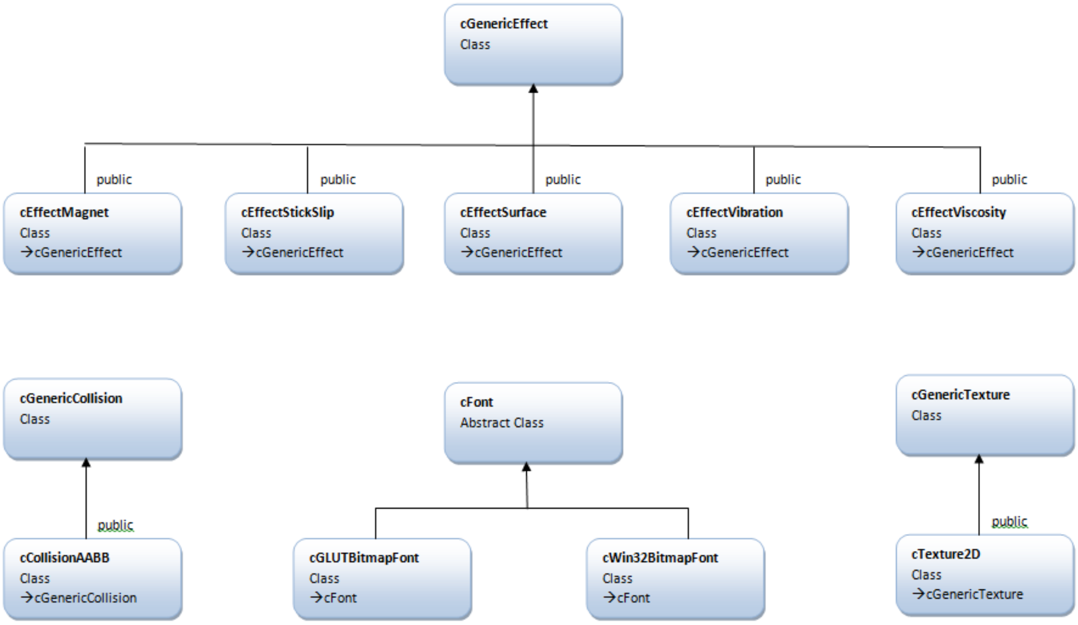


Figure 6-8: Class Diagram 3

cGenericEffect provides the basis to add haptic effects to models built in CHAI3D. **cEffectMagnet** and **cEffectStickSlip** model the reaction force – magnet and stick and slip effect - on a tool (e.g. Novint Falcon's grip) located near or on a virtual object. **cEffectSurface** models the reaction force of on tool pushing against the surface of an object and **cEffectVibration** models vibration force on a tool located on a virtual object by defining a frequency and amplitude. **cEffectViscocity** models the reaction force of a tool moving through a viscous environment.

cGenericCollision is an abstract class for collision detection and **cCollisionAABB** provides methods to create an Axis-Aligned Bounding Box collision detection tree.

cFond is a generic virtual Font interface which has two sub-classes: **cGLUTBitmapFont** an OpenGL Fonts provided the GLUT library and **cWin32BitmapFont** which is a 2D, texture-based, win32-specific implementation of **cFont**.

Use Cases

The following Use Cases describe the i-HALE’s Level One and 2 [See Appendix E].

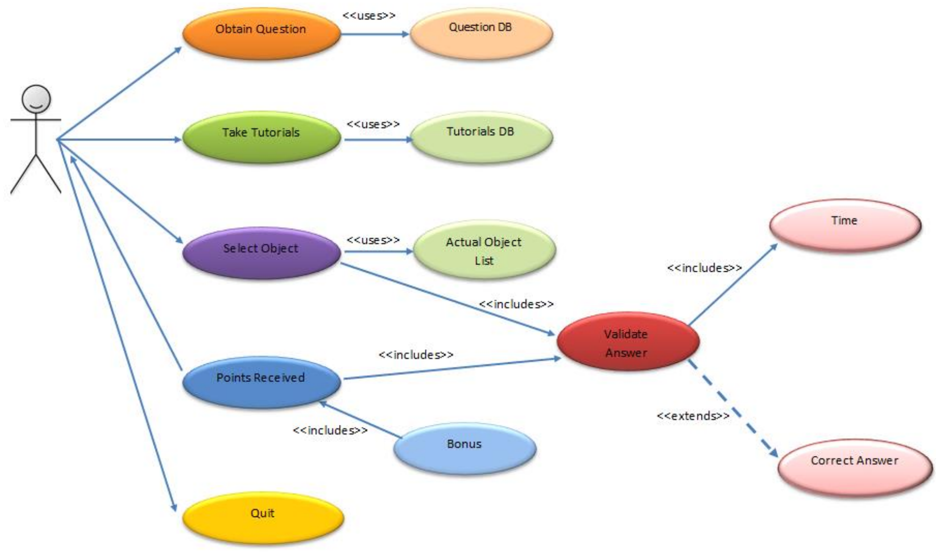


Figure 6-9: Use Case Level 1

The user is offered the choice of going through the tutorials before starting the actual game [Take tutorials]. Tutorials are available to be accessed throughout the process. In order for the next object to be loaded along with a question (e.g. Find the cube) [Obtain Question], the user is required to press the spacebar. Questions and objects are randomly loaded from the corresponding database [Question DB], [Actual Object List]. After the launch of the game, the user has to make a selection on the object he/she believes is correct [Select Object]. The answer then is processed and validated [Validate Answer]. Validation is based on two conditions: Answer within Time, and if the selected object corresponds to the actual object. Points awarded include the Validation Answer and applicable Bonus points.

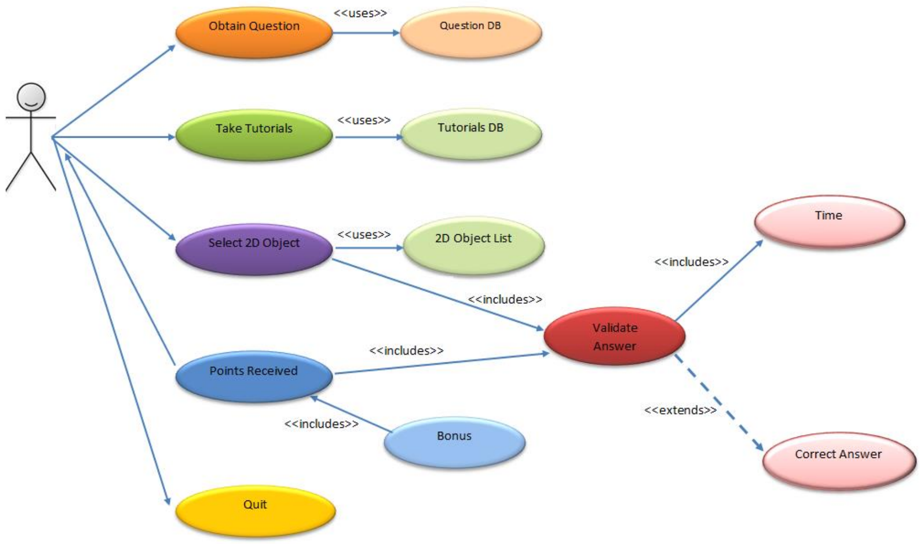


Figure 6-10: Use Case Level Two

Level Two follows the same process as Level One Use Case.

Flow Chart

The following flowchart describes the flow of processes of i-HALE [see Appendix G for further detail]:

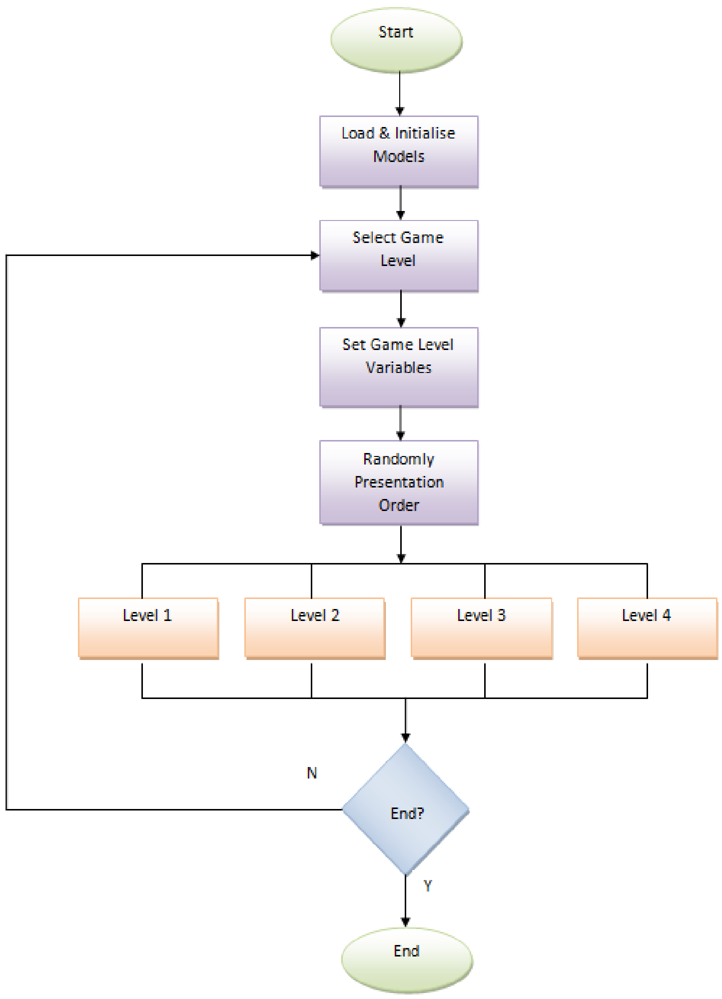


Figure 6-11: i-HALE Flow Chart

a) Since i-HALE is an Event –driven software every time the program is launched all the virtual models are initialised and loaded.
b) Then the appropriate game level is selected and therefore the corresponding virtual objects and set of questions are loaded.
c) Questions and virtual objects appeared on the screen in random order.
d) Users compete in game level *i.*
e) Every time a level is completed and a user does not choose to quit and/or conditions are not met, the process looping over steps b-e.

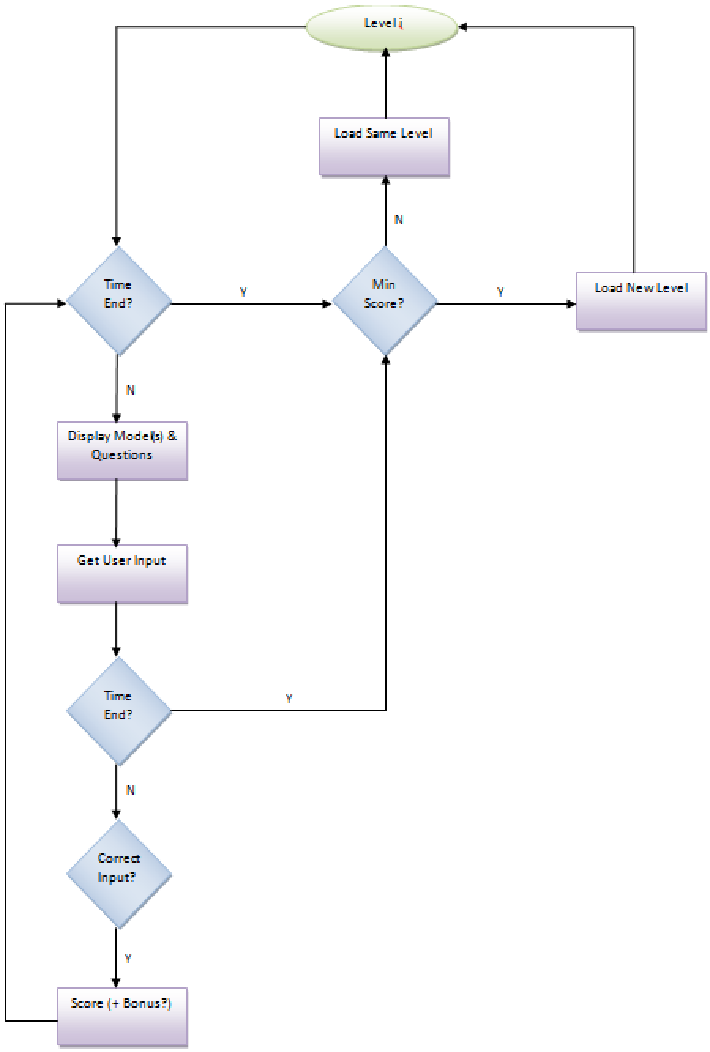


Figure 6-12: Level One-3 Flow Charts

1. The very first thing to be checked is time. If Time End? is No, then:
   - Display Models and Questions
   - Get User Response

   Else
   - Check if conditions are met. Min Score? Is Yes, then
     - Load New Level
     - Else
       - Load Same Level
2. Evaluation of User Response, first check time. If Time End? is No, then:

- Check if Response is Correct. If Correct Input? Is Yes/No, then:
  - Add corresponding marks to the Score

Collision Detection

The use of a force feedback device – which consists of motors and angular sensors – that can generate forces that end users can feel is called haptic rendering. Haptic rendering enables users to touch and feel virtual objects rendered by a computer. It may be split into two parts 1) the collision detection part, which tries to answer "if, where or when" two or more objects collide, and 2) the haptic rendering algorithm that calculates the force to apply on the end-user via the haptic device (Sjoberg & Ylinenpaa, 2009).

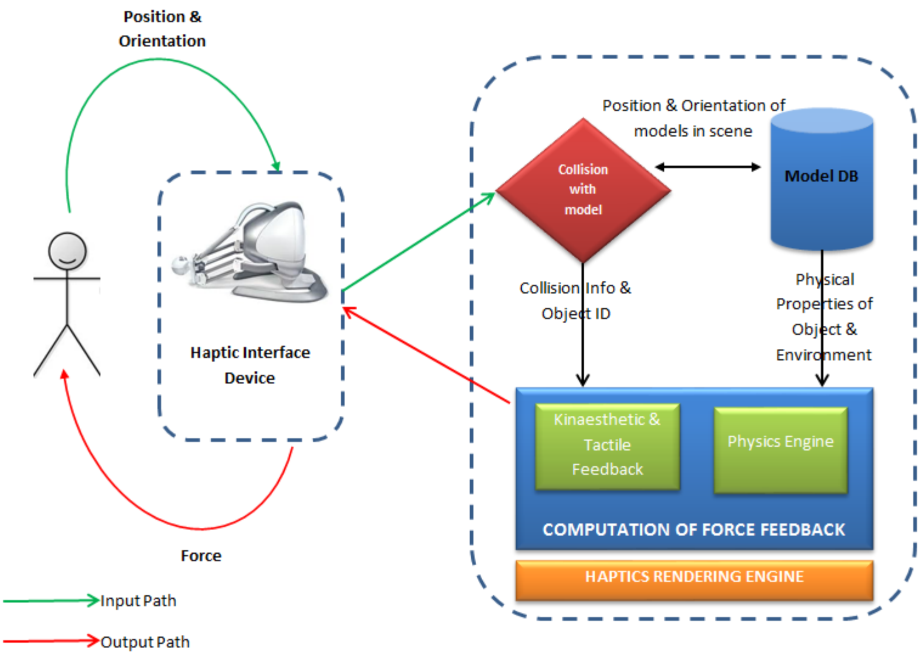


Figure 6-13: Collision Detection
(Adopted from Manav Kataria – Haptics Rendering for VE)

Figure 6-13: Collision Detection shows graphically the collision detection of a virtual object in VE. It represents the input and output path from and to the user. To illustrate this series of processes, the following scenario is described based on the i-HALE haptic exploration:

User scans the VE to locate a virtual object by using the Novint Falcon as the haptic interface device. A collision is sensed since a virtual object is reached.

```
sphere->createAABBCollisionDetector(1.01 * proxyRadius, true, false);
```

The latter is stored in a database – Model DB - which is responsible for positioning and orientating these objects in the virtual scene. Collision information and the object ID and physical properties of the object along with the environment's information are passed on to the computation of the force feedback process. The calculated force feedback is then presented to the user. i-HALE is an Event Driven program and therefore whenever the user touches the Novint Falcon's grip the software is called (hardware calls software) .

```
bool inTouch;
(...)

// read user switch
        bool userSwitch = cursor->getUserSwitch(0);
            runPhase2();
```

CHAPTER 7

i-HALE Level ONE: Identification of 3D objects

7.1 Introduction

The i-HALE Level One was designed to primarily enable participants to explore the virtual scene, locate and identify the randomly displayed 3D virtual objects. Knowledge gain from this level would eventually enrich the experience of the participants to proceed to the other levels. All participants were prompted to ask any questions they might have in order to eliminate to the minimum unsuccessful attempts caused by lack of satisfactory knowledge or misunderstood instructions. Furthermore, there was a brief verbal description of the level just to ensure that they knew exactly what they had to do. Level One was tested by all participants except participants E, F and G. All objects were solid 3D primitives. Users' exploratory performance in the tasks was automatically logged in a '.csv' file. At the end of each level, users were asked to fill out a questioner giving their opinions on the system and what they thought about the experience. The set of questions can be found in Appendix D [Same apply for Levels One, Two, Three]. Following in this chapter there is a description on the design of Level One, its results and closing with discussion.

Goal

The investigation was set to two dimensions:

1) to rate the level of understanding:

- ✓ What they were asked to do
- ✓ Extract necessary information to answer questions
- ✓ Awareness of the literature

2) to evaluate the level of success:

- ✓ Easily scan the scene
- ✓ Construct an accurate mental model of the scene
- ✓ Locate/explore the object
- ✓ Correctly evaluate the tactile cues received.

The participants and researcher developed a close friendship throughout the trial testing. This relationship cannot be characterised as the traditional teacher-student connection. It was based on mutual understanding, encouragement and consultation. They became friends on social networks and have exchanged emails on issues that had to do with the research itself and on personal issues as well. The resulting opinions are thus coloured by the response to the relationship and more emphasis is thus given in later experiments to performance in using the software and reactions to it, rather than opinions given by the participants. For this reason, during the experiments the author, along with the teachers, believed it would be more appropriate for the teacher to run the experiments in order to minimize the possibilities the status of the relationship to interfere with the participant's judgement and evaluation. The author, though, was present throughout all sessions.

Participants

The participants who took part in this meeting were students from the school in Cyprus. Teachers and teaching assistants participated in the testing and evaluation session. Seven out of the twelve participants were born blind and eight of them (66%) wish to practise with Novint Falcon prior the launch of Level One. The allowance was maximum 15 minutes. Participants M and O had residual vision (<20/200) and they insisted on having visual contact with the screen. The same participants took part in Levels One-Two and Three and the table below lists them along with their characteristics.

Participant	Age	Residual Vision	Use of Novint Falcon before test	Computer Knowledge	Mathematics Knowledge
A	14	No	N/A	Excellent	Excellent
B	14	No	5 min	Excellent	Average
C	17	No	N/A	Excellent	Excellent
D*	15	Not Used	3 min	Average	Average
I	14	No	10 min	Average	Average
J	28	No	N/A	Excellent	Excellent
K	15	Not Used	5 min	Excellent	Excellent
L	16	No	N/A	Good	Excellent
M	66	Used	15 min	Poor	Poor
N	55	Not Used	7 min	Good	Poor
O	57	Used	11 min	Poor	Good
P	51	No	10 min	Excellent	Poor

Table 7-1: Levels ONE, TWO, THREE Participants

7.2 Design

During Level One participants were given an audio instruction to find a specific object by navigating through different randomly displayed 3D objects. The objects were designed in Autodesk 3DMax Studio with solid texture and then loaded in the program. By pressing the space bar on the keyboard the next object was loaded; and in order to make it more of a challenge for users the 'next object' didn't have the same position in the VLE as the previous one. Therefore, users had to first locate the object by scanning the VLE and then start the virtual exploration using the Novint Falcon's grip.

A time limit of 100 seconds was given to identify as many objects as possible. The selection was made by pressing the Enter button on the grip

[See Figure 3-15: Novint Falcon's Grip]. For every correct answer participants received 15 points and no points for the wrong ones. If they managed to find a correct object in less than 10 seconds then an extra 10 points were received as bonus. The initial thought was to have negative marking for every wrong answer, but after thorough thought this idea was abandoned since the majority of the participants (66%) expressed the view that it would mean "losing its playful character" and that it would add additional stress and negative feelings. This work was presented in the paper: User Centred Design and Development of an Educational Force-Feedback Haptic Game for Blind Participants (Petridou et al., 2011).

The researcher and the teachers were in full control of the testing period. They observed reactions and level of interaction and comfort throughout the process. The appropriate quantitative data (time against accuracy, right position and measurements of the position against object) and qualitative data (comfort, excitement, obstacles, possible drawbacks) were recorded in order to extract overall conclusions from Level One. Participants were allowed to stop, restart or listen again to the tutorials at any time during the play. In order for participants to successfully proceed to Level Two they had to collect 60 points from Level One. Below is Level One screenshot; instructions are at the upper left hand side corner, Score in the middle and remaining Time at the upper right hand side corner.

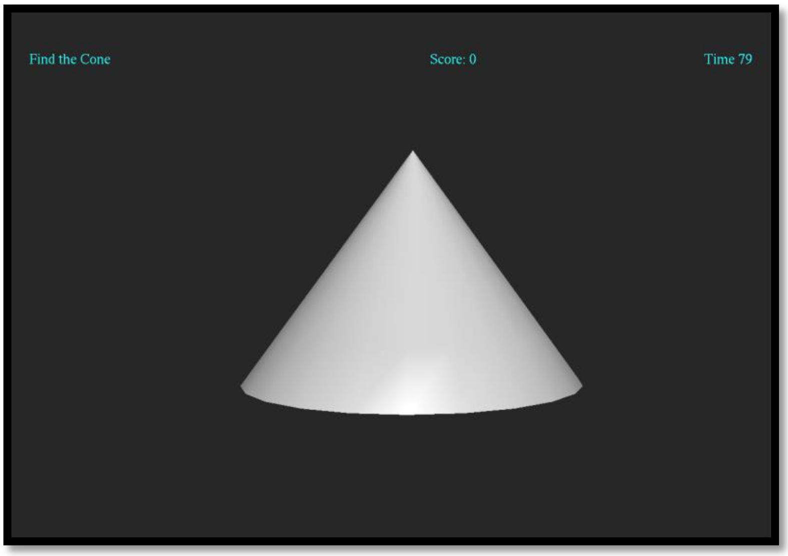


Figure 7-1: Level One Screenshot

Audio Instructions

The set of audio instructions given to participants during Level One were:

1. Find the Object i (where i = randomly selected an object's name).
2. Instructions of the position of the grip in respect to the object. Higher pitch sound as grip comes closer to the object.
3. For every correct matching, an audio message of "Correct, Well done" is played associated with a celebratory sound at the background.
4. If there is a bonus it is announced along with the correct answer.
5. For every wrong matching, an audio message of "Not correct, You can do it" is played. It's a message that aims to encourage participants not to give up because of a fail response.
6. When 5 seconds remain, a countdown tone is played.
7. "Time is up" message to inform participants that they have reached the end of Level One.
8. "Your Score is {the actual score}" is announced after the end of Level One.

7.3 Results and Discussion

The very first observation coming out of this level was that all the participants managed to locate at least one object. There is a distinct difference in performance for users who have strong technological background. See Table 7-2: Participants' Performance during Level One.

There were some participants who requested to restart the game and/or listened to the instructions again. However the majority of users who requested to have the game restarted did so as they felt that the second time, they could do better. The researcher and the teacher believed that it was fair for them to have a first actual practice with the game and then formally record their performance.

Engagement and Knowledge Transfer

There is no sufficient data to evaluate engagement and learning factor at this stage of the play. These would be more appropriate to measure during the next levels and to detect if, and in what degree, there is knowledge transfer. A brief observation during this level shows that participants who managed to locate more than 1 object show some sort of ease in locating the next objects. Moreover, based on their feedback, the majority of them found this level very interesting and looked forward to trying out the next levels.

Detailed report of each participant's comments and feedback can be found in Appendix I.

The following table gives an overview of Level One. Table metrics are:

Locate it AVG (sec): Refers to the mean time in seconds a participant needed to locate a new object. It is calculated by 100 seconds allowed for this level, divided by the number of the overall objects located – NOT identified.
No of objects: Number of objects located within the allowance time.
Points + Bonus: Points earned 15 pts for every correct identification plus 10 bonus points.
2nd Time Success: Only applicable to those participants who failed to meet the minimum requirements to proceed to the next level. √ indicated that participant succeeded during the second trial; *"No" indicates those participants who did not manage to collect the required points after the*

second trial.
Computer Knowledge: Based on academic performance.
Maths Knowledge: Based on academic performance.
Feedback: At the end of each level participants gave an immediate response of what they felt about the experience.

These are applicable for Levels One, Two and Three.

Part.	Locate it AVG (sec)*	No. Objects	Points + Bonus	2nd Time Success	Computer Knowledge	Maths Knowledge	Feedback
A	8.33	12	45+20	-	Excellent	Excellent	Positive
B	10	10	45+30	-	Excellent	Average	Positive
C	10	10	60+10	-	Excellent	Excellent	Positive
D	14.29	7	50+0	√	Average	Average	Average
I	14.29	7	30+20	√	Average	Average	Positive
J	12.5	8	45+20	-	Excellent	Excellent	Good
K	9.09	11	60+10	-	Excellent	Excellent	Positive
L	20	5	15+0	No	Good	Excellent	Neutral
M	100	1	0	No	Poor	Poor	Negative
N	16.66	6	30+10	√	Good	Poor	Average
O	50	2	15+0	No	Poor	Good	Negative
P	14.29	7	45+10	√	Excellent	Poor	Average

Table 7-2: Participants' Performance during Level One

*Within the given 100secs/number of objects locate

Students who failed to meet the score to move on to the next level and had to run the same level again.

needed the objects to be big enough to have large surfaces to explore. When virtual objects were smaller, the participants could not correctly evaluate them and determine their nature very easily. Furthermore, the participants expressed the opinion that they needed some sort of active notification as to where they were on the object (Petridou et al., 2011).

The results from Level One had shown that participants had spent most of the allowed time to gain control of the grip on the virtual object. Their movements seemed very quick and clumsy. Even though they didn't find it particularly difficult to locate an object in the first place they spent significant time searching for it every time they lost track of it. The other problem recorded was that mature participants and participants D and I didn't realise when the grip was not in contact with the object. In order to feel the virtual object the users needed to keep pushing the grip against the surface so as to create a constant collision. Whenever lack of contact occurred, participants were informed that they had to locate the object again.

According to the data presented in Table 7-2: Participants' Performance during Level One, one observation generated was that participants with strong computer background in combination with an acceptable level of mathematical knowledge scored better when compared to participants who had a poorer background in either or both of these areas. Participants with strong computer knowledge showed steady improvement in the use of the grip, and their interaction with the VE was positive and comfortable from the initial trials. They could successfully develop a model of the object and they could describe their position on it. Some of these participants requested having verbal description of their position in the VE in relation to the object. The view of participant B was interesting when they said that verbal directions given were misleading and confusing. Focusing on his reaction to a specific set of instructions like *"move slightly left"* or *"you are far away"* enabled us to realize that these descriptions meant very little to him. The same seemed to be endorsed by participants C and K with the latter giving a very informative view for relative distances, presenting at the same time their difference in perception. He supported the view that topological measurement instructions are subjective and cannot have the same meaning to all people.

Topological measurements and directions may have different meanings to different people and especially people with low or no vision. The fact that the instructions were given by a sighted person led to a significant difference in perception and the instruction “slightly left” may have a completely different meaning to people who lack the ability to have a complete and immediate perspective of the environment.

The verbal information had been shown to negatively affect the exploration and navigation for some participants. The respondents felt audio and verbal instructions were disorientating to them in their attempt to keep focus on the two principal tasks. Pakkanen and Raisamo (Pakkanen & Raisamo, 2004) have previously tried to illustrate and explain that exact recognition of geometrical objects by combining vibro-tactile feedback and audio technology is hard. On the other hand, there were participants for whom the absence of verbal instructions led to deterioration in their performance and accuracy as they seemed to spend most of their allowed time trying to construct a model of the scene without any feedback. Since these views represent personal preferences and do not express a general and thoroughly thought through view, this issue was monitored by leaving the option open to users of having audio instructions and feedback turned on or off. Another possible solution is the use of a wordless set of instructions that will have less impact on users’ concentration and motivation. Such a system would then rely mostly on haptic and tactile cues for the user to receive the necessary feedback on their position in the VE for instance.

As far as the playful and enjoyable characteristics are concerned, there were participants who wished to have the option to adjust the educational training according to their preferences. One participant expressed the view that there should be a way to either turn off audio instructions or play their favourite music instead. As far as the notification on the remaining time was concerned, some participants preferred to be informed when 10 and 5 seconds remained and some others expressed the view of having a sound that would become more intense as the end approached. The latter though was rejected by six of the twelve participants involved in Level I with the reason that it would cause anxiety and negative feelings.

Participant D had expressed a distressed attitude and sometimes looked incapable of collecting the correct and necessary tactile cues to move on. Even though she successfully located the object sometimes she couldn't detect the collision. She later explained that her desire to do well caused her to panic and didn't allow her to concentrate on the task. Later on her teacher explained that because she is a late blind person she has not yet managed to find a way to cope with her disability. At the same time in an attempt to reach the same academic performance level she used to have before her sight loss she panics and gets distressed.

Performance Groups

Participants' results can be grouped into the three categories mentioned in section 7.1 based on the average time (x) they needed to locate an object.

1) Performance group 1

Participants L, M, and O: These were mature participants who showed resistance and negativity towards the system from the initial trials. They couldn't see any potential value in the system and how it could be of any help to them at their age. These persons appeared to find both the concept of virtual reality and a haptic environment in general difficult to understand. For this specific group the concepts tested might not have been of any immediate interest, but the interaction with a VE and the understanding of tactile cues may have been used to enhance their knowledge for future expansions of the current game or for similar haptic environments.

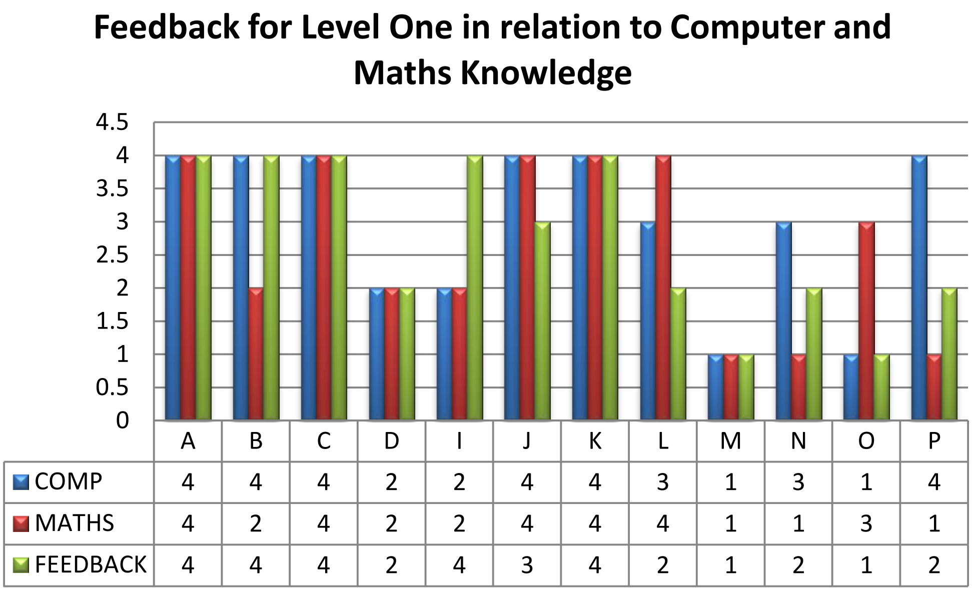
2) Performance group 2

Participants D, I, J, N, and P: With the exception of participant J all the other participants did not meet the minimum time/accuracy requirements for Level One tasks and had to repeat the level. Participants' knowledge in mathematics and computers varied in this group. The performance (in mathematics and computers) of both participants D and I was average in both areas but they managed to locate 7 objects during the trial, which was very positive. One explanation for this may have been due to the experience they gained playing with the platform during their free time. The performance of participant P is interesting as she managed to locate 7 objects and recognised 3, even though her mathematical background is very poor. However, she had a strong computer background due to the nature of her work. She showed confidence in handling the grip and constructing a mental model of the virtual world, a possible result of her experience with computers. Her interaction with mathematics has been rather limited to basic calculations and as a result she failed to optimally extract the correct tactile cues that would enable her to identify the object.

3)Performance group 3

Participants A, B, C, and K: With the exception of participant B, the rest of the users in this group had strong computer and mathematical background. The combination of the two was a relative advantage that enabled them to have the best performance. Participant B's mathematical knowledge was average but he managed to extract the correct tactile cues and evaluated them optimally to identify the object. The specific group could see short-term and long-term potential of the current level, starting by including more advanced and complicated shapes.

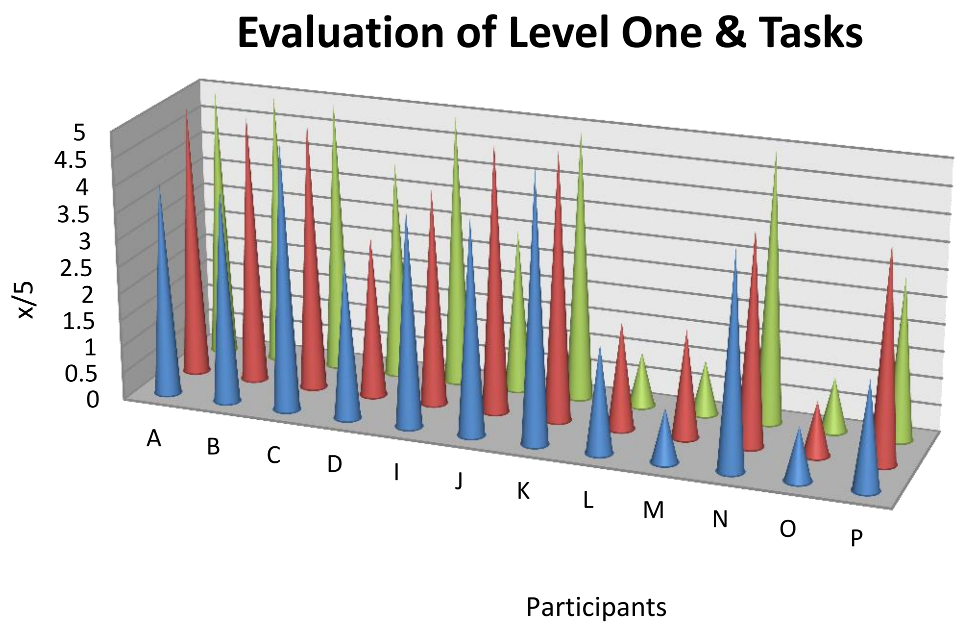
The following Chart 7-1 shows how participants' feedback for Level One may be associated with their mathematical awareness and computer knowledge. The following equivalents were used: Feedback (according their own estimation): Negative =1, Average = 2, Good = 3, Positive = 4. Knowledge (according to academic performance): Poor =1, Average = 2, Good = 3, Excellent = 4.



	A	B	C	D	I	J	K	L	M	N	O	P
COMP	4	4	4	2	2	4	4	3	1	3	1	4
MATHS	4	2	4	2	2	4	4	4	1	1	3	1
FEEDBACK	4	4	4	2	4	3	4	2	1	2	1	2

Chart 7-1: Level One Feedback against Computer and Maths knowledge

Based on the chart above, participants' feedback was mostly in line with their knowledge of both mathematics and computers. The most out of line results can be found in users N, O and P who were the mature participants and the reason for this variation in their feedback - in relation to the status of their subjects' awareness - might be traced to the fact that participants hadn't had a complete and crystallised view of the system so their evaluation was muddled and vague.



	A	B	C	D	I	J	K	L	M	N	O	P
Rate Ph1	4	4	5	3	4	4	5	2	1	4	1	2
Locate objects	5	5	5	3	4	5	5	2	2	4	1	4
Manipulation	5	5	5	4	5	3	5	1	1	5	1	3

Chart 7-2: Relation between performance and evaluation (Level One)

Participants were asked to rate Level One from 1 (very difficult) to 5 (very easy) and its major tasks [See Appendix D]. It is obvious that their evaluation of Level One was closely related to how easily they managed the tasks of manipulation and navigation [See Chart 7-2].

Exploration Pattern – A Virtual Traffic Environment

In addition to the above observations the program itself logged the way the user interacted with it. These log files show interesting patterns in that they reflected some of the explorative behaviours of the users. The following figures contrast the log files of two participants (A and L) during the exploration and manipulation process in Level One. Their quantitative and qualitative performance data was very diverse. <u>Small squared dots</u> represent the users' position in the VE each second. A *"glow" dot* indicates a correct selection click by the participant; it specifies the position of the object. Based on the chart below user A appeared to have a rather clear picture of where he was heading and his movements follow a tactic. Everytime he sensed a collision his exploration movements significantly slowed and by using small movements he was able to explore the object – this confirms the preliminary results. This shows control of movements on the virtual object – grip didn't slip away from the target. There is only the presentation of two participants' exploration patterns with very diverse attitude.

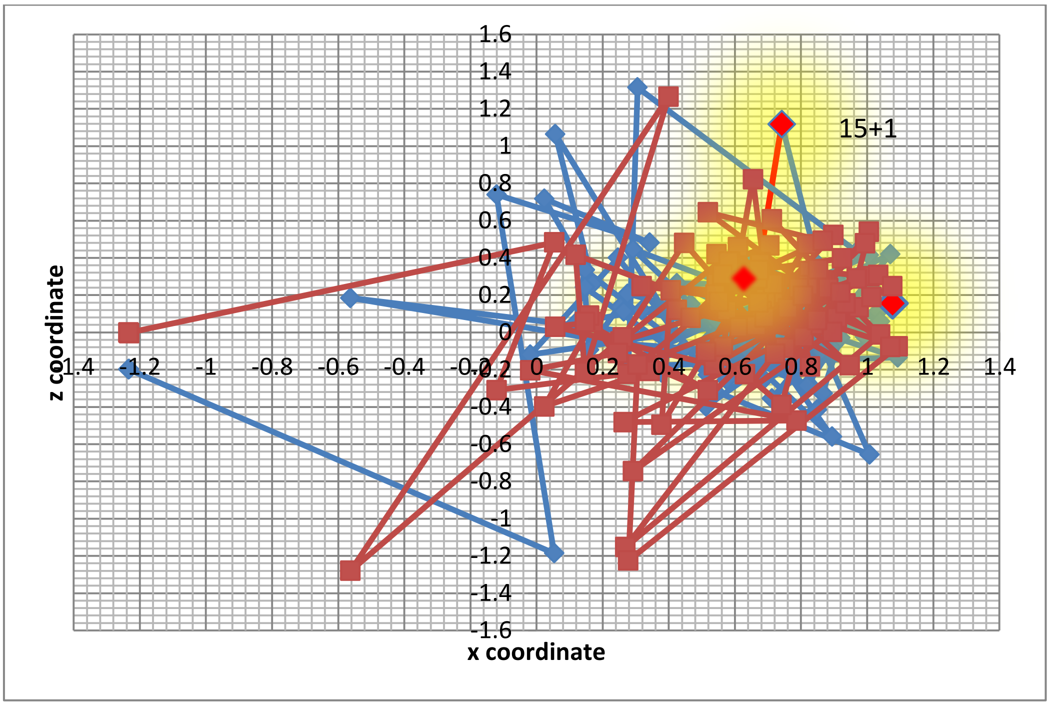


Chart 7-3: Novint's Falcon grip position in z-x plane and correct selection (Participant A)

His first correct answer was after the first 45 seconds and this was because he explored the scene and explored all objects before the first selection. The following correct selections were relatively easy since he was aware of the most characteristic tactile cues of each object. Again, this confirms the initial observation made during the actual test, that users' progress had been closely linked with the experience gained.

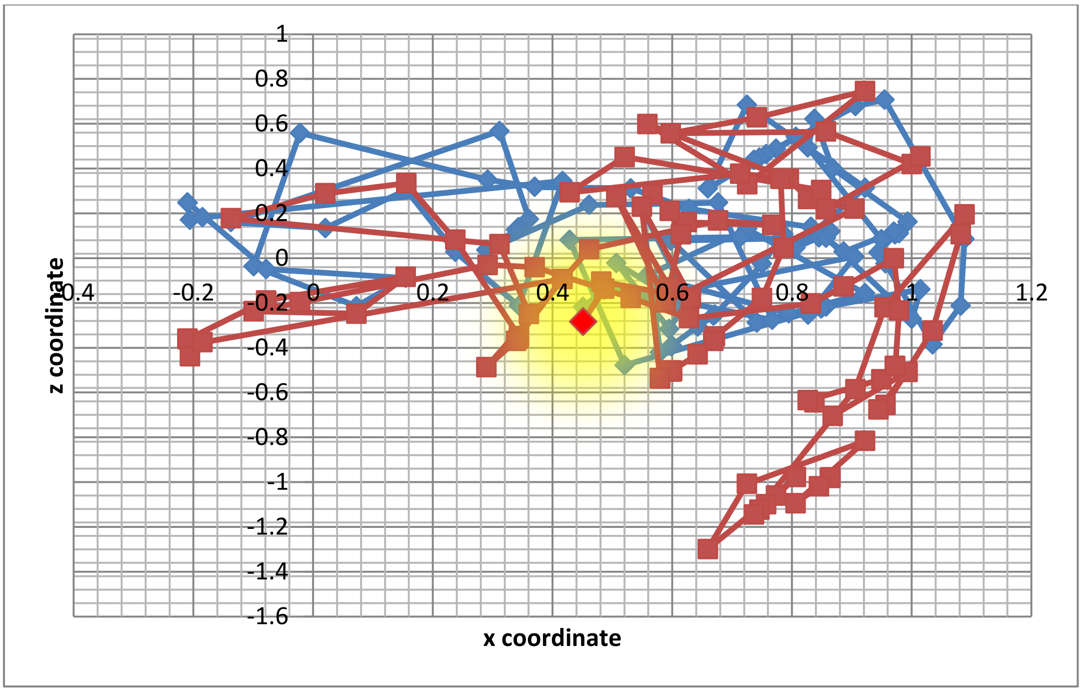


Chart 7-4: Novint's Falcon grip position in z-x plane and correct selection (Participant L)

Even though participant L managed to locate 5 different objects, she failed to follow a successful investigation pattern to identify them. Based on the log file above, she appeared not to have a clear picture of where she was heading. This confirms the observations made during the test.

Comparing the two charts above, one can understand the difference in the exploration patterns the two users use. Participant A performed a detailed exploration of the VE when compared with participant L who made significantly fewer movements within the given time. Another characteristic of the latter is that her movements were rather slow and not relaxed. Also, when the first user located an object his movements became more intense as the grip remained in the same area for much more time.

In a sense these figures also reflect the two types of exploration behaviour that were seen during the tests. Some users relied heavily on performing haphazard, disorganised movements in the scene and therefore leaving object location to be a result of random collision. Others performed methodical movements (e.g. Participant A) following an exploration pattern whenever an object was reached.

CHAPTER 8

i-HALE Level TWO: Reproduction of 2D Illustrations to 3D Objects

8.1 Introduction

i-HALE Level Two had two dimensions, firstly to evaluate the participants' ability to match the 3D objects with its 2D illustration and furthermore, to show whether the experience gained from Level One could have been of any use. With this task, participants were not only using their reasoning and memory ability but they also tested and practised their knowledge and understanding of this conversion. The reproduction of 2D illustrations to 3D objects lacks meaning specifically to people with no vision. Teachers explained that especially participants who are blind find it almost impossible to understand how *"a circle may be expanded in some way and create a cylinder or to a more challenging level, to a cone".* Teachers use real objects and raised line figures to illustrate reproduction through the extensive use of haptics. Before the launch of Level Two all participants were prompted to ask any questions they might have.

This game is the digital transformation of the traditional learning game where children have to match the 3D bricks with a corresponding slot.

Further on, this chapter contains a description on the design of Level Two and its results and ends up with discussion.

Goals:

The investigation was set to two dimensions:

1) Ability to match 2D illustration with the corresponding 3D object how easily they could locate the base:
   - ✓ How easily they could extract the characteristics of the 3D object and to name it
   - ✓ How well they know literature
2) Experience and knowledge transfer from Level One:
   - ✓ How comfortably they explored/scanned scene
   - ✓ How comfortably they could extract characteristics of 3D objects
   - ✓ How comfortably they could manage the grip.

Participants

For more info on participants - refer to 7.1 Introduction – Participants.

8.2 Design

During Level Two participants were given an audio instruction to match the randomly presented 3D object with the corresponding 2D illustration. The objects were designed in Autodesk 3DMax Studio with solid texture and then loaded in the program. This time, the virtual scene was divided into two sections: the active part – where the 3D objects appeared – which cover 75% of the screen and the static part – where the 2D illustrations were placed – which cover the remaining of the screen [See Figure 8-1: Level Two Screenshot]. The two parts were separated by a tactile line. Every time the grip was in contact with one of the 2D illustrations an audio sound with its name was set off. It was very difficult at this stage to find a way to haptically enable blind users to identify a 2D illustration in a VE. Participants tried to make the contours more distinct but again it was difficult for the users to follow the contours using the Novint Falcon grip. Therefore, it was decided to present illustrations that way. Possibly, it could form a future area of research as to how to haptically represent 2D figures in a VE using Novint Falcon.

Participants had 140 seconds to match as many 3D objects with the corresponding 2D figures as possible. For every correct answer they received 20 points plus 10 as bonus if they managed to find a successful match in less than 10 seconds. In order for the users to proceed to the next level, they were required to collect 80 points otherwise they had to repeat the task.

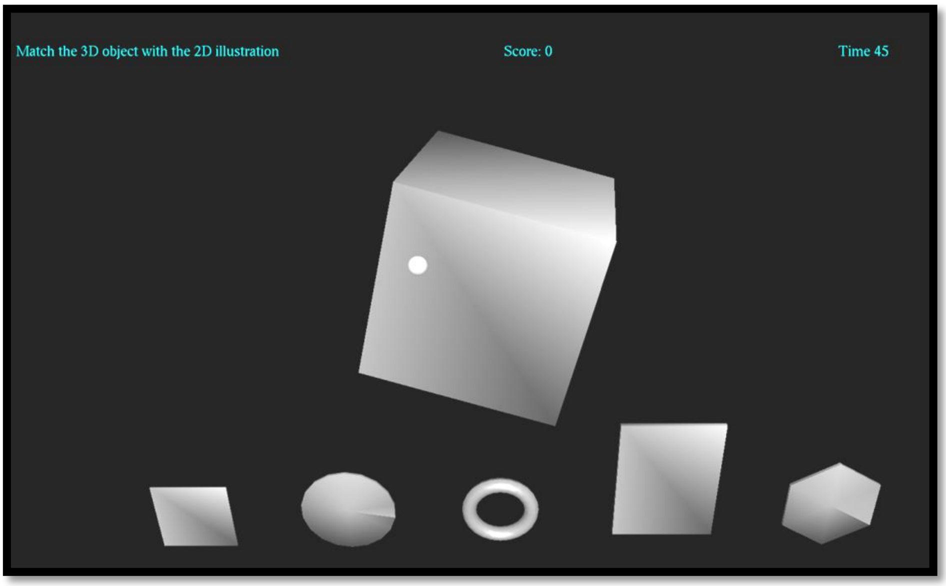


Figure 8-1: Level Two Screenshot

Audio Instructions

The set of audio instructions given to participants during Level Two were:

2. Match the 3D object with the corresponding 2D illustration
3. Instructions of the position of the grip in respect to the object. Higher pinch sound as grip comes closer to the object.
4. When grip comes in contact with an illustration an audio feedback with its name is set off.
5. For every correct matching, an audio message of "Correct, Well done" is played, associated with a celebratory sound at the background.
6. If there is a bonus, it is announced along with the correct answer.

7. For every wrong matching, an audio message of "Not correct, You can do it" is played. A message that targets to encourage participants not to give up because of fail response.
8. When 5 seconds remain a countdown tone is played.
9. "Time is up" message to inform participants that they have reached the end of Level Two.
10. "Your Score is {the actual score}" is announced after the end of Level Two.

8.3 Results and Discussion

When participants were asked to explain what this conversion meant to them there was an obvious misunderstanding on the question itself. One of the participants clearly gave the most accurate and specific view for the reproduction of 2D figures into 3D objects, "for us there are two categories; the 2D objects which can be drawn on a piece of paper, and there is the other category of the 3D objects which are real things that you can hold in your hands. So, in my mind it's either 2D or 3D, and definitely 2D cannot grow and be 3D." It was very clear from the very beginning that participants needed guidance to either develop a successful mental model or to simply explain to them how a circle can be expanded into a cylinder!

During this level the majority of the participants showed complete comfort in using the grip, and their movements looked organised, controlled and relaxed. When they were asked if they felt more determined now, the overall response was that they knew what to do when they sensed the collision. There was also the view that they felt less stressed and therefore they performed better.

Even though the time allowed was more than in Level One, it was observed that there was an increase in frequency of locating the objects. Also, participants with a strong mathematical background earned more points. Another notable observation was that they seemed more relaxed, calm and in full control of the activity. See Table 8-1: Participants' Performance during

Level Two. Detailed report of each participant's comments and feedback can be found in Appendix J.

Part.	Locate it AVG (sec)*	No. Objects	Points + Bonus	2^{nd} Time Success	Computer Knowledge	Maths Knowledge	Feedback
A	8.23	17	120+20	-	Excellent	Excellent	Positive
B	9.33	15	100+30	-	Excellent	Average	Positive
C	10	14	100+10	-	Excellent	Excellent	Positive
D	23.33	6	60+10	√	Average	Average	Positive
I	14	10	100+0	-	Average	Average	Positive
J	7.77	18	120+10	-	Excellent	Excellent	Positive
K	10.76	13	80+20	-	Excellent	Excellent	Positive
L	23.33	6	60+0	√	Good	Excellent	Good
M	140	1	20+0	No	Poor	Poor	Negative
N	20	7	60+0	√	Good	Poor	Average
O	46.66	3	20+0	No	Poor	Good	Negative
P	70	2	0	No	Excellent	Poor	Negative

Table 8-1: Participants' Performance during Level Two

*Within the given 140secs/number of objects locate

[Students who failed to meet the score to move on to the next level and had to run the same level again.
c

outcomes during the feasibility study, users performed better as they progressed through the tasks. They also expressed the view that they felt more relaxed and confident as time progressed. One possible reason for this view - other than that of experience - might have been the fact that it was not a simulation primarily built to test their knowledge on mathematics and therefore no affect would have been applied on their current marks. There were participants who expressed concern as to what effect their performance in the VE tasks would have on their marks.

Overall, more participants returned positive feedback for this level even though it was not correlated with their performance. Participants justified their feedback because of the more challenging tasks they had to complete [See Chart 8-1: Level Two Feedback against Computer and Maths knowledge].

Performance Groups

The given time for this task was increased by 40% (to 140 seconds) therefore the groups boundary limits were readjusted. Participants' results for Level Two may be grouped as followed:

1) Performance group 1

Participants M, O and P: The mature participants continued to perform at low levels and persisted in their initial view of not detecting or foreseeing any positive effects use of the VE would have at their age.

2) Performance group 2

Participants D, I, L and N: In contrast with the same group in Level One, participant L improved her performance and was promoted to this group whereas participant P dropped to group 1. The performance of participants D, I and N remained stable.

3) Performance group 3

Participants A, B, C, J and K: Participant J improved his performance and was included in this category. Remaining users were the same. This group showed an improvement in performance and most of its members asked for more challenging tasks in future expansions.

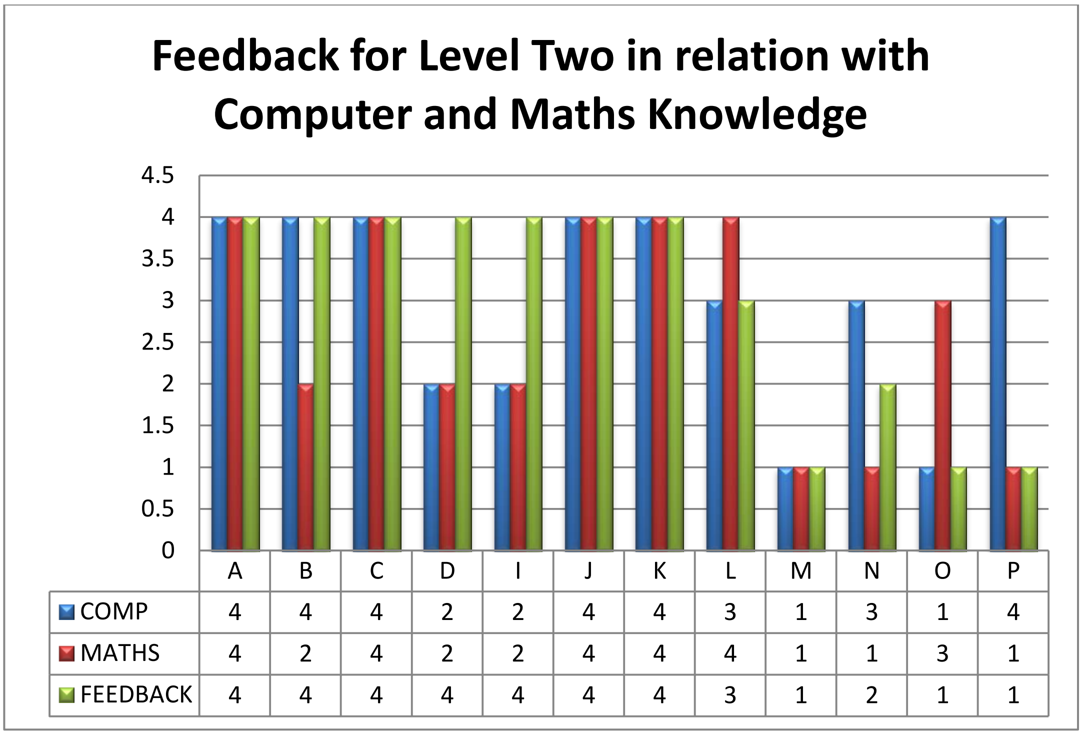


Chart 8-1: Level Two Feedback against Computer and Maths knowledge

With the exception of two participants (D and P) all other participants managed to locate more objects when compared to the objects they located during Level One. An increase was observed in the successful progress to the next level from the first trial; a quarter of the participants (participants M, O and P) failed to complete the required tasks after the second run. Two of these participants had also failed to proceed to the next stage during Level One (participants M and O). With the exception of Participant D who had a decrease in the number of successfully locating objects and Participant M who located the same number all the other participants managed to locate more objects during Level Two. These findings show that 83.3% of the participants have improved their performance in the specific task. Since navigation and exploration were the two major tasks tested in Level One, during Level Two participants showed a more relaxed and comfortable attitude in better managing the grip and navigating in the VE.

Regression Analysis of Level One vs Level Two

With reference to Chart 8-2 the data is linearly correlated (score in level one indicates score in level 2) with most of the values being "close" to the regression line. However there are two major outliers: **Participant P** who performed significantly worse in Level Two than in Level One and this was because she found it extremely difficult to grasp the idea and her performance in level one involved a degree of chance in her random choice of objects. The other outlier is **Participant J** who improved dramatically during Level Two. He explained that he didn't feel completely sure what was happening during Level One but as soon as he grasped the idea he achieved much better results. Overall, in general all participants improved in Level Two compared to Level One.

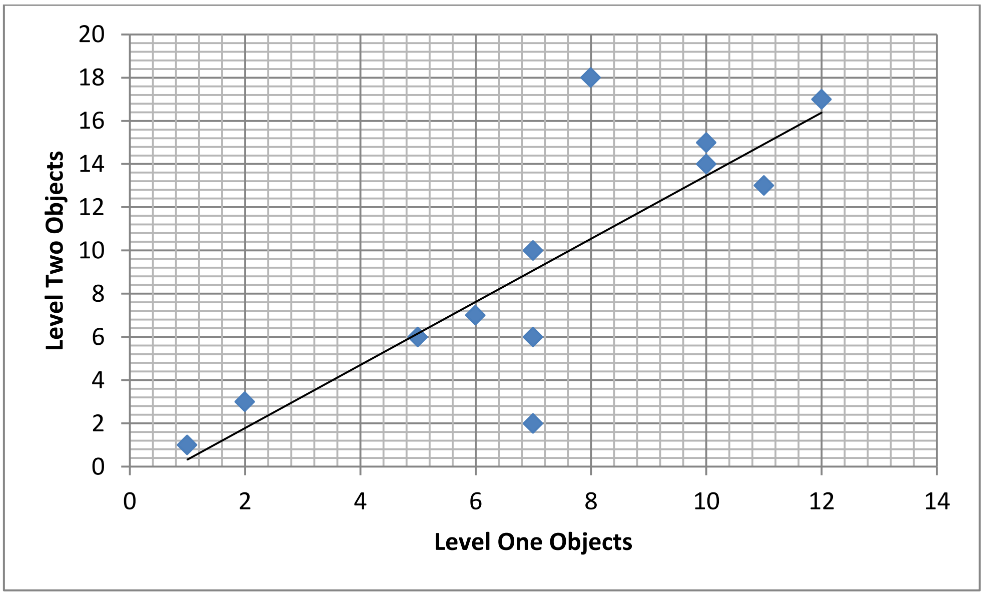


Chart 8-2: Regression Analysis: Number of located objects during Level One and Level Two (including outliers)

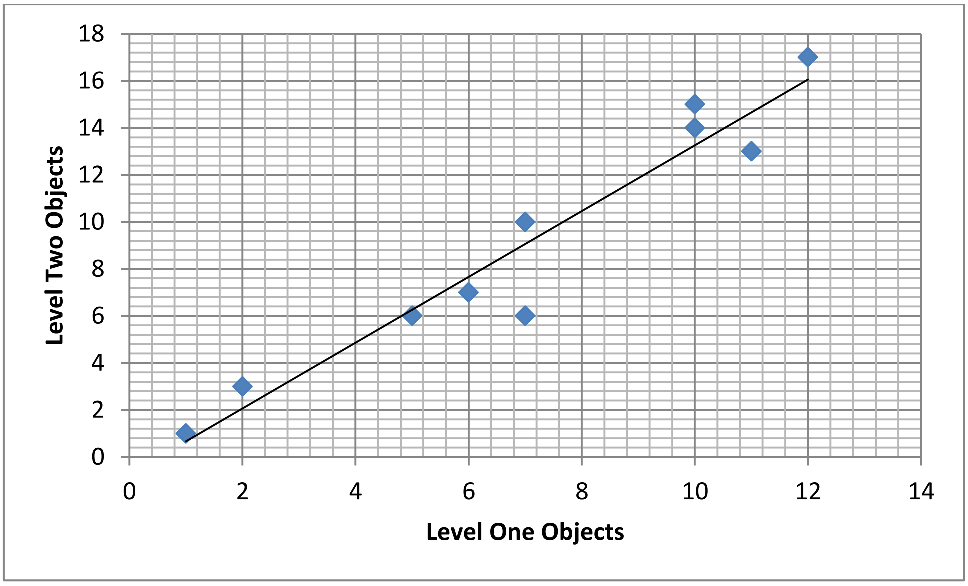
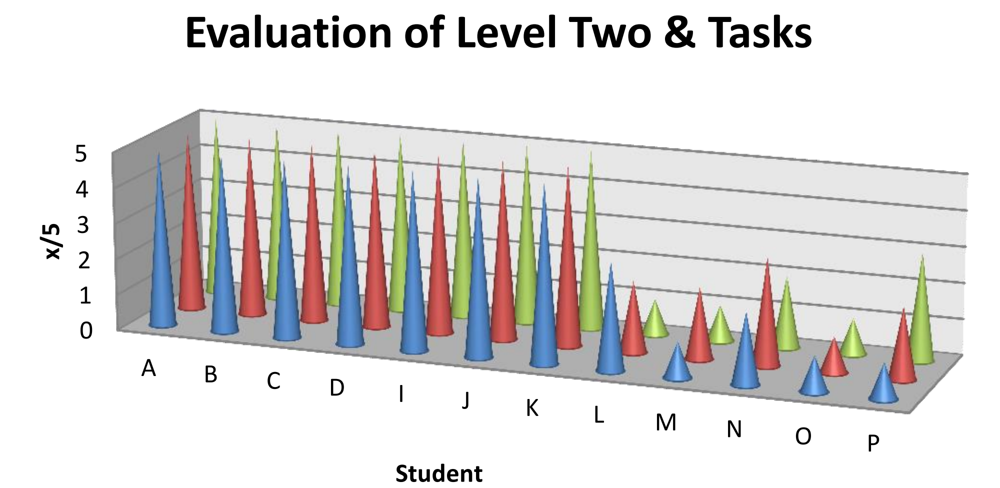


Chart 8-3: Regression Analysis: Number of located objects during Level One and Level Two (excluding two outliers)

Based on Chart 8-3 which represents regression analysis having the outliers removed, there is a very close correlation between Level One and Two performances with *the standard deviation* falling from 3.54 to 1.54. The regression line clearly shows that that there was indeed knowledge transfer from Level One to Level Two.

Participants Evaluation Level One vs Level Two

Positive outcomes have characterised the effort of all participants as the majority of them managed to successfully use knowledge previously earned to perform better during this level. The fact that participants continued directly from the end of Level One could be a reason why they did better. This helps support the previous observation that memory is affected by time spent on the task and the time that elapses between the trials. The two negative performances (participants D and P) had to do more with the psychological aspects governing the participants' attitudes rather than the technical and haptic aspect of the system. Participant D had a negative attitude because she felt uncomfortable working in the presence of other people. Having in mind the psychological state she was in because of losing her vision only recently it was believed that the fact that she couldn't reach a high performance during the initial steps of the trial confused her and eventually caused her to lose concentration and determination. Participant P continued to have the same negative approach towards the system and the inability to correctly identify some objects at the beginning of the trial reduced her enjoyment.



	A	B	C	D	I	J	K	L	M	N	O	P
Rate Ph2	5	5	5	5	5	5	5	3	1	2	1	1
Locate objects	5	5	5	5	5	5	5	2	2	3	1	2
Manipulation	5	5	5	5	5	5	5	1	1	2	1	3

Chart 8-4: Relation between performance and evaluation

Based on performance and participants' evaluation was in line with their performance in locating and manipulating the 3D objects.

The second part of the evaluation was the assessment of the methods blind participants used to match a 3D object with the corresponding 2D illustration. Most of the users employed an elimination method which primarily involved them to examine the existence of edges. So the exploration pattern for this specific task followed different steps, as users paid more attention to edges. Once an edge was haptically discovered, then they started exploring and evaluating faces.

In general participants seemed to enjoy the interaction better than during Level One and there were some suggestions of having this game available online in order to be able to practise at their own pace and compete with other users. The view expressed by some pupils that they wish to see an upgrade of the system and the introduction of more advanced concepts was interesting. This opinion gave an insight into what might be interesting and engaging for a game designed for educational purposes.

Exploration Patterns – A Virtual Traffic Environment

As mentioned earlier, the majority of participants seemed more relaxed and comfortable in using the grip and optimally navigating in the VE. The performances of two participants (J and P) are notable. The first who did much better during this level and the latter whose performance declined compared to previous results. Charts 8-5 and 8-6 show the contrasting exploration patterns of these two participants.

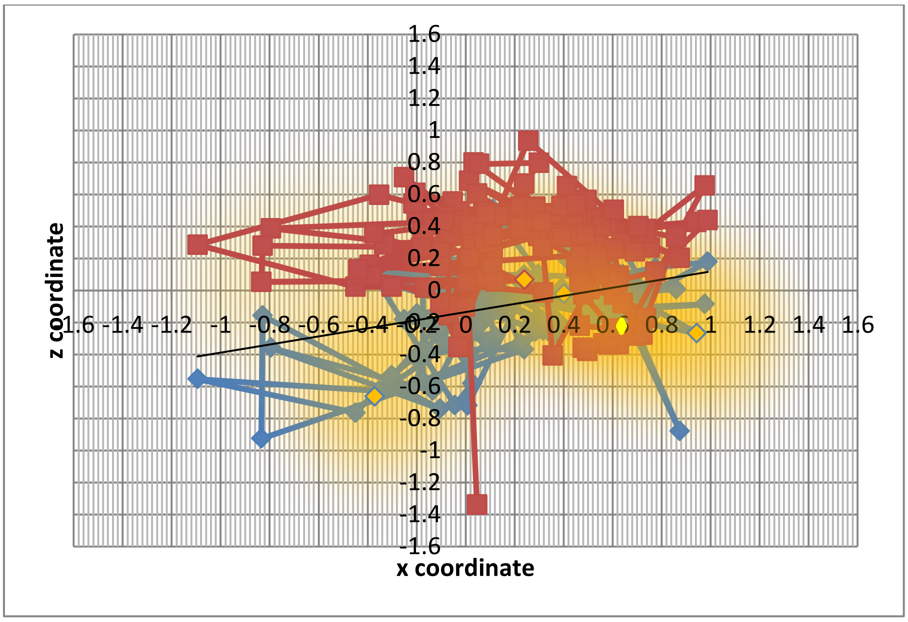


Chart 8-5: Novint's Falcon grip position in z-x plane and correct selection (Participant J)

Participant J's exploration pattern is graphically presented in Chart 8-5: Novint's Falcon grip position in z-x plane and correct selection (Participant J) that presents a specific exploration pattern the user followed without losing control of the grip. The total number of dots was also influenced by how carefully the user explored the environment. As soon as he detected collision with small movements he started the investigation of the object. His accuracy may also be reflected by the number of objects touched (18 objects), the most out of all of the participants in the study.

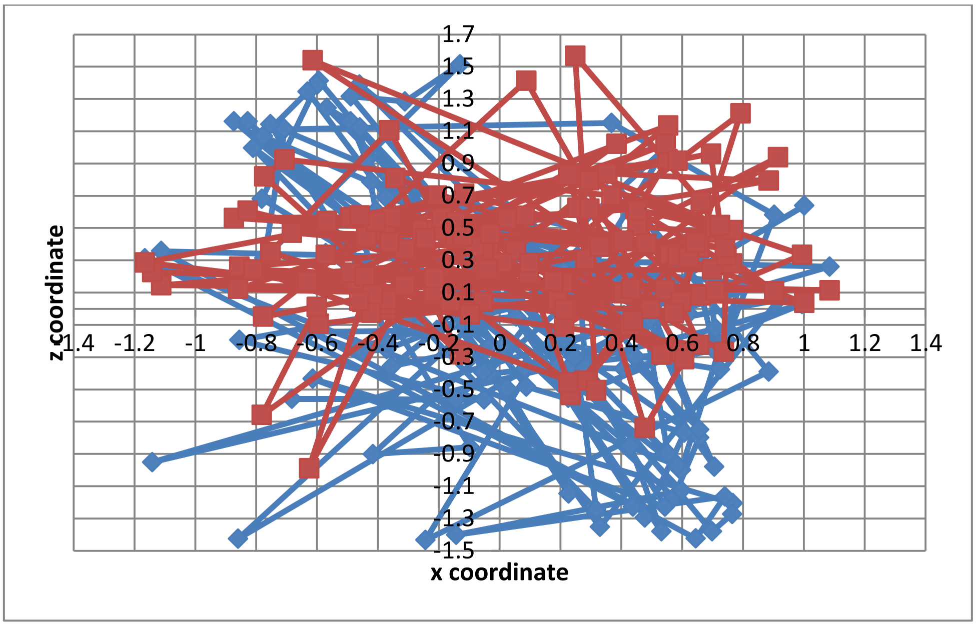


Chart 8-6: Novint's Falcon grip position in z-x plane and correct selection (Participant P)

Participant P failed to correctly match at least one 3D object with its 2D illustration. Even though she was able to locate 2 different objects, her lack of concentration prevented her from optimally examining the surface and base of the objects. Based on her virtual traffic, her movements could be characterised as very disorganised, random and quick. It is interesting as well to look a little more in detail at how these dots are distributed. Compared with user J, for whom one may distinguish that there are more haptically centralised dots, user P's dots were distributed in the whole environment and she kept changing location significantly every second. Even when she traced the 2 objects she didn't manage to stabilise the grip on the object. It was interesting that when she lost track of the objects she didn't try to relocate them.

CHAPTER 9

i-HALE Level THREE: Size Order

9.1 Introduction

i-HALE Level Three was designed to enhance the participants' ability to compare objects and to remember them, to construct a mental model of the scene and to move quickly between objects under time restriction. The task was for the participants to put them in order according their size starting from the biggest and moving down to the smallest. This required participants to show expertise in navigating around the VLE, something that eventually had been earned from Level One and Two. All participants were prompted to ask any questions they might have in order to eliminate to the minimum unsuccessful attempts caused by lack of satisfactory knowledge or misunderstood instructions. Furthermore, there was a brief verbal description of the level to explain its parameters and what are the main differences from the previous levels. During this level participants were aware of the nature of virtual objects and that every virtual scene had always three of these objects placed one next to the other in a limited workspace. This was also announced to them every time a new scene with a new set of objects was launched.

The specific task helped participants to distinguish different sizes and furthermore add meaning to *"what is big/bigger/biggest or small/smaller/smallest".* Teachers explained that participants find it particularly difficult to compare the size of a number of different objects as they only compare pairs. *"If you give them 6 objects and ask them to find the biggest they got stuck into a loop of comparisons; but if you only give* *them a pair of objects immediate they spot the biggest",* the mathematics teacher stated. This loop of repeating the same steps may possibly occur because participants split the 6 objects into 3 pairs and then they got lost in the comparison of each biggest! In order to avoid this confusion but at the same time try to offer an engaging game to participants, they only had to compare three objects at a time.

Later in this chapter there is a description on the design of Level Three and its results. The chapter ends up with discussion.

Goals:

The investigation was set to two dimensions:

1) Correctly appreciate the difference in size
   - ✓ Remember the size of the previous investigated object –Memory Ability
   - ✓ Ability to construct a mental model of the scene and move between objects under time restriction. Even though they were aware of the number and position of the objects (due to the narrow workspace) they had to understand *where* the next object is – left, right? Locating and navigating had been extensively tested and investigated in previous levels.
2) Experience and knowledge transfer from Level One:
   - ✓ How comfortably they explored/scan scene
   - ✓ How comfortably they could manage the grip.

Participants

More info on participants, refer to 7.1 Introduction – Participants.

9.2 Design

A virtual scene with 3 identical geometrical objects of different size was constructed [See Figure 9-1: Level Three Screenshot]. The objects were designed in Autodesk 3DMax Studio with solid texture and then loaded in the program. Users were given 2 minutes to complete this task and earned 10 points when they had successfully managed to complete at least 1 scene. If they failed to complete the task, they received 0 points. The minimum required points were 20 and no bonus points were applied for this level. The workspace was set to be smaller than in previous levels in order for participants to primarily focus their efforts on the main goal of this trial. By pressing the space bar on the keyboard, a new scene was loaded. Participants made a selection of which they believed was the smallest object of the three by pressing the Enter button on the Novint Falcon grip. If the object selected was correct the objects were reduced by 1.

During this level participants had to complete a number of inner-steps. In the first instance they had to locate the first object and examine it. Then they had to move to the next available object and make sure at the same time that this was indeed a new object and not the one they had just explored. Basically two things were required up to that point: 1) to remember the previous object – location and size 2) to construct a mental model of the virtual scene – moving to the right/left of the previous object. These inner-steps had to be progressively repeated as they progressed.

The method they followed to investigate the virtual scene was, first to search for the biggest or the smallest (whichever was immediately recognisable) and then compare the remaining two.

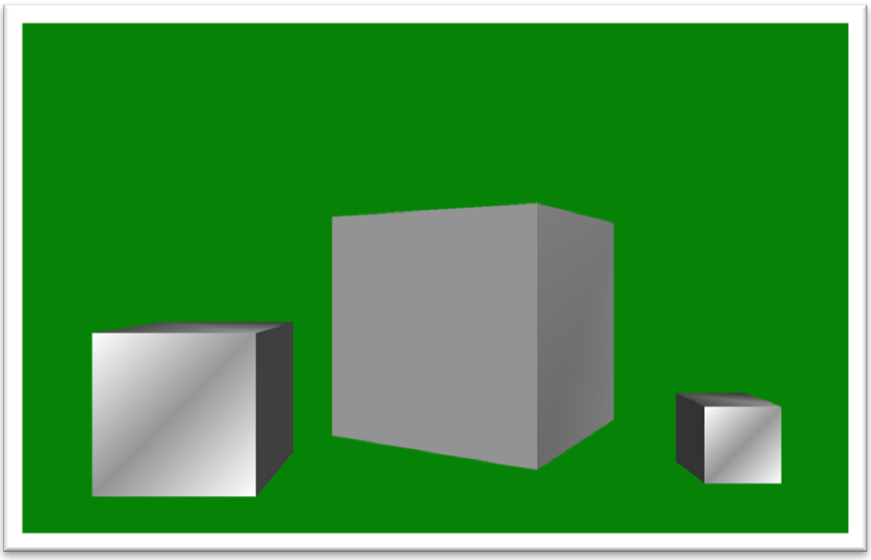


Figure 9-1: Level Three Screenshot

Audio Instructions

The set of audio instructions given to participants during Level Two were:

1. Find the smallest object.
2. For correct selection, an audio message of "Correct, Well done! Number of Objects Left {n-1[6]}" is played, associated with a celebratory sound at the background.
3. For every wrong matching, an audio message of "Not correct, You can do it! Number of Objects Left {n-1}" is played. message that targets to encourage participants no to give up because of fail response.
4. When 5 seconds remain, a countdown tone is played.
5. "Time is up" message to inform participants that they reach the end of Level Three.
6. "Your Score is {the actual score}" is announced after the end of Level Three.

9.3 Results and Discussion

During Level Three the focus was to investigate the hypothesis of correctly appreciating the difference in size. All participants participated in this level showing increasing comfort in using the grip. Some of the participants faced problems in navigating between objects and that was mainly caused by the fact that objects were placed too close to each other. See Table 9-1: Participants' Performance during Level Three.

During this level no record was kept regarding the time participants needed to locate the first object. Only two participants failed to meet the minimum requirements during their second trial. These participants' performance and adaptability declined as the game proceeded. Participants who gave negative and average ratings to previous levels gave a positive rating to this one. They stated the reason to be the busy virtual scene which helped them to easily locate the next/previous object.

[6] n = number of objects before successful selection

Detailed report of each participant's comments and feedback can be found in Appendix K.

Participant	Points	2nd Time Success	Computer Knowledge	Maths Knowledge	Feedback
A	40	-	Excellent	Excellent	Positive
B	30	-	Excellent	Average	Positive
C	40	-	Excellent	Excellent	Positive
D	20	-	Average	Average	Positive
I	20	-	Average	Average	Positive
J	40	-	Excellent	Excellent	Positive
K	30	-	Excellent	Excellent	Positive
L	0	√	Good	Excellent	Good
M	0	No	Poor	Poor	Negative
N	20	-	Good	Poor	Average
O	0	No	Poor	Good	Negative
P	10	-	Excellent	Poor	Negative

Table 9-1: Participants' Performance during Level Three

*Within the given 120secs/number of objects locate

Participants who failed to meet the score to move on to the next level and had to run the same level again.

The most noteworthy observation in this stage was that, independent of their performance, participants controlled the grip in a much more confident and comfortable way than in previous levels. Therefore, their navigation and exploration was smoother. Only three of the twelve participants had to repeat the level and two failed to meet the minimum requirements (participants M and O). The specific level obtained the most positive user feedback.

It is interesting to see the fluctuations that appeared in the categories based on their performance. Due to the fact that time locating an object was not taken for this level, categorisation is based on an approximation of the time spent to locate the objects. Therefore the formula used is:

$$x = \frac{a}{3b}$$

$$a = Total\ Time\ (180)$$
$$b = Complete\ Scenes$$
$$3 = Number\ of\ objects\ per\ scene$$

However these approximations do not represent the actual time users needed to locate the next object as these include the duration of exploring the surface. Still it is an indication of how well they performed in this level, and the points earned by the participants correspond with these estimates.

Performance Groups

1) Performance group 1

Participants L, M, O and P: These participants' performance remained about the same throughout all levels. Participants M and O were always included in this group. The last three were mature participants and continued to show resistance to the game they had shown from the early stages. They expressed the same concern as far as the immediate effects this game will have for them. In a sense they were right. The game was primarily designed and developed for younger learners with the ultimate desire that they would practise basic geometric concepts and hence improve their understanding. From this perspective, this game has very little to offer to these senior participants. However, knowledge, practice and experience of interacting with a non-visual haptic learning environment can be beneficial in the future. Having in mind the advancements of today's technology and the emergence of haptic interaction systems, it is more likely that they will be exposed to this technology in the near future. Participant L had managed to do better during Level Two but failed to improve or maintain her performance. Noteworthy is the fact that based on her academic performance her mathematics knowledge is rated as excellent whereas her computer background is only good.

2) Performance group 2

Participants D, I and N: These participants were part of this group for all the levels. Participant D (who was late blind) had to repeat the two first levels whereas she successfully managed to complete from first trial. During her last trial she felt more confident and had a better control over the grip. She faced some difficulties in relocating an object, but that was seen as a drawback of the system rather than an inability of the user. Familiarity and experience gained from previous levels appeared to apply to this group.

3) Performance group 3

Participants A, B, C, J and K: These are the same members as of the corresponding group in Level Two. Participant J had the most significant performance as he moved to this group after Level One. His adaptability to the use of the grip and the study of tactile cues tended to improve as he progressed in the game. With the exception of J the other participants were included in the group from Level One. One common characteristic for this group's members was that they all had a strong background in both mathematics and computers. It can be said that these participants had the ability to construct a mental model of the VE more easily than the other groups. However, this may not be applicable to all cases, as some users were extremely careful in their exploration, and investigated the virtual objects with much more attention to detail; consequently the time they needed was greater.

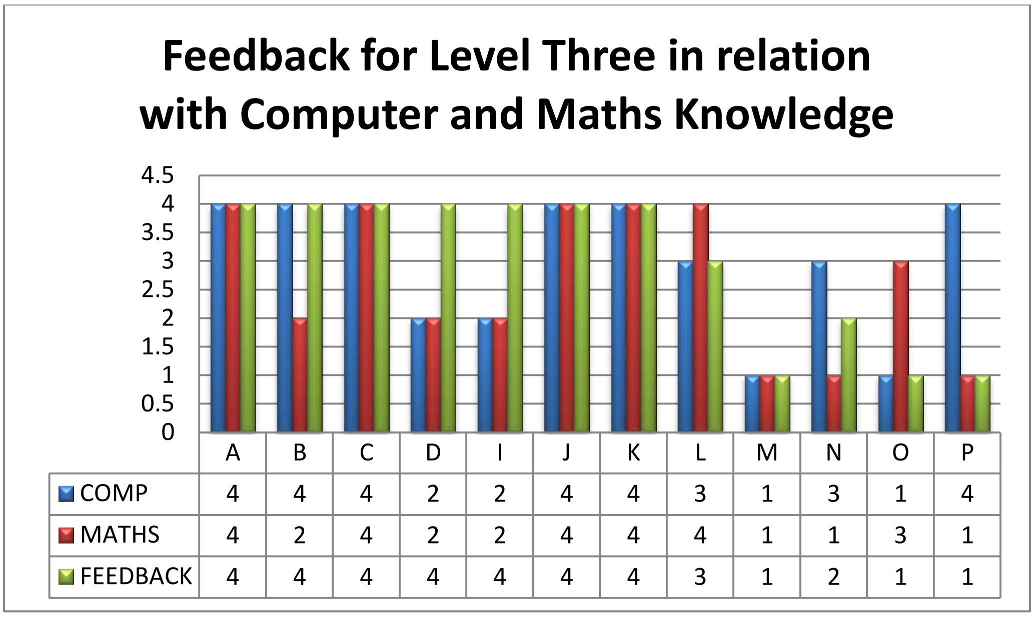
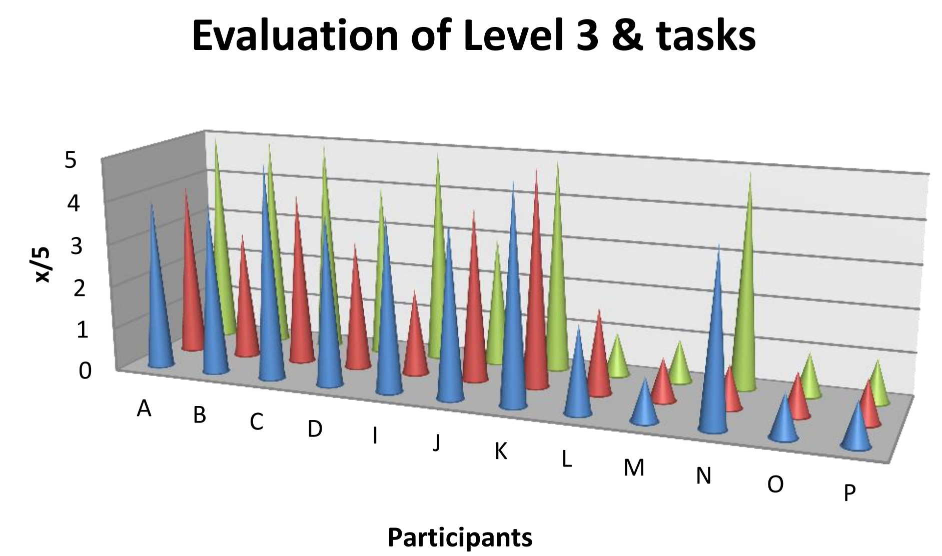


Figure 9-2: Level Three Feedback against Computer and Maths knowledge

Even though a number of drawbacks were observed, excitement and challenge engaged users more when compared to the previous level. The nature of the game was more controlled than in the previous ones, as the workspace was smaller, hence participants were focused on comparing the objects.

One of the main problems participants faced was the inability to distinguish a new object or relocate the same object every time they lost track of it. Despite the fact they didn't have to scan the whole environment it was particularly difficult to differentiate between similar objects. This problem was noted early in Level Three, therefore participants were verbally informed about their exploration status. One possible immediate improvement of the system will be the addition of active haptic or audio feedback that will resolve the specific drawback.

Another issue that added barriers to their exploration was the relatively small difference in sizes between the objects. The problem was justified by the limited workspace (computer's screen) that was available to place the different objects. One possible solution is to have a single object per screen in a controlled workspace. This will require participants to switch between screens to explore the virtual objects. This solution might give more possibilities, for example the freedom to add a 4th object and thus make the level even more challenging.



	A	B	C	D	I	J	K	L	M	N	O	P
Rate Ph3	4	4	5	4	4	4	5	2	1	4	1	1
Locate objects	4	3	4	3	2	4	5	2	1	1	1	1
Manipulation	5	5	5	4	5	3	5	1	1	5	1	1

Chart 9-1: Relation between performance and evaluation

The above chart clearly shows that even though participants faced some difficulties in locating and exploring the objects, the majority of them (8/12 participants – 66%) rated the level with a relatively high mark (6 participants gave 4/5 and 2 participants gave 5/5). As mentioned earlier in this section, participants found it more interesting and enjoyable than in the earlier levels, mainly because of the task they had to complete and because of the small workspace they had to work in. Another possible explanation may be the transferable knowledge and experience they gained from the previous levels, which maximised their levels of comfort and enjoyment.

Regression Analysis of Level One vs Level Three

Chart 9-2 shows the regression analysis of the number of objects located in Level One against the marks they collect in Level Three. The graph shows that the majority performance is still in-line with Level One. The *Significance f* is 0.0006337.

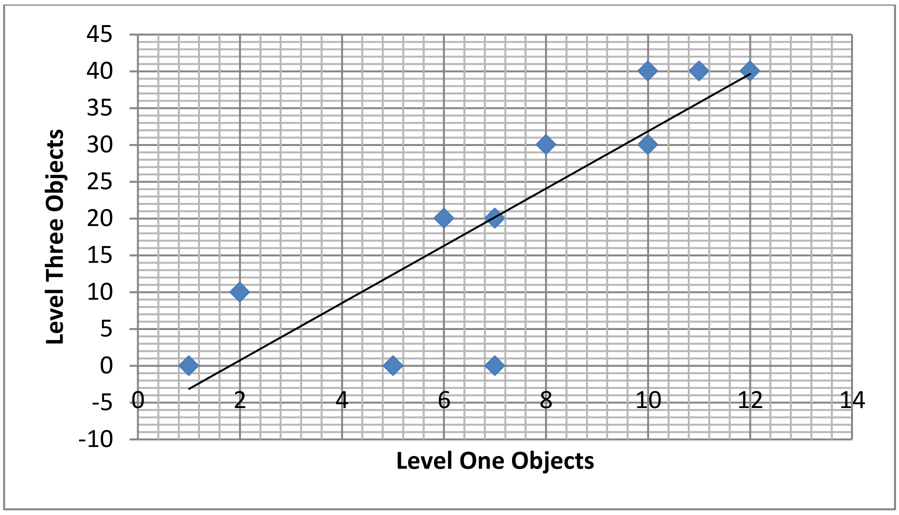


Chart 9-2: Regression Analysis: Number of located objects during Level One and Level Three (including outliers)

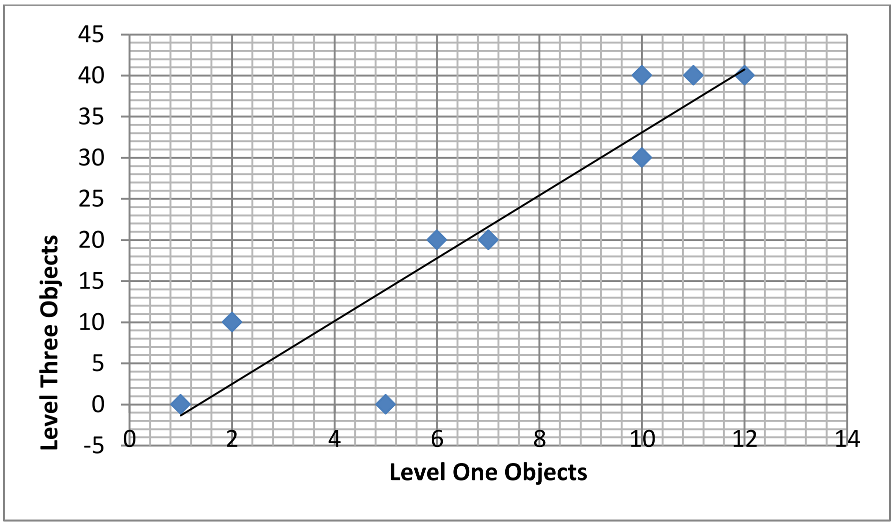


Chart 9-3: Regression Analysis: Number of located objects during Level One and Level Three (excluding outliers)

Chart 9-3 shows the regression analysis having removed the outliers. *Significance f* is 0.00016, which didn't go down as much because there was such a lot of variability in the scores. If participants had more time, it was likely to get more significant variation in scores. The standard deviation fell from 8.91 to 6.43.

Based on the feedback participants gave at the end of i-HALE (Chart 9-1) and the regression analysis, it is clear that the evaluation for the overall level is analogous to how well they evaluate the tasks for this level.

Total Points Collected

By the end of this level all users at school level wanted to know how well they did compared to the rest of the users and what the reward was; one of the major characteristics of a game! Based on the marks plus the bonus they collected from all levels the following rankings were derived:

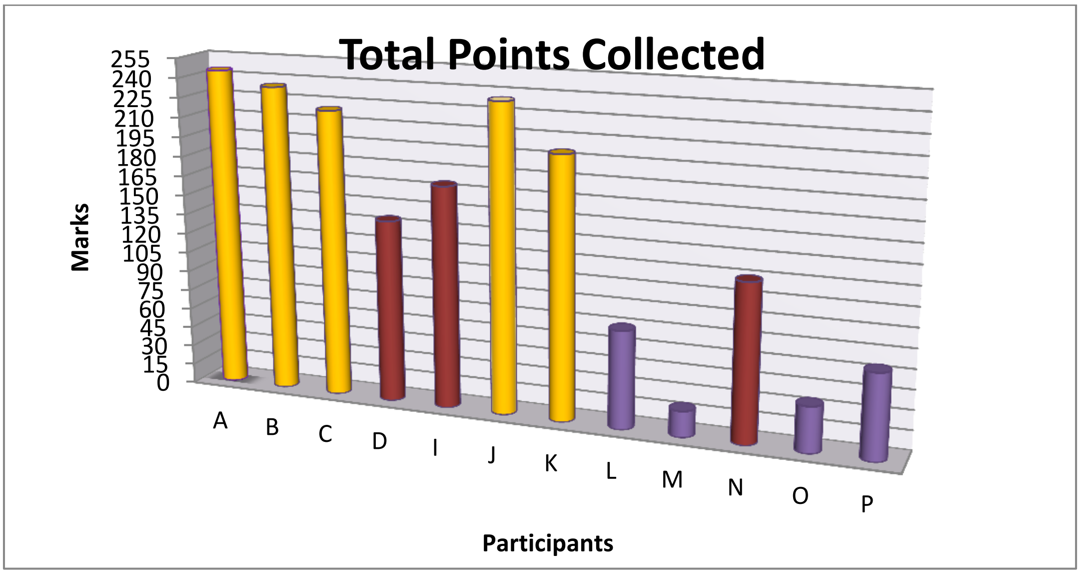


Chart 9-4: Participants Total Points + Bonus Collected

Participant A was the winner of this game beating the rest of Performance group 3 by a small margin. All the participants received a small gift with the winner receiving a voucher for a bookshop.

At the end of the trial participants had to complete a questionnaire regarding the exploration, navigation and how well they managed each level [See Appendix D]. Responses to the last question were very interesting where users were asked to describe how they perceived the VLE based on personal feelings caused by the interaction. Below there is the graphical presentation of the feedback given by each participant. Participants A, B, C, J and K had been given full marks (5/5) therefore they are grouped together as is the case with participants M, N, O and P. Participants D, I and L's feedback varied and they are presented in separate graphs.

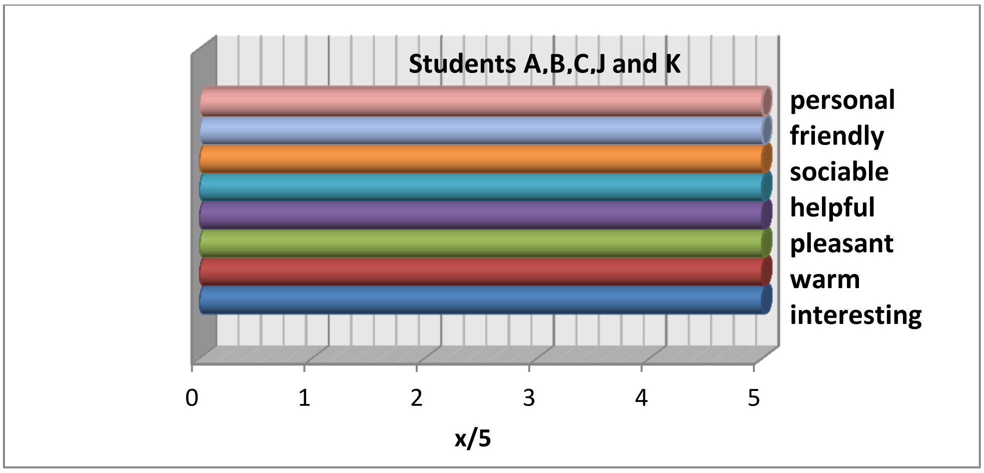


Chart 9-5: How participants A, B, C, J and K perceived the experience with VLE

Participants A, B, C, J and K, are those ones who had the most stable high performance during the course of the trials and they all rated their experience with VLE with the highest mark (5/5). They are the participants who showed the most engagement and the ones who may foresee applications of the game in a bigger range of modules. They managed to keep concentration levels at very high levels; they were able to construct a mental model of the screen in less time compared to the rest of the participants; they expressed the characteristics of enjoyment, relaxation, comfort, competition and a positive and playful attitude towards the game itself and the persons present in the room. Their recommendations were specific and clear; they all wished to see a more challenging set of tasks and a gradual increase in difficulty. They perceived it to be a very sociable activity, as they see the collaboration with the teacher as a positive indication for future group work with sighted peers. They evaluated the haptic experience as very interesting and pleasant and overall they stated that playing the game gave them very positive feelings.

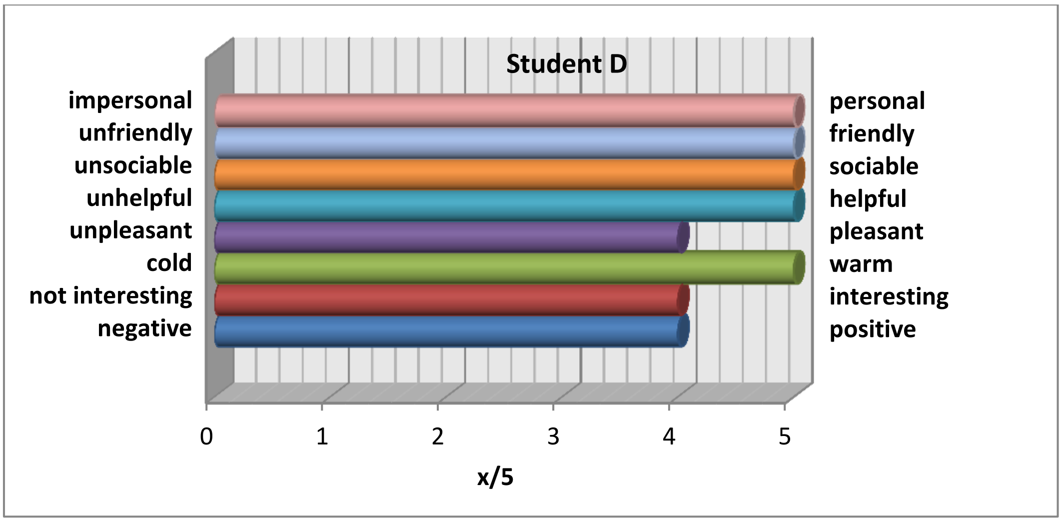


Chart 9-6: How participant D perceived the experience with VLE

The peculiar case of participant D who despite the fact that she had to deal with a feeling of panic at some stages of the play, her feelings were still positive. Her attitude throughout the current and previous meetings was very encouraging and she seemed to be really interested in learning to cope with new technology. The recent loss of her sight gave her great desire to learn new ways to interact with her surroundings. Comparing her skills with the ones of the congenitally blind participants it was clear that she needed time to adjust to the new reality. It was interesting to observe that she seemed to have problems in navigating with a cane, something that was reflected to some extent in her virtual exploration and navigation. It is very interesting to test the hypothesis whether practising in a virtual world using Novint's Falcon can be shown to improve navigational skills in the real world. She, however, showed a successful gradual trend in navigating in the VE. She considered the experience to be very friendly and interesting with potential to become a whole new medium of collaboration between sighted and blind users. She stated that her inability to optimally communicate with family and friends, especially on school material, made her introverted and not as sociable as she used to be. Therefore, she could describe i-HALE as a positive first attempt to bridge this gab.

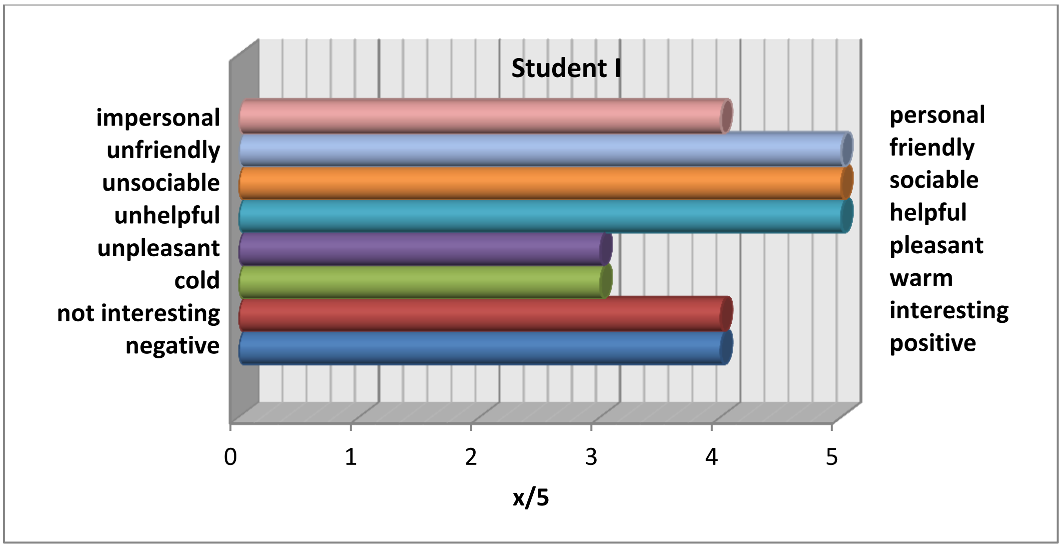


Chart 9-7: How participant I perceived the experience with VLE

He found the whole experience very interesting and playful. At the beginning he faced some difficulties to fully adapt to the concept. He is a participant with particular issues in working and collaborating with others. He suffers from 'Attention Deficit Hyperactivity Disorder (ADHD)'. He may be characterised as an introverted, lonely, reactive, hyperactive person with intentional problems. His teachers find it very difficult to engage with him. He was persuaded to take part in the experiment only when he was informed that it was a game-based learning application. He finds games a pleasant and interesting way of spending his time. His performance with i-HALE, even though it may match with his academic performance, may not reflect how well he did. His movements, even though they were slow at the beginning, were very well controlled and organised. The specific participant needed more time to explore the VE; a reason that may have caused him to collect fewer marks.

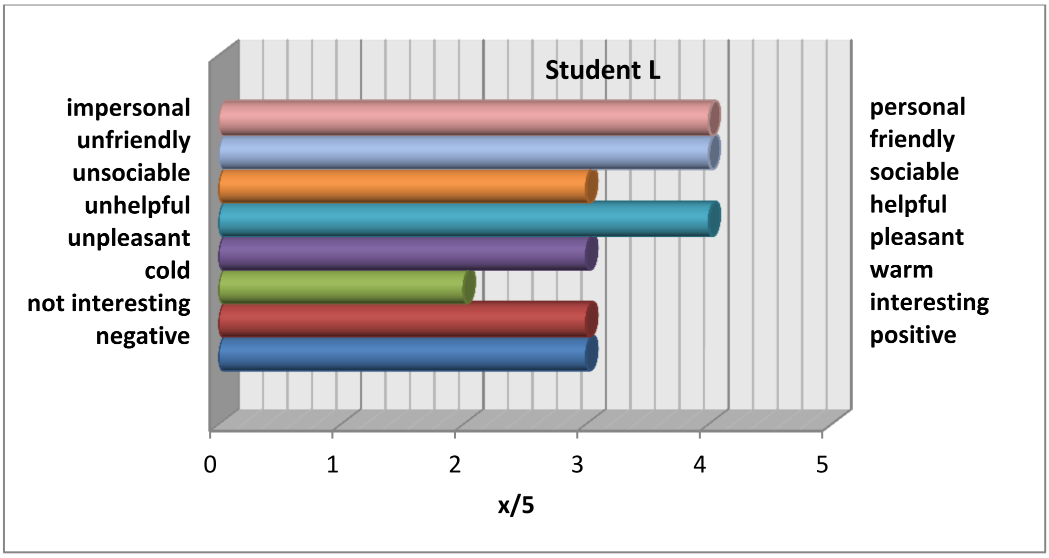


Chart 9-8: How participant L perceived the experience with VLE

Even though there were periods during the play that she felt particularly uncomfortable, which caused her negative feelings, she found the concept to be interesting and helpful in the mathematics field. She believed that the grip itself made her feel stressful and that is why her navigation movements were restricted. She became well engaged with i-HALE as she progressed.

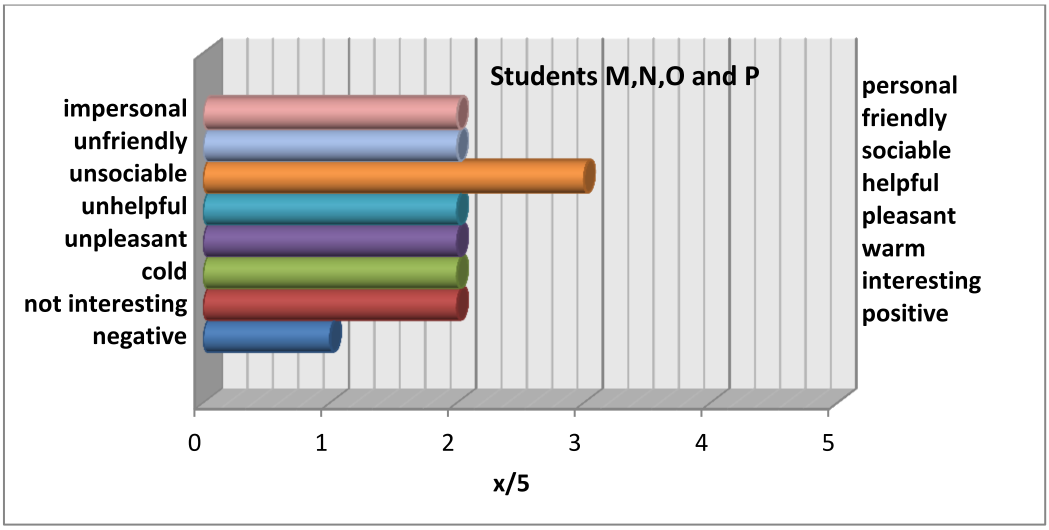


Chart 9-9: How participants M, N, O and P perceived the experience with VLE

The mature participants all gave the same ratings. They didn't seem to enjoy the interaction and they saw no potential for the system that will be beneficial to them. Their lack of experience in using computers and the relatively poor mathematical knowledge the majority of them had were two fundamental reasons why they showed negative feelings towards and resistance to the system. As mentioned earlier, due to the fact that all the levels were primarily designed for participants at school level and the content was based on mathematical literature, it was in a way expected that it would be rejected by this specific group of participants. They did feel it could form a sociable medium for blind users at a younger age.

CHAPTER 10

i-HALE Level FOUR: Complex Environments

10.1 Introduction

After the completion of the i-HALE testing, another test was carried out on a piece of software developed by a colleague, Reham Alabbadi. The main goal of her work was to enable visually impaired people to access computer-based visualisation techniques, mainly pie charts, bar charts and line graphs with the use of haptic feedback. The study also tried to investigate to some extent the integration of sounds so as to create a multimodal visualisation system. The system allowed users to evaluate a graph but also to construct their own by importing data from Microsoft Excel into the program. The characteristics of the virtual objects – main difference from the ones used in i-HALE – were the addition of haptic effects, like vibration and stiffness [See Figure 10-1: Haptic Graphs].

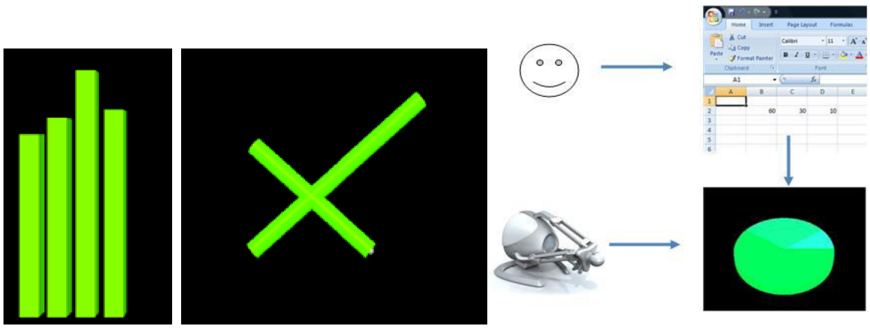


Figure 10-1: Haptic Graphs
(Adopted from Reham Alabbadi thesis)

After participants tested the specific software, 8/12 of them (~67%) said that they found the vibration and stuffiness effects particularly helpful in better exploring the haptic scene. The rest of the participants expressed a neutral attitude and commented that it hadn't made any positive difference to them. This outcome was in contradiction to the very initial findings that showed a tendency to prefer objects with no haptic effects. Since 2/3 of the participants expressed this opinion, it was essential to run another set of experiments to test whether their personal opinions were reflected on their performance. The aim was to explore and test the hypothesis of achieving better results than before and whether their personal opinion was consistent with their performance.

Participants had to examine similar virtual scenes as the ones they had already examined but with haptic effects added. Virtual objects with no haptic effect were built in Autodesk 3DMax Studio and the ones with haptic effect in OpenGL.

Following in this chapter there is a description on the design of Level Four, its results and ending with discussion.

Goals:

The investigation was set to two dimensions:

1) Explore and test the hypothesis of achieving better results:
- ✓ Locate objects in less time
- ✓ Easy in exploring of the virtual scene
- ✓ More objects identified
- ✓ Better feedback

2) Knowledge transfer
- ✓ Observe the ease on using the Novint Falcon grip
- ✓ How to explore the virtual scene
- ✓ How easily they explore a virtual object.

Participants

Level Four testing took place 2 weeks after the testing of the three first levels. Not all the users were available during Level Four but 6 of the 8 participants who preferred haptics effects took part in this additional level. The table below lists the participants who took part in this study, along with their total points earned so far, the feedback they left in the previous three levels, their computer and mathematical knowledge and whether they expressed their preference in having haptic effects.

Part.	Total Points	1st Level Feed.	2nd Level Feed.	3rd Level Feed.	Computer Know.	Maths Know.	Effect ?
A	245	Positive	Positive	Positive	Excellent	Excellent	Yes
B	235	Positive	Positive	Positive	Excellent	Average	Yes
C	230	Positive	Positive	Positive	Excellent	Excellent	Yes
D	140	Average	Positive	Positive	Average	Average	-
I	170	Positive	Positive	Positive	Average	Average	Yes
J	235	Good	Positive	Positive	Excellent	Excellent	-
K	190	Positive	Positive	Positive	Excellent	Excellent	-
O	35	Negative	Negative	Negative	Poor	Good	Yes
P	75	Average	Negative	Negative	Excellent	Poor	Yes

Table 10-1: Participants Participating in Level Four, Previous Performance & Feedback

10.2 Design

This level was built to evaluate in which extend accuracy and comfortless were affected when vibration and magnetic effects were on. The task participants have to complete is to reproduce the virtual scene using real objects. Level Four has 3 sub-levels:

1) A scene with no haptic effects

2) A scene with Vibration & Magnetic Effects On

3) Dynamic Scene.

The system kept track of users' movements in the VE, level of exactness and how easily they could keep track of their exploration activities when exploring a virtual object. They have 2 minutes to complete at least one virtual scene earning 20 points (5 for each correct position).

1) No Haptic Feedback

Four primitive objects with no vibration or magnet effects appear on the VLE.

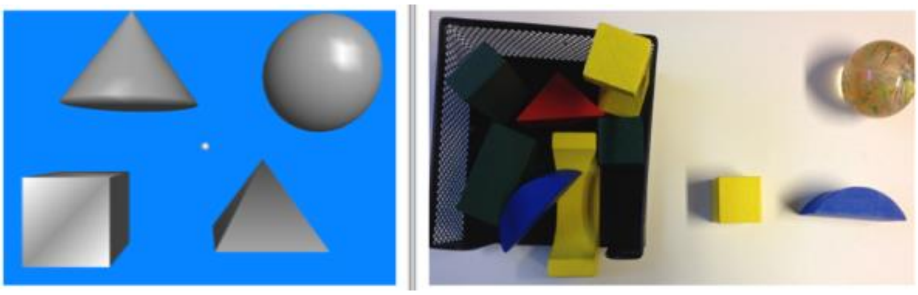


Figure 10-2: No Haptic Feedback Scene - Real Shapes to compare with

2) Vibration & Magnetic Effects On

Four different primitives appear on the VLE having the vibration and magnetic effects on.

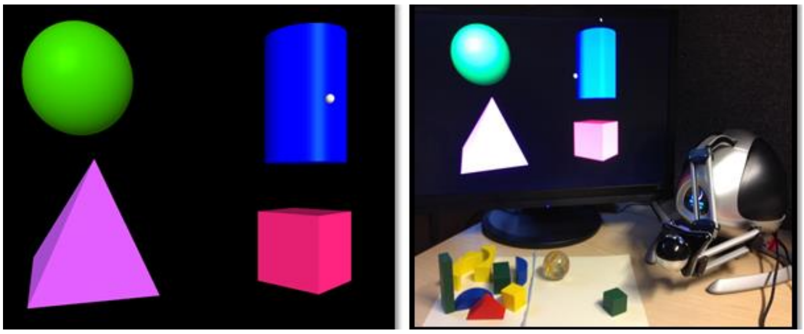


Figure 10-3: Vibration & Magnetic Effects On Scene - Reproduction of Virtual Scene with Real Objects

3) Dynamic Scene

The last scene had again four objects placed in the virtual scene, two of them without haptic effects and the other two with haptic effects. Participants were not informed for the nature of the virtual objects. The intention was to see the immediate results of how well/badly they perform in a dynamic scene.

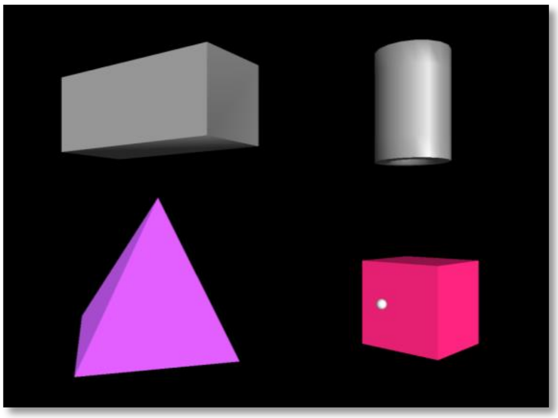


Figure 10-4: Dynamic Scene

Audio Instructions

The set of audio instructions given to participants during Level Four were:

1. Locate the objects, remember their position and try to reproduce this scene using real objects.
2. You have two minutes.

   * Immediate feedback is given by the research group.

10.3 Results and Discussion

The overall feedback from this level is that the experience they gained from previous levels has been proved to be of great importance. All participants correctly identified the majority of the objects very quick. Even though Level Four was tested 2 weeks after the last meeting, participants were able to complete the tasks with a distinct ease and increased satisfaction. All participants rated the specific level as the most interesting, engaging, playful and attractive of all the levels.

Table 10-2 lists the performance of each participant during each sub-levels, whether they said they preferred haptic effects on (before level four), to rate how easily they can explore and locate objects with haptic effects on.

Part.	Haptic Effects ON*	Haptic Effects OFF *	Dynamic Scene*	Effects Preferred? (before Level Four)	Exploring objects with haptic effects **	Locating objects with haptic effects **
A	20+10	30+10	20+5	Yes	3	5
B	20+0	20+5	20+0	Yes	4	5
C	40+0	40+5	20+10	Yes	3	5
D	15	20+0	10	-	3	4
I	20+5	20+15	15	Yes	3	4
J	20+10	40+5	20+10	-	2	4
K	20+15	20+5	20+0	-	2	3
O	10	15	5	Yes	2	4
P	0	5	5	Yes	3	3

Table 10-2: Participants' Performance during Level Four

* Number of completed scenes + any additional object positioned correct
**Rating in a scale of 1-5 (1=Very Bad, 5=Very Good)

*Within the given 120secs/number of objects locate

Students who failed to meet the score to move on to the next level and had to run the same level again.

Participants who preferred haptic effects added on the virtual objects, performed better in the vibration-off virtual scene. All participants however showed ease in locating the objects and were immediately aware when they were getting off the objects. This appears to explain why participants seemed more independent this time and the number of questions asked being significantly fewer than in previous levels. The second observation showed that participants did better during the vibration-on scene rather than during the compound scenes. During the latter, participants seemed to have difficulties in adjusting to the different haptic effects and as a result they lost time in the exploration. Interestingly, by the end of Level Four, the group of 6 participants (who originally expressed the opinion that they preferred haptic effects) continued to defend their view even though results did not agree with their preferences.

Participants O and P: These participants had the least positive performance, continuing to face problems concerning the adaptability of the grip. However, even at very low levels, the participants' exploration and locating of the objects showed some improvement compared to previous levels. Vibration was a distinct haptic cue that enabled these users to immediately understand that the collision with the object had occurred. At the end they expressed the opinion that vibrations with a magnetic effect were most preferable.

The last level had provided an excellent opportunity for us to evaluate the participants' performance against their personal preferences. Results showed that these were not always aligned. Participants scored better in studying scenes with no haptics effects. They (haptics effects) were only valuable and helpful to inform participants when they were on/off the virtual object. During compound scenes there were participants who failed to adjust to the immediate haptic changes. They commented that they needed more time when effects were on; whereas the same time allowance actually worked perfectly well when there were no effects on or not. An optimal solution needed to be efficient, effective and enjoyable. No effects scenes had all the characteristics according to users' views. The question became "what needs to be done, changed or improved to make these characteristics even stronger?" Participants had pointed out the need of having an active information mechanism so that they could be immediately informed whenever they were on or off the virtual object. In this area personal opinions and preferences emerged. They remain critical factors when it comes to building systems for third parties; it is wise to take them into consideration and find a way to blend them with functionality. Therefore, effects like vibration can be set on every time the grip gets close to the object and off every time it gets further away from it. During exploration of the virtual scene no vibration or other effects will be on. One outcome from

Level Four and the feasibility stage was the fact that participants failed to deal with too much haptic information. They were primarily trying to remain focused on collecting the necessary characteristics of the object and at the same time trying to control their vibrating hand.

Extending the discussion on feedback collected from all the levels, it can be said that participants did better and were more contented when they felt the exploration process was controlled. Their level of comfort and effectiveness had reached a very high level when using the narrowed down workspace. In a teaching/learning simulation this might be useful, as the primary focus will be strictly teaching the concept. The i-HALE's purpose, though, lies between two fundamental parameters; one, to offer a well-defined and well-designed VLE to practise basic geometrical concepts, and on the other hand to achieve it through a playful and enjoyable mechanism. Therefore 'seeking to locate the object' was a characteristic that required effort, concentration and space awareness - characteristics that added to the degree of difficulty. Moreover, the specific exploration may be helpful for future similar concepts software and to enhance their navigation skills in VLE environments that may reflect real scenes' navigation and exploration too.

CHAPTER 11

Discussion

The application and the user trials with evaluation led to some interesting and diverse result clusters. The feasibility study is in itself a result, since it was based on usability problems that were observed during the initial users' testing with virtual environments and haptic interaction and feedback. During this stage and the blindfolded testing, the fundamental characteristics of the game were generated. One of Human Computer Interaction's main principles is the involvement of end-users in all phases of SDLC. Following this principle, all participants have been involved from the very early stages of the project from the conceptualisation of the idea until the shape of the final systems requirements. The process of building i-HALE followed the agile approach of iterative methods of determining requirements which followed a loop of re-design until a functional piece of prototype met end-users' expectations.

Valuable information regarding the teaching material and the support participants receive was also collected since this information helped the research group to evaluate the level of coaching blind participants received. Furthermore, this information served as a prediction guidance of what to be expected by the participants.

Findings from data collected from all four levels revealed some very interesting and significant trends. It revealed that evaluating only personal preferences may lead to the wrong design direction and constructing an incorrect hypothesis. It is necessary to optimally evaluate and justify personal opinions and preferences with actual data collected by trials. It also revealed that spending time and exercising with the VLE and the use of the Novint Falcon grip may show some improvement in performance and increase the level of engagement in the game and its contents. Participants with a strong background in computers adapted more quickly to the use of the grip. There were a small number of participants whose performance did not show any improvement throughout the trials and who consistently rejected the system. This phenomenon was mostly among mature participants. The main reason for this was linked to their poor knowledge of mathematics and computers, something that made the process more difficult for them. In addition to the latter, the nature of i-HALE and the concepts that are elaborated maybe of no interest to mature participants. But experience gained from this interaction with VLE may help them in future similar applications.

Both the objective measure of time to perform tasks and the subjective measure of perceived task performance, improved as participants further proceed in the game. In addition, participants' questions dropped down to minimum as they proceeded with the game. They managed to resolve some of the issues (like controlling the grip better) they faced at the early stages and confidence increased.

According to Gee (2004), good video games incorporate good learning principles if they manage to attract and maintain the learners' attention. The fact that all participants tried to complete all levels is an indication that i-HALE managed to **engage** their interest and kept competitive levels very high. Most of the participants at school level expressed the opinion that this type of applications may form a whole new method of learning and practising modules literature.

Is i-HALE a game?

One of the main goals of this study was to develop an application with playful characteristics. According to (Malone, 1981) the three elements a game needs to have to be a fun are:

1) **Challenge**: Participants have a clear set of goals, an active score and immediate feedback on their progress. As they proceed to the game they have more challenging and difficult levels to complete which requires

knowledge and experience gained from previous levels and/or tutorials.
2) **Fantasy**: The game has audio feedback to help them interact with the VLE. It also has celebration sounds for correct answers and supportive messages for wrong answers. Fantasy is closely linked with **Motivation.** When a game attracts a user's attention then there is the goal to master it. Therefore, there is strong motivation. But in order to achieve better results or the goal of a game, certain things need to be done, like imagining or thinking new ways to overcome an obstacle or achieve better time – this is fantasy.
3) **Competition**: Participants were very competitive throughout all the trials starting from the very early stages of the feasibility study. This serves as an interpersonal motivation to achieve better in later levels.

Does i-HALE have the right learning principles a good game should have to be engaging?

Continuing on Gee's (2004, 2005) findings, he explains that if a game was too difficult to learn to play then learners/games quickly lost interest and abandoned it. Furthermore, he argues that players will not accept easy and dumped down games, therefore challenge and learning are very important in defining a good, fun and educational game. Through a series of studies, Gee (2003, 2004, 2005) concluded on some of the learning principles a good game must incorporate to be **engaging**:

1) **Identity**: Participants spent time and became committed to the VLE. They became familiar with the environment, tried to enrich their knowledge and understanding in order to dominate the game and finish off as winners.
2) **Interaction**: Participants had active live feedback throughout their testing. This feedback was either force-feedback, oral or audio.
3) **Risk Taking**: This aspect was at a low level in i-HALE since there was no penalty for wrong choices.
4) **Well-Ordered Problems**: i-HALE levels were ordered from easy - tasks that helped participants to build up understanding – to the more challenging later in the play.
5) **Challenge**: Good games provide players with a clear set of challenging

problems to solve. When players manage to solve these problems then a new set of challenging problems with increased level of difficulty are presented to them. Similarly with i-HALE participants needed to re-think, re-evaluate, learn something new and integrate this new learning with their old mastery in order to dominate the game by collecting the minimum points required to proceed to the new next level.

6) **Explore, Think Laterally, Rethink Goals:** Participants in i-HALE had to explore the virtual scene to develop a mental model and then think how to resolve the tasks.

Is i-HALE educational?

There are two sets of findings that indicate the educational character of the i-HALE.

1) As participants were further proceeding in the game they showed comfort in understanding the tasks they had to complete. This became evident from the reduced number of questions asked, the more organised movements, the fact that they did not consume time on pointless movements in the VLE, and from their own feedback.

2) The experience gained from previous levels clearly showed that it played an important role in the improvement of participants' performance. They felt more comfortable in scanning and constructing a mental model of the scene and as soon as they detected a collision they controlled the grip better (than in previous levels) and they easily collected all the necessary tactile cues to identify the objects. This is shown by the increase in the number of identified objects and the improvement of the average time needed to locate a new object. Furthermore, the fact that participants' questions dropped to a minimum is another quantitative measurement that supports the finding of knowledge transfer. Lastly, according to participants' feedback and comments, they all felt more experienced and aware of what to expect regarding the force-feedback.

Sighted and non-sighted collaboration

Even though one of the aims of this thesis was to test the hypothesis of how well sighted and visually impaired participants in class can collaborate on the same tasks using the Novint Falcon, this was not fully achieved. Due to the fact that the researcher attended only one school for blind children in Cyprus it was difficult to get sighted participants of the same age to join the research. During one of the meetings two sighted participants, who had taken part in the blindfolded study [See 5.2 Tests with Blindfolded Participants] were present. The intention was to let the sighted participants guide the blind participants during their exploration of the virtual scene. Sound and time were turned off and primarily the intention was to evaluate the set of commands sighted participants gave and how these were evaluated and perceived by the blind users. One of the difficulties was getting participants of the required age who did not previously know each other to collaborate on similar tasks. Only four of the blind participants agreed to collaborate with the sighted girls. Observing the reactions of the two girls as well, it was clear that they seemed anxious and uncomfortable since it was the first time that they had to work with visually impaired participants. This finding supported the initial suggestion of the school's teachers that blind participants need to feel safe and comfortable in order to be in a position to collaborate, work and socialise with other people, regardless of their level of vision.

The four participants who agreed to collaborate with the two sighted girls were participants A, B, C and D. The latter was felt to be the least likely to take part as she had expressed some social issues during trials, however her collaboration and social interaction with participants of the same age was remarkable. At some points she was in full charge of the experiment and she was giving instructions to the sighted girls. The fact that her experience as a sighted person was recent put her in a position where she was able to deconstruct the instructions given to her. All the girls used a set of language terms less associated with mathematics but more associated with simple daily expressions. For example instead of "find the vertex" they used terms like "find the mountaintop". The same terminology was used with the rest of the blind participants also.

Of particular interest was the way the two sighted participants gave the blind participants specific instructions of how close/far they were to/from the object. Commands like "very close" or "move a little bit to the left" revealed that they did not represent accurate and reliable instructions. The two sighted participants tried to explain the distance as well as they could. What they came up with was very thought-provoking. They showed the distance in free space, by taking real objects (in that case 2 erasers) such that the distance from the one object to the other represented the actual distance of the grip to the object. Then blind users had to measure distance in real time.

The very last task sighted participants had to explain was the volume formula of a cube. They "showed" each face of the object by helping the blind participants to reach each face by grasping the grip and leading them to the objects.

Overall observations made from the interaction between sighted and non-sighted participants could be described as positive. The participants tried to establish new ways of communication and describe aspects in the way their age group and experience allowed them to do so. It is a matter of how they conceptualise some ideas themselves and to illustrate the age difference in understanding these different aspects.

CHAPTER 12

Conclusions

The initial goal of this study was to investigate the hypothesis that blind participants can learn and practise understanding 3D geometrical shapes in a tactile VE with the help of audio and haptic feedback. Towards that goal a series of game prototypes were carefully designed and developed in close collaboration with end users. The purpose of these prototypes was to identify the needs of blind participants and furthermore to collect valuable data and feedback to enable the designer to draw conclusions about the final version of the educational game.

In particular a user-centred game was built – i-HALE- for non-visual haptic learning environment - to engage blind participants to explore a virtual scene containing primitive geometrical objects. The focus was to evaluate whether this type of teaching medium can be beneficial for blind users and in the meantime if they can form a gateway to future use of this technology.

The literature review had demonstrated what the needs of blind people were for interacting with the world and how their spatial-cognition and spatial awareness work. (Klingenberg, 2007) pointed out the importance of knowing the geometry literature and how it is connected to the spatial understanding and visuo-spatial memory of people with visual difficulties. Studies have also demonstrated the importance of spatial representation and understanding regarding problem solving and language understanding (Kennedy & Tipps, 1994).

Available technology today has some significant tools which could possibly be beneficial to blind people. However, as yet there is no standardised and commercially available educational system which has been used and accepted by blind people. A system that will meet end-users' needs and expectations and allow them to practise basic geometrical models through a well-designed force feedback VLE. In addition, the limited number of available systems that allow users to interact with graphics and specifically digital graphics through haptic devices (Sjostrom, 2001) increases the need of progressive solutions.

The main focus of the tool developed in this research has been for blind participants learning geometry. Geometry is the main theory of space and the basis of mathematics, one subject that participants cannot avoid throughout their life (Erwin et al., 2001). Studies have pointed out the importance the awareness of geometry (Edwards et al., 2006), which is not limited only to school subjects but to everyday processes. It is crucial for participants with visual impairments to develop an accurate sense of spatial relationships and reasoning. It lays the foundation for systematic thinking through the numerical and spatial aspects of objects. (Klatzky & Lederman, 2003), expressed the view that the correct process and manipulation of different objects in space along with the required spatial thinking, provides a strong background for other more advance modules, like trigonometry.

These are some to the reasons why mathematical science is not an isolated part of the curriculum. Unfortunately, most science teachers have very limited or indirect experience in teaching students with special needs and as a result they hold a stereotype view of what the blind students are capable of (Ballesteros et al., 2005). This is very significant for blind students who want to be included in today's society and share equal opportunities with sighted students.

Therefore, the approach of avoiding teaching geometry to blind students is definitely not a solution; it is probably rather the source of developing a barrier to future expansion to optimal thinking and reasoning skills.

Assistive technology is something that needs to be integrated into schools and all stakeholders should gain the appropriate knowledge of how to optimally use it. However, studies have shown that this technology is perceived to be expensive and too complicated to learn and use (Gentaz & Hatwell, 2003). This was a parameter that was taken into consideration from the initial steps of the investigation of this research. This has also been the view of the end users involved in this research. The i-HALE is a game-tool that is specifically designed to allow users to practie basic geometrical models, on a consumer affordable platform. Most commercial haptic products cannot be tested by potential users prior to purchase and this is a drawback, taking into consideration the amount of money to be invested when products like the PHANToM are considered. With i-HALE, users not only had the chance to test it but also it was built based on on-going collaboration with the author involving an exchange of valuable ideas, so that the outcome better meets their needs and expectations.

Even though haptics is one of the primary senses blind people use to interact with their surroundings, it hasn’t been extensively used in building systems that would use it as the primarily medium for interacting with a VE. The combination of haptics and a playful VE to practise geometrical concepts to empower blind people to cope with virtual worlds had not been used before this study.

A haptic system along with a tactile kinaesthetic and motor capabilities combined with cognitive processes present a *“uniquely bidirectional information channel to the brain”* (Kataria & Tapudum, 2010). (Petrie et al., 1998) support the effectiveness of non-visual interaction and through studies they have demonstrated that haptic interfaces allow users to effectively communicate with a computer.

This research proposed what technological research previously failed to offer: a haptic force feedback VLE that engages blind students in the practice of the geometric literature in a playful environment. Equally important was to propose a game platform that would be affordable for end users to buy. Furthermore, the Novint Falcon is a device that combines the major characteristics of all commercial haptic devices which are otherwise only found in research groups. It is a device that provides users with meaningful cues to interact with i-HALE in a playful and enjoyable way. As Grohn correctly annotated, it is important that the design and development of audio-haptic technology be moved from *"research vehicles to tools designed for practical use"* (Grohn, 2008), if it is to reach a larger audience.

Based on the results, it has been shown that this type of VLE has the potential to become a new promising medium for improving education for blind students by providing an enjoyable and effective way of teaching, learning and practising geometrical models. Participants showed enjoyment of the experience of testing their knowledge in a game-based environment and at some stages they were very competitive irrespective of their individual performance in each level. Participants were interested to know how well they did, whether they scored more than their colleagues and what the first prize was! They expressed their satisfaction every time their performance was high and disappointment every time they did not do well, but at the same time they were determined to do better in the next level. They were willing to spend as much time as needed to familiarise themselves with the concept of haptic feedback VE interaction and with geometrical models as well. This was evident from the time they spent practising with the Novint Falcon during school breaks. The majority of the participants expressed the desire to have more complicated and demanding tasks to complete in the near future and described the specific tasks as *"easy once users understand what to do"*.

Also another notable observation was that those participants with excellent computer knowledge and an acceptable level (better than good) in mathematics scored better in all levels of the game. This has mostly to do with adaptation to the use of the Novint Falcon grip and how easily participants could construct a mental model of the VE. The first explanation has to do with experience in using computers and assistive technologies and the second reason is closely related to the conceptual level of understanding tactile cues and experiences participants received throughout their lives.

Participants at school level were more engaged in the nature of the study. It was interesting that participants who were born blind showed more positive adaptability to the system and faced the least problems during testing. The reason behind this might be the fact that the born-blind users have a more developed sense of touch and are more experienced in extracting the correct tactile cues to be able to construct a mental model of the environment. On the other hand the ignorance of any visual models allows them to concentrate on pure tactile cues they receive through their haptic sense whereas the late blind or low vision users may lose time in trying either to see or match visual models with the tactile cues.

Mature participants at the beginning showed no excitement at all and expressed the idea that the concepts being tested were of no interest to them. From one point of view they were right because at the age of 55, learning about 3D geometrical shapes is not of any immediate use. But extending benefits mature participants may achieve in the way of learning to use force-feedback devices and understanding the potentials of haptic interaction with a VE could still be valuable. If force feedback devices and audio-haptic interaction with a VE may form *"tomorrow's technology",* then gaining experience will be of great value. Even though mature participants did the least well, they all concluded that the experience gained from mastering such devices was very positive. They also added that they can foresee other applications using the same technology that can be more suitable for their age (e.g. exploring unknown scenes).

In an attempt to approach the question of whether this type of technology can be used in other areas besides mathematics, participants themselves expressed their wish to see more applications of this technology in other subjects of the school's curriculum. They expressed the idea of having similar game-based applications in physics and anthropology. They were especially keen on an application in anthropology which has the potential to enable blind users to feel and interact with concepts that were beyond their capabilities. There are already medical applications designed using the Novint Falcon which may benefit not only blind users but sighted users as well. Extending the positive returns, this new technology may be used in other areas beyond education, like navigation and exploration of scenes. There are already preliminary studies being carried out that allow blind users to virtually explore an area – this can be a room, a building, a campus etc. – and afterwards use knowledge gained from the virtual exploration in navigation around real scenes. Results from i-HALE have shown that users' spatial awareness developed as participants proceeded in the game.

In addition, results collected from this research have shown that spending time on exploring virtual scenes increases users' sense of comfort and awareness of virtual space and furthermore enhances their knowledge. The particular finding applies both to mature and visually impaired participants. Combining this finding with the competitive mood and easy adaptation by congenitally blind participants, it can be said that the specific game managed to engage all users but to a different extent for each group.

Examining i-HALE's engaging performance with regard to geometrical concepts, this was described as successful. Focussing primarily on participants at school level they all showed understanding of and appreciation for interaction with the haptic VLE. Progress has been very encouraging and participants showed that they knew exactly *what* they were asked to do and *how* to reach the goal from the very first trials (before testing the actual game). A repeated task for all levels was to locate the virtual object(s) in the VE. At least half of the participants managed to locate a new object within15 seconds. Participants at school level successfully maintained control of the grip every time they were exploring an object and by using an elimination method they could identify the nature of the object. This method of course, requires critical thinking and it can be an indication of how well participants practise geometrical concepts. For instance, when a participant found no edges on the surface then the base was rounded, therefore options were narrowed down to a smaller number of objects. There were occasions where, even though participants were able to describe the object in detail, they couldn't identify it. This shows the level of basic geometrical coaching participants had already received.

The results obtained show that most of the participants performed better in environments with limited or no haptic effects such as vibration and/or magnetic and/or texture effects added to the objects that are felt every time participants reach the objects. Even though these effects can be useful during navigation, they may be misleading and disrupting when it comes to object exploration. It is assumed that the main reason for this is the fact that users have to deal with lots of parameters in a short time constraint so that any additional information may have a negative impact. Expanding on what characteristics a VLE for blind users should have according to data collected and opinions expressed, the majority of the participants need to have active information of their position in the VE with respect to the object(s). A small number of participants had the opposite opinion stating that topological instructions may be misleading. This latter opinion points out the need for further studies to determine what are the meaningful instructions that can be given in a non-visual audio-haptic environment when taking time restrictions and users' psychological states into consideration.

Regardless of their own performance, more than half had a positive attitude towards their experience with the haptic interaction. Participants at school level found the game experience very engaging and they all expressed their hope to have similar applications integrated into the school curriculum. They enjoyed the idea of a game and rewards and they have also expressed their opinion on future expansions of the game and what other characteristics they wish to find. Mature participants see much potential of this technology and believe that different concept applications, like navigation or rehabilitation games can be beneficial for them.

One of the goals set at the beginning was to test and evaluate collaboration between sighted and non-sighted participants on the same tasks. However, it was not possible to examine this in detail because of the unavailability of sighted participants at that school. However, a very small test was performed that actually showed that sighted participants can appreciate the capabilities a blind participant has and that collaboration can be established despite the visual impairment.

12.1 From the Present to the Future

Expansion of i-HALE: Immediate future work will have to do with the expansion of the game to more challenging and advanced tasks that will also require knowledge about geometrical formulas. Moreover, compound 3D geometrical objects will be designed to test users' awareness in recognising geometrical shapes in a more complex environment.

Social i-HALE: Many participants expressed the wish to develop an e-society for this application and have the option to compete with other users online. Therefore, another goal is to test the hypothesis of having i-HALE available online to enable potential end-users to download the software and practise with it. Also, to encourage and open the door to potential researchers who may be interested in similar applications, a forum with details and information about the game itself, haptic technology and virtual learning environments for people with low or no vision will be established to exchange novel ideas and suggestions.

Audio Instructions: One of the drawbacks of i-HALE was the insufficient audio feedback given to the users. One of the immediate purposes is to examine different ways of integrating meaningful audio instruction into virtual learning gaming environments. A method to allow for this hypothesis is to work with end users to determine what a "meaningful" message should contain in order to cause the least distraction and stress to users.

Sighted and non-sighted Collaboration: More work is needed to examine and explore the hypothesis that having sighted and blind participants working on tasks with rich visual contents will promote collaboration and teamwork between sighted and non-sighted participants at school level. In order to determine a common understanding between the two groups a series of tests must be carried out. As a starting point, i-HALE will be a task to collaborate on and work together on similar tasks using the Novint Falcon.

Integration with other technologies: One of the designers' aims is to make i-HALE and similar applications accessible through a number of different technological devices. One of the main focuses is to design and develop Apple and Android mobile educational applications.

Accessing the impact of the methods supported by this thesis: This and similar research may contribute to the future goal of developing a world of equal opportunities regardless of any disability. Investigating and analysing the audio-haptic usability and educational games potential will result in guidelines for future applications. Research illustrated above shows how haptic learning tools can be used towards exploring virtual scenes and investigation of 3D geometrical objects. Furthermore, it has extended the application areas this technology has, and established that it can be used in many different school subjects as well as being a powerful navigation map. The frequent use and the benefits end-users may earn can make game-based learning a usable educational tool for students with low or no vision. Also, ad hoc use of game-based learning environments through a haptic channel can render new ideas and demonstrate to the reference group that this technology is available and possible to be developed further. Hopefully, this may stimulate other researchers to initiate ideas and research in the near future.

Appendices

Appendix A: Spending Time with End-Users at the School in Cyprus

Spending time with end-users and all the students in general at the school in Cyprus, gave the time to observe and study a number of other parameters of their living, beyond learning and teaching. Although most of the students have never had any visual experience, they spontaneously learn to use and are comfortable, using vision-related language. Blind students "watch TV", "see" a friend and say "I'll see you tomorrow". Even when they were exploring the virtual scene, they made extensive use of the verb "see" a cone or a sphere. They have actually used it more often than the verb "feel".

One interesting thing to observe was how they navigate around the school. The school's premises were not designed to the standards for use by blind people; but a number of adaptations have made it a friendly and safe environment for severely disabled children, of which impaired vision is just one.

The interior design of the school is characterised by large halls and corridors to give space for children with mobility problems and wheelchairs to move around. All doors are always closed and they have a small braille sign just above their handle saying what classroom it is. Students are very familiar with the internal structure of the building and they move around very quickly with no assistance. When a blind student was asked to describe how he managed to find a classroom without the need of somebody to give him directions, he explained: *"I know approximately how many steps is one place to another. I have this map in my mind and I know exactly where I'm. I don't have to think or be very concentrated to find the right classroom. Everything comes so naturally to my mind".* Some other times the voice of a person or the sound that is coming out of a room serves as the leading instructor. When participants entered the class one-by-one to test the game, the voice of the instructor was leading them where to head to.

Another observation is that they only use the cane to locate the stairs. Other than that, one can say that they navigate around just as the sighted do, with the same confidence and determination. At the beginning and on every stair there is attached a felt fabric which can be felt when students step on it. This distinct feeling works as a notification that stairs are following.

The layout of a classroom is organised in such a way as to allow students plenty of space to walk around. Therefore, desks are all attached to the perimeter walls of the class. Students respond to the usual instructions, like *"Take a sit at the third desk on your left hand side".*

Another notable finding is the fact that some of them are aware of the lights being on/off, that they can distinguish day and night or sunny and cloudy weather. While I was working with one of the blind students, he asked whether it was raining. Very interesting was the fact that none of the sighted persons in the classroom hadn't realised cloudiness before the student mentioned it. He said that he could feel that clouds covered the sun. It's like *"the sky puts on its grey coloured clothes"*, he explained. This statement raised another brainstorming question:

What do colours mean to the students?

It was surprisingly found that blind students coloured not only 'pictures' in their minds, but also thoughts, wishes, desires, expectations, feelings. Some of the most noteworthy views are listed below:

BLACK

"The condition I'm in", "Black Sea", "A funeral", "Sadness and Desperation", "Dark Chocolate", "Bad Weather", "A fashionable colour", "Favourite colour, it goes with everything", "Black Horse that will save our people from the occupier", "A knight who will free Famagusta from the Turks".

BROWN

"Trees", "Chocolate Cake", "A homemade coffee".

RED

“Love, Passion”, “Strawberries”, “A beautiful lady”, “A lipstick”, “A woman in love”, “I need a cuddle”, “Kisses”.

BLUE

“The colour of the sea”, “Happy weather”, “The blue sky”, “Gorgeous eyes”, “My favourite football team”.

WHITE

“Chaos”, “Snow and Ice”, “A horse”, “A rabbit”, “A painting without a story”, “A plain scene”, “A bride”, “Feeling sad and cannot do anything about it”, “Cold people”, “loneliness”.

The colour they had more to say about was black. They explained that they try to ‘warm up’ their mental picture all the time by adding happy colours to the black background. Even though the majority of the students had negative feelings about this colour, these feelings are influenced by the sighted people’s opinions. At the end of the discussion about colours, it was obvious that black is not particularly associated with negative feelings as the majority of the sighted people believe. It forms more like a scene with prospects to develop a beautiful picture.

During afternoon classes, students attend a number of different classes; sculpture, painting, kitchen/cooking skills, basketry, music, computers, learning braille (mostly for late blind people). Each student may also receive assistance on school’s materials, mostly on science subjects.

Sculpture

Their creations are exhibited every year during one of the school’s raising money fairs. Also, the school has its own shop that sells these products. Sculpture is considered one of the favourite classes! Students are split into small groups of 5-6 members depending on the level of their blindness. They are offered a real object to explore it haptically and then they have to create a sculpture model of it. This includes tangible items like a chair, a ball, a desk, a tree and/or a person. They may also be asked to develop models of objects that are not immediately available to them to explore (intangible) like the sun, the sea, an aeroplane. They may also recreate an imaginary scene.

The tutor helps them with building the right model and more importantly she enriches and/or corrects the students' mental model they have of a particular real object.

Wikistix Painting, Fabric Profile, Corrugated Paper Butterfly

(All images adopted from http://eid-scholi-tyflon-lef.schools.ac.cy/)

Painting

Very similar to sculpture, students have to paint real objects, a real or imaginary scene. Many of these paintings are not offered on sales and they are exhibited on school's walls. Students use many different materials like fabric, corrugated paper, wikistix, acrylic paints, oil pastel, watercolours and tempera.

Basketry

Another very interesting activity they have during afternoon school is the basket weaving. Groups of 4-5 low vision and/or blind students, work on similar tasks to create a variety of baskets for personal use or for sale. They first have to decide on the wood base of the basket; then small holes are bored in the wood to accommodate the spokes forming the sides of the basket. They start up from the base and students locate these small holes haptically and laying out a series of spokes that are stiff enough and work like rods to support more flexible woven material. Afterwards, the spokes are cut to be long enough to form the sides. When they finish with the base, the spokes are soaked to softened, squeezed with pliers at the perimeter of the base and finally bent up to form the sides . The speed at which they bent up the sides and laid out the spokes to the base is amazing. They seemed very organised and concentrated on keeping track of their movements and their next immediate action. The majority of the students made baskets as presents to friends and family, some others to give them to the school's shop and one student made a child's crib for his new born baby sister.

Music

All students from a very early age receive music classes. When students express their interest and show talent in music, they have intensive classes on a more frequent basis. Twice a year the school hosts a festival night where students perform in music, vocals, dance and theatre. There are students who give professional performances at concerts at national level and serve as the representatives of the island at foreign events. Most of the students are passionate about the piano, the guitar, the violin and the flute.

Computers

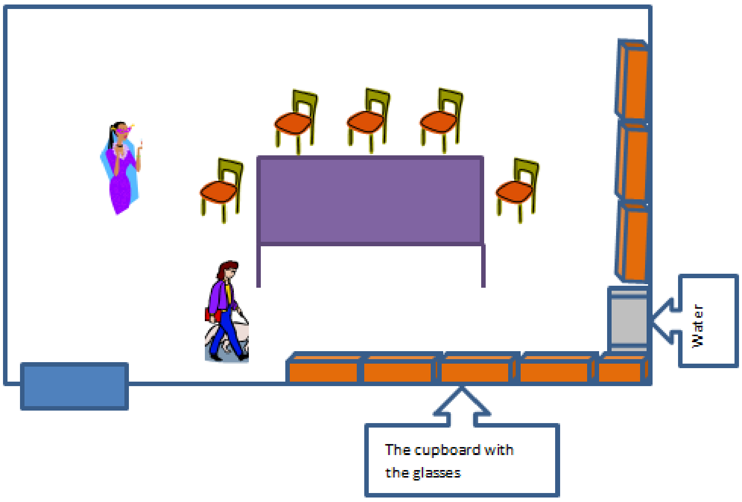
Computer teachers stated that there is an on-going aim to provide students with the latest technology's advances that will improve the quality of their lives. He explained that *"Many of the problems resulting from visual impairment as a sensory handicap can to a high degree find solutions in modern technology".* Children's first interaction with PCs is at age 9 or 10 years old. He went on to explain that at first, the lessons aim to teach students the necessary skills in keyboard use, to help them towards learning basic commands for using the operating system (Windows) and furthermore to be able to use a word processor as a tool for school work. Learning computers class is very popular among not only young students but mature ones as well. Mature students see computers as their gateway to a bigger world beyond where they can meet people (socialising aspect) and having access to an endless open encyclopaedia (information and learning aspect). Many students at secondary school use their own laptop PCs in class to deal with problems that may occur during the class. For students with low vision for whom screen display is not completely useless, this seems to be the ideal and ultimate solution. But for the braille readers this solution encompasses the danger of illiteracy and decreases reading skills since they will completely depend on the sound feedback. What educators try to achieve at the school is narrow down the options students are offered by making them use the Braille Displays to solve coursework or tutorials.

Kitchen tasks/ Cooking

It is very important for the students to learn and be able to take care of themselves without the constant need of a companion. This ability will not only encourage their personal confidence but will make them feel and be independent. Students have a number of different daily tasks to complete during the kitchen capabilities' classes. One task they had to do was to prepare their own meal. They had to choose between cereals or salad. They were taught ways to hold the knife and cutting the vegetables by using mainly their palms as a pointer reference; and putting the right amount of oil and vinegar in it by using a small espresso cup and measuring the quantity using their index finger. They also learn how they can tell that the food in the plate is over and finally to clean the surface of the table and wash the appliances. The teacher pointed out that these tasks are important for their independence. They need to take care of themselves and rely on what they can do and not what the others can do for them. *"Most of these students",* she continued, *"will continue with higher education and at some point in their life they will have to live on their own".*

Mobility and Orientation

In another task blind students had to explore and find the changes to previously known scenes. In this particular experiment some changes had been made to the very well-known kitchen area. For example, changing the location of where the glasses were kept – and requiring the students to locate them and bring the teacher some water. The purpose of these tasks was mainly to teach the students ways to find the things they need by themselves, again improving the level of their independence. Since they were aware of the kitchen design, they used the edges of the table - that was in the centre of the area to orient themselves – they could then move to the cupboards – opposite the table- and follow the edges.



Kitchen Layout

All 4 students completed the task in less than 2 minutes. Only the 17-year-old student faced minor difficulties in locating the new position of the glasses because he didn't open all the cupboards. When asked why he was always failing to open one specific cupboard he said that he *"forgot there were five cupboards in the row".* Repeating the same task but having the glasses in the known position one could easily understand that position is very important to the students. Students needed a maximum of 30 seconds to complete the second task. The general outcome from these two simple tasks is that the position of the objects in space is very important for blind people and the change of location requires them to explore and reconstruct a new model of the scene. In micro-spaces this is not very challenging and, along with the correct directions, students find it fairly easy to adjust to the change.

Appendix B

Proposed System – Plan A

The proposed system requires the use of sensors during both exploration and evaluation levels.

- **Purpose of sensors in the proposed system-solution**

1. Exploration Level

For the exploration of movement, sensors are required to detect the location of the user's fingers on the display, preferably in more than one location simultaneously, without the user having to push very hard.

2. Modification Level

In shape modification it is necessary to have force information on the user's touch. It is essential when the user will perform basic geometrical calculations e.g. the calculation of the surface area of a cube. With modification the user can be expected to exert much larger forces than when exploring an object. The user can wear FSR force sensitive gloves, or FSR sensors could potentially be placed under the strip actuation points.
Tactile Pressure Sensors are used to detect the pressure distribution between a sensor and the target. They are often used as robot grippers or flat tactile arrays. Flexible sensors can be moulded to curved surfaces such as the human body. Most tactile pressure sensors use resistive-based technologies where the sensor acts as a variable resistor in an electrical circuit.
Specifications for tactile pressure sensors include (2009):

- Width, length, and thickness;
- Pressure range and allowable over-range;
- Sensing area, spatial resolution, response time, force range and operating temperature;
- Saturation force: the point at which the output no longer varies with the applied force;
- Repeatability: measures a sensor’s ability to respond in the same way to a repeatedly applied force;

- Linearity: refers to the sensor's response to the applied load over the range of the sensor;
- Hysteresis: the difference in the sensor's output response during loading and unloading, measured at the same force;
- Drift: the change in output when a constant force is applied over a period of time to tactile pressure sensors.

- **Proposed haptic technologies for the proposed system**

It has been observed during the analysis of the current technologies that are available today, that designers of aesthetic products create and manipulate shapes on the basis of curves (characteristic curves, aesthetic curves etc.). The concept of curve as basis for shape generation and modification is not only used in digital models, but also in physical models.
Model makers use physical splines for driving the modification of the object during the design development process. Functionalities of CAS/CAD tools oriented to shape analysis have been developed over the years: functionalities for representing and checking sections, functionalities for representing and checking curvature of surfaces, reflection lines, and porcupine diagrams. Each of these functions have been introduced for quantifying and simplifying the perception of the quality of class A[7] surfaces, and is in general oriented to the evaluation of a single aspect. Therefore, several functionalities are used together for a better and overall evaluation of the shape (Stedmon, et al., November 2007).
The possibility to immediately touch a curve would add an additional and innovative modality for shape evaluation where the perception of the quality of the curve is not based on mathematics or visualization, but is based on touch. Curves and its importance towards the recognition of objects by the visually impaired people is discussed in more details in a following chapter. This would be very innovative in the field of tools oriented to designers.
With regard to shape modification, typical actions of users also start from a characteristic curve belonging to the surface that is pulled, pushed, stretched, in order to reach the desired shape. Of course, that is done by manipulating the mathematical description of the curve or by modifying a

[7] Class A surfaces: describe a set of freeform surfaces

physical maquette (that implies acquisition of the digital model of the shape through reverse engineering procedures).
The idea of using existing commercial software like CAD to design virtual objects that will have a new interface based on a haptic strip was actually generated by these observations. Therefore, the system to be proposed aims at integrating into a CAD tool a haptic interface consisting of a deformable physical strip that acts as an input/output interface:

- the strip haptically renders a curve on a shape (output);
- the strip may be deformed for changing the shape of the rendered surface (input with haptic feedback).

In particular, the system is expected to allow haptic exploration of a shape in order to fully perceive its geometric characteristics along a curve (trajectory) and in the neighbourhood such as continuity of tangency (G1) and/or curvature (G2) mimicking and extending what is currently done with physical splines on Physical Mock-Ups (PMUs). In a general sense an application oriented to design should:

- support the representation of G1 discontinuities (such as sharp edges)
- highlight and be able to communicate G2 discontinuities, since they are usually considered defects in stylish continuous surfaces and are in any case one of the major concerns in designing shapes.

With regard to shape modification task, the haptic strip should act as an interactive, real-time, tangible input interface for applying local or global modification to the shape by physically deforming the strip (Stedmon, et al., November 2007).

The major idea is to integrate existing technology in such a way that it will offer the visually impaired people a more effective way of experiencing the same things the sighted people do with their vision. A sighted person can actually perform three fundamental steps when it comes to real object manipulation and basic mathematical calculations:

1. Draw an object.

2. See a physical geometrical object and recognise its type e.g. triangle, cone.
3. Manipulate the object to perform basic mathematical calculations e.g. the area of a trapezium or more complex models that can combine two different geometrical objects.

These three simple tasks are impossible to be performed by blind people and today's technology offers limited options. There are some systems available that can actually offer haptically cues to enable people to perform visually one single task each time. The proposed system exactly aims to borrow techniques and methods of the currently available technology -that are discussed later in this chapter-, to enable this specific group of users to perform these three tasks simultaneously in the same way their sighted peers do.

The analysis of the state of the art in the haptics domain shows that the evolution of technology has been rather slow. Since the appearance of the first devices (around 15 years ago) most of the research and development activities have concentrated on point based force-feedback devices with limited workspace. Force feedback hardly matches real industrial working conditions, and much less on surface based tactile devices currently limited to proof of concepts of technological principles and very far away from prototypes allowing the possibility of addressing industrial applications. The two aspects are kept separate mainly because of technical difficulties when trying to consider both of them together (Stedmon, et al., November 2007).

Appendix C

A detailed presentation of the pre-test applications end user's had to undergo to familiarise themselves with the environment of the game and the use of haptics. End users were allowed to spend as much time as they felt they required in order to be positively sure of what exactly was required of them and therefore the goals they should have for the actual testing. The focus on the test tasks and the pre-tests was to allow users to explore a virtual scene and be able to locate the objects in it, and extract the necessary information to name the objects.

The pre-test applications were written using the Chai3D haptic open source library, the models were built in Autodesk 3DMax Studio and OpenGL and the hard coded in C++. The author of this thesis implemented all these test applications.

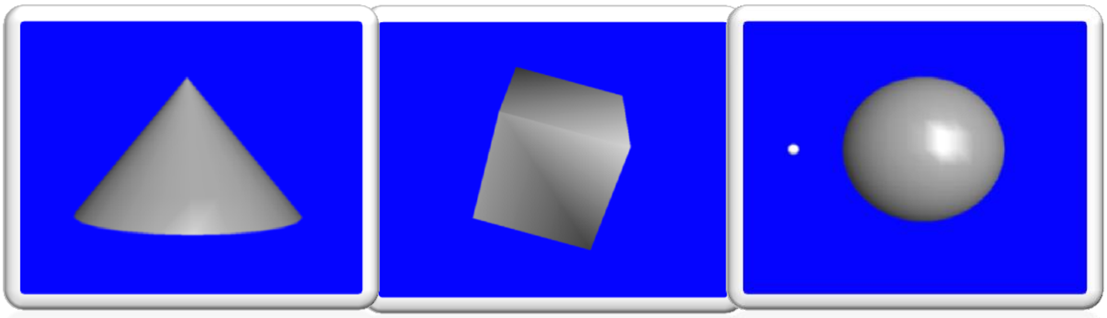
Introduction to the test

All research persons performed all the tasks without any visual interaction in the cases with low vision persons. They were introduced in the game, its aims, its objectives and what the researcher wished to get out of these series of experiments. Then end-users were given the time to explore the device haptically. Meanwhile, there was a verbal description of each component of the device. Users were able to feel the Novint's Falcon grip as well as the three mechanical arms. Any questions about the technology were also answered. Students were particularly interested in the games that come with the device and they wanted to feel the experience of actually playing them.

Pre-test tasks 1,2 and 3

The VE with limiting boundaries – walls, floor and ceiling. This limited box is necessary to give users a reference and to prevent them from trying to reach the maximum workspace of the Novint's Falcon grip. In one experiment with no limited boundaries, the research group observed that some users were led to believe that there was an object at the maximum reach of the grip. The first pre-test tasks aimed primarily to help participants locate the object immediately and feel it, rather than adding a level of difficulty.

In the first VE, there is a single cube rotate by X, Y and Z axis by 40, 90 and 10 degrees respectively. It was placed in the centre of the VE. In the second VE, a cone is positioned again in the centre of the VE, in the third VE a sphere was placed 3 cm east of the centre point. These pre-test tasks gradually encourage and help end-users to explore a virtual object and to get used to the movements they had to do towards haptic exploration of virtual scenes. Furthermore, they helped them train themselves on how to correctly handle and control the grip and feel how haptic feedback was generated to their palms.



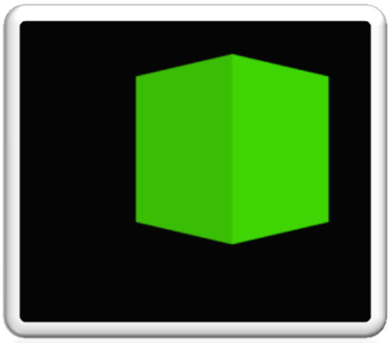
Pre-test task 1 Pre-test task 2 Pre-test task 3

Dynamic Environments

To increase the level of difficulty, the second part of the training session required research persons to deal with dynamic environments. The VE was not limited down to the size of a box, like previous tasks, therefore research persons had to scan a much bigger VE to locate the object. Objects were randomly placed in the scene.

Pre-test tasks 4

A 5*5*5 cm cube was developed with OpenGL and loaded into the program code. Vibration and magnet effect were added to the object. Every time the user was getting close (< 1 cm) to the object, the magnet effect was enabled.



Pre-test task 4

```
mat.setMagnetMaxDistance(1.0);
```

In addition users were able to feel a vibration and magnetic effect every time they positioned the grip on the object. As long as they were exploring the object these two effects were enabled.

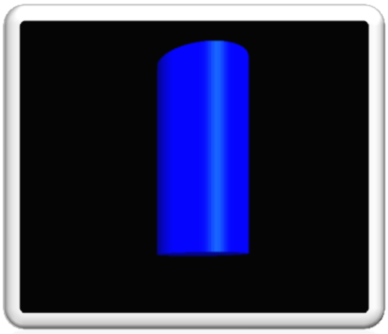
```
                // vibration

mat.setVibrationFrequency(100);
mat.setVibrationAmplitude(0.4 * forceMax);
```

These effects primarily aimed to help users maintain control over their movements and moreover to give them immediate feedback whenever they were close to the object, were exploring the object, and every time they were getting off it.

Pre-test tasks 5

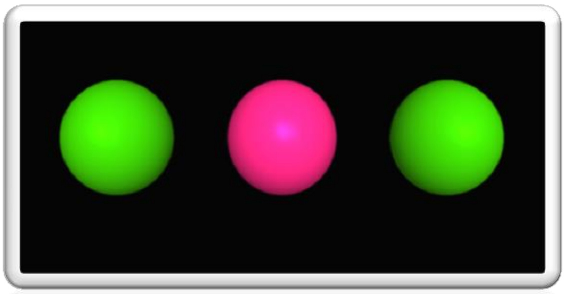
A cylinder was positioned in the VE with only the magnet effect on. Research group wanted to test and hear users' opinion of what they feel is better towards the exploration. Most of the participants (>75%) believed that vibration was a tiring feeling and sometimes misleading. When they were asked about the magnet, almost all participants reported that the magnet did not make a noticeable difference.



Pre-test task 5

Pre-test tasks 6

The last pre-test task from the second part of the training asked users to test three different spheres of the same size but different haptic effects. The first ball had both vibration and magnet effect on, the second one only vibration and the third one only magnet.



Pre-test task 6

There was the need to have all possible combinations of haptic effects into a single virtual scene and observe how comfortable users feel with them.

Complex Environments

In the last level of the step-by-step training session participants had to complete a number of different tasks similar to the ones they had during the game, like locating an object in free space and naming it. No time restriction was applied.

Pre-installed games experience

Participants were allowed to feel and experience some more effects like gravity, bouncing of virtual objects through the examples that come with Chai3D library (Chai3D 1-2-3)

Chai3D pre-installed games

Appendix D

The following questions consider how you perceived the experience of testing the game and ask you to evaluate a number of different aspects. Please mark with an X the alternative that corresponds to your answer.

1. How well do you think you managed to do the tasks in the system?

Not at all well						Very well

2. How easy did you feel it was to learn how to use the system?

Very Difficult						Very easy

3. How easy did you feel it was to use the Novint's Falcon grip?

Very Difficult						Very easy

4. How do you rate the haptic interaction?

Very Inaccurate						Very accurate

5. How difficult did you find Level One?

Very Difficult						Very easy

6. How easy was it to locate the object?

Very Difficult						Very easy

7. How easy was it to manipulate the object?

Very Difficult						Very easy

8. How did you find Level Two?

Very Difficult | | | | | | Very easy

9. How easy was it to locate the object in Level Two?

Very Difficult | | | | | | Very easy

10. How easy was it to manipulate the object?

Very Difficult | | | | | | Very easy

11. Was it hard to move to the 2D shapes section?

Very problematic | | | | | | Not at all problen

12. How did you find Level Three?

Very Difficult | | | | | | Very easy

13. How easy was it to locate the object in Level Three?

Very Difficult | | | | | | Very easy

14. How easy was it to manipulate the objects?

Very Difficult | | | | | | Very easy

15. How easy was it to explore the whole Virtual Environment?

Very Difficult | | | | | | Very easy

16. Was it hard to move between objects quick?

Very Difficult						Very easy

17. How do you rate the system?

Poor						Very good

18. How accurate do you rate the tactile cues provided by the grip?

Very Meaningless						Very meaningful

19. How playful do you rate it?

Not at all playful						Very playful

20. How did you find the collaboration with your participants/teachers?

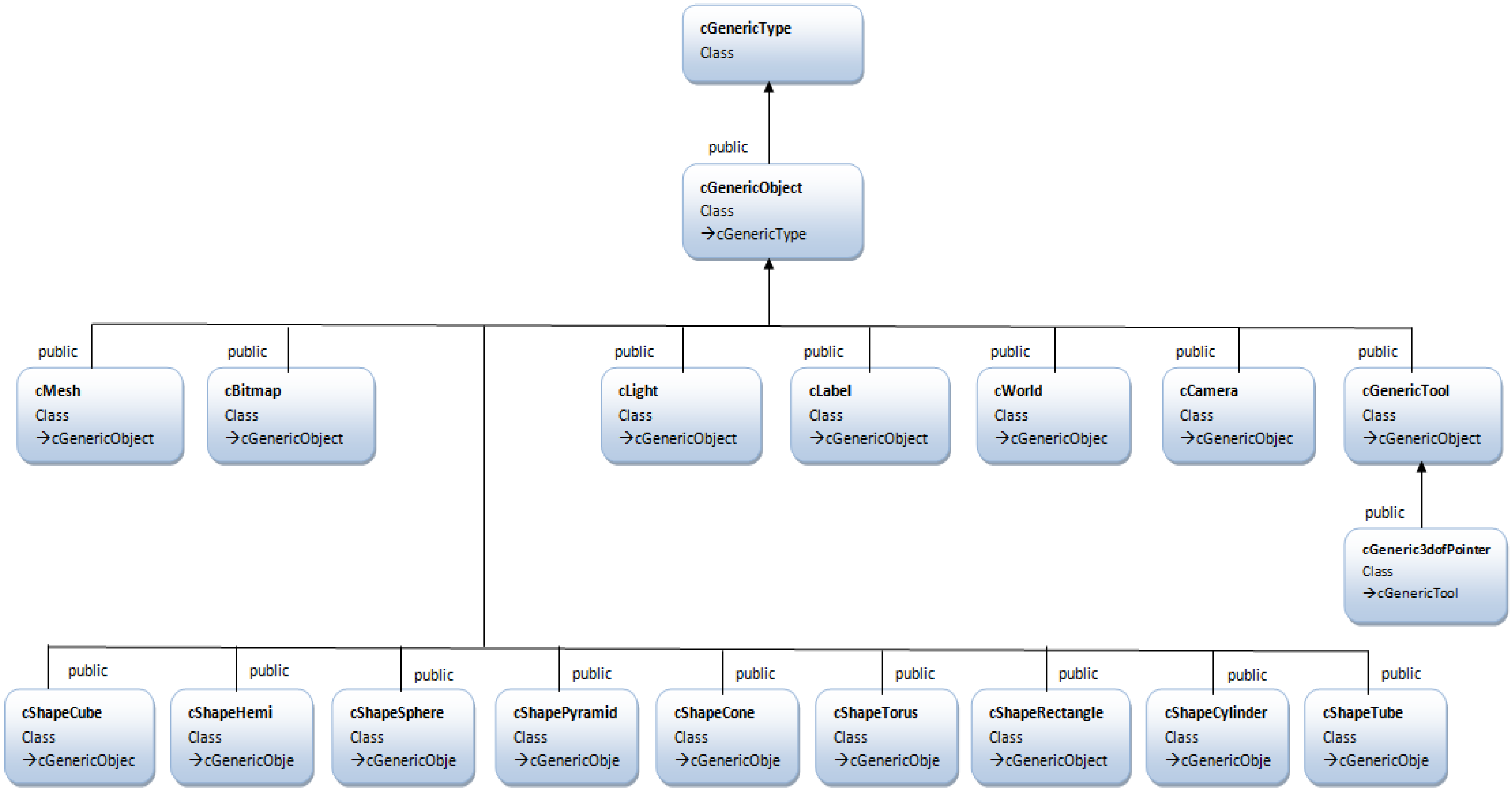
Very negative						Very positive

The following pairs of words describe how you could have perceived the Virtual Learning Environment. Please write an X below the number that corresponds to your answer.

I perceived it to be:

	1	2	3	4	5	
Impersonal						Personal
Unfriendly						Friendly
Unsociable						Sociable
Unhelpful						Helpful
Unpleasant						Pleasant
Cold						Warm
Not interesting						Interesting
Negative						Positive

Appendix E



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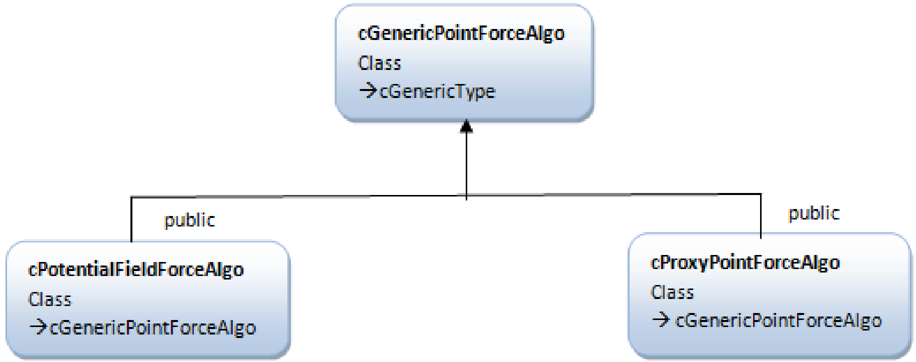
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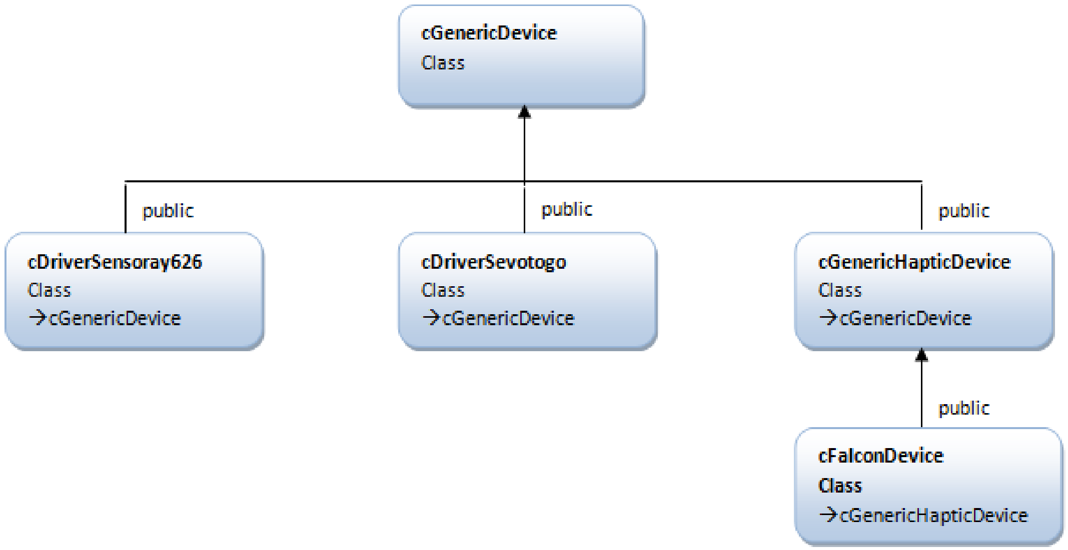
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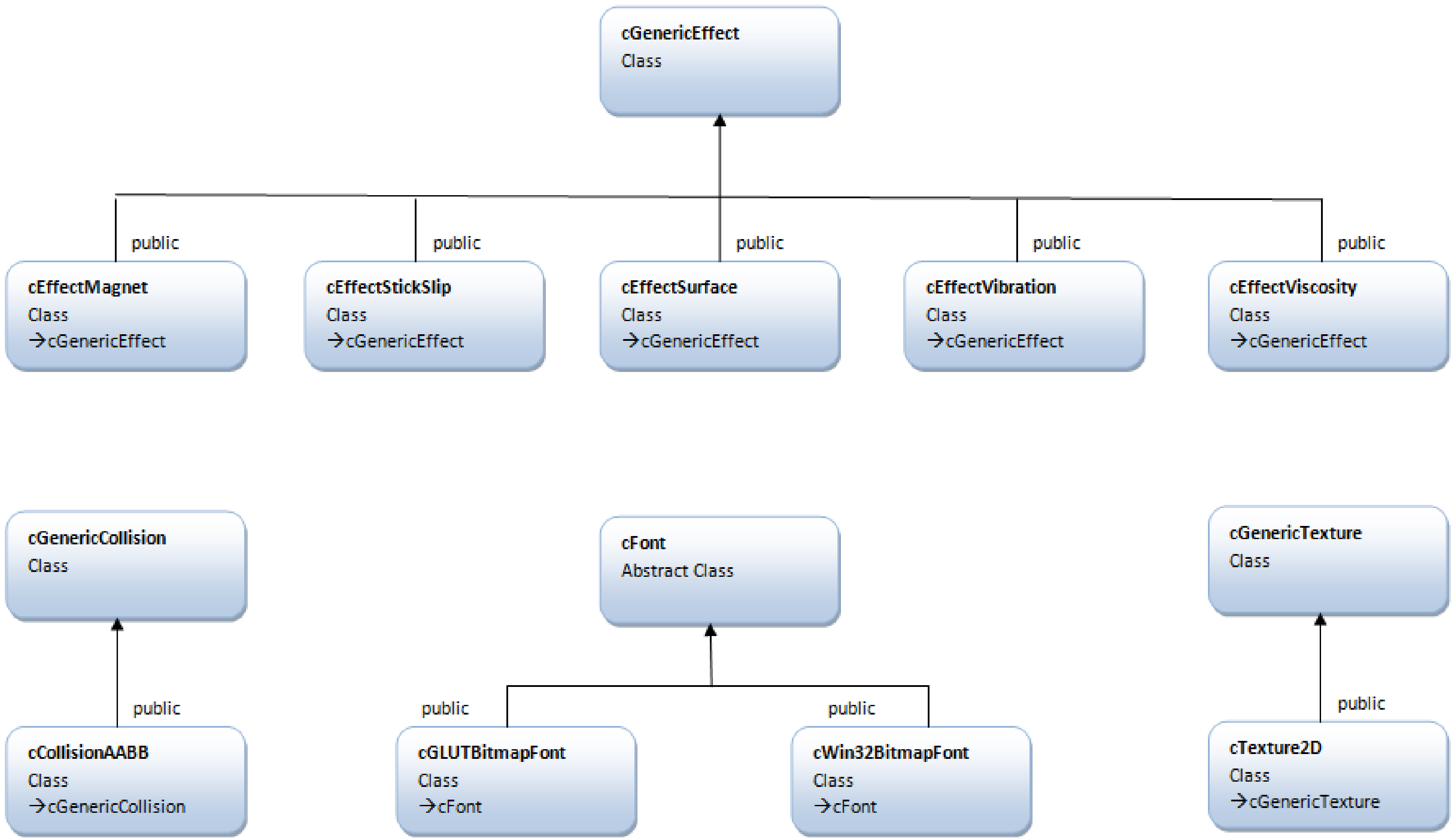

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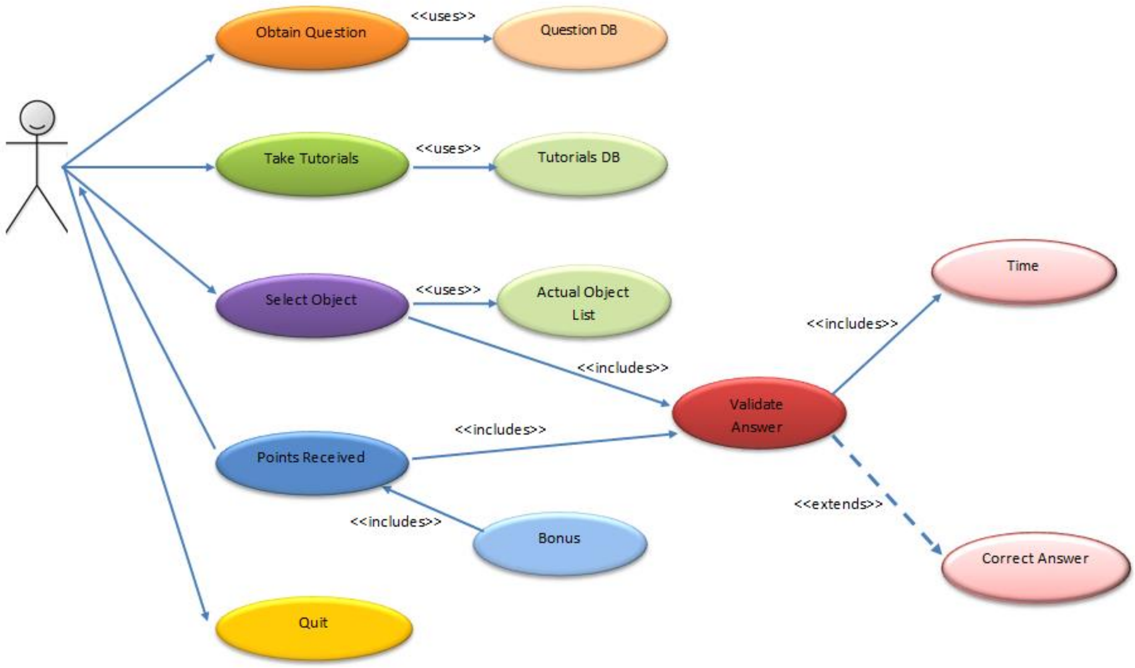
Appendix F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Question DB
Take Tutorials
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Actual Object List
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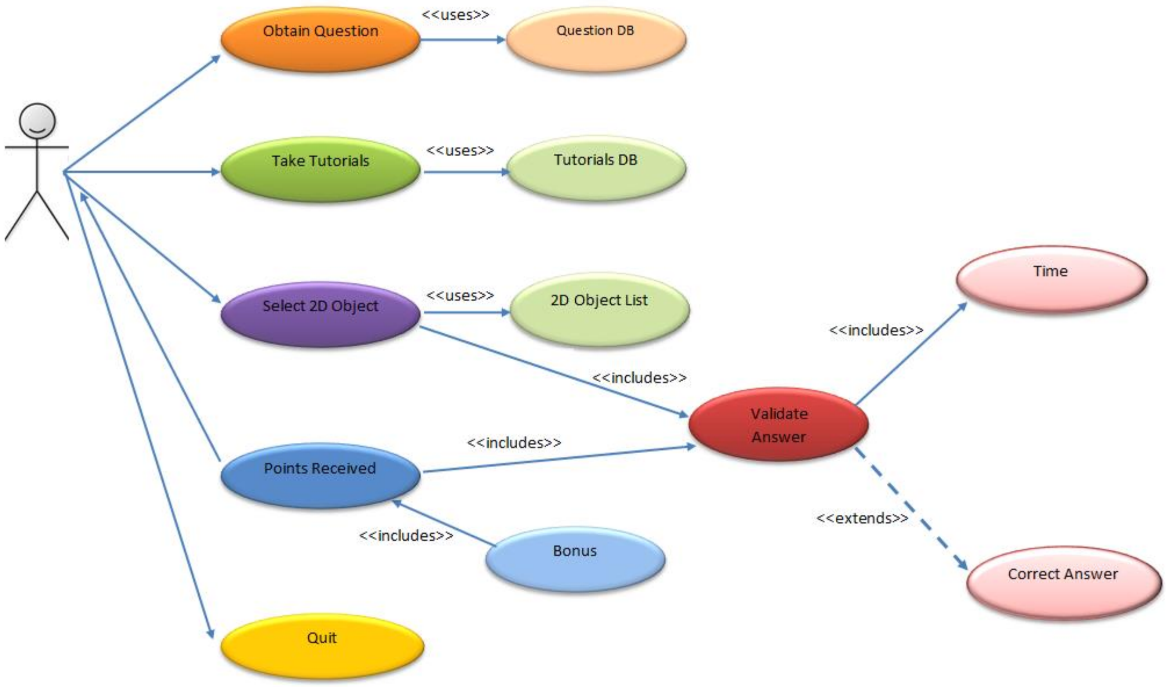
Bonus
Correct Answer
Quit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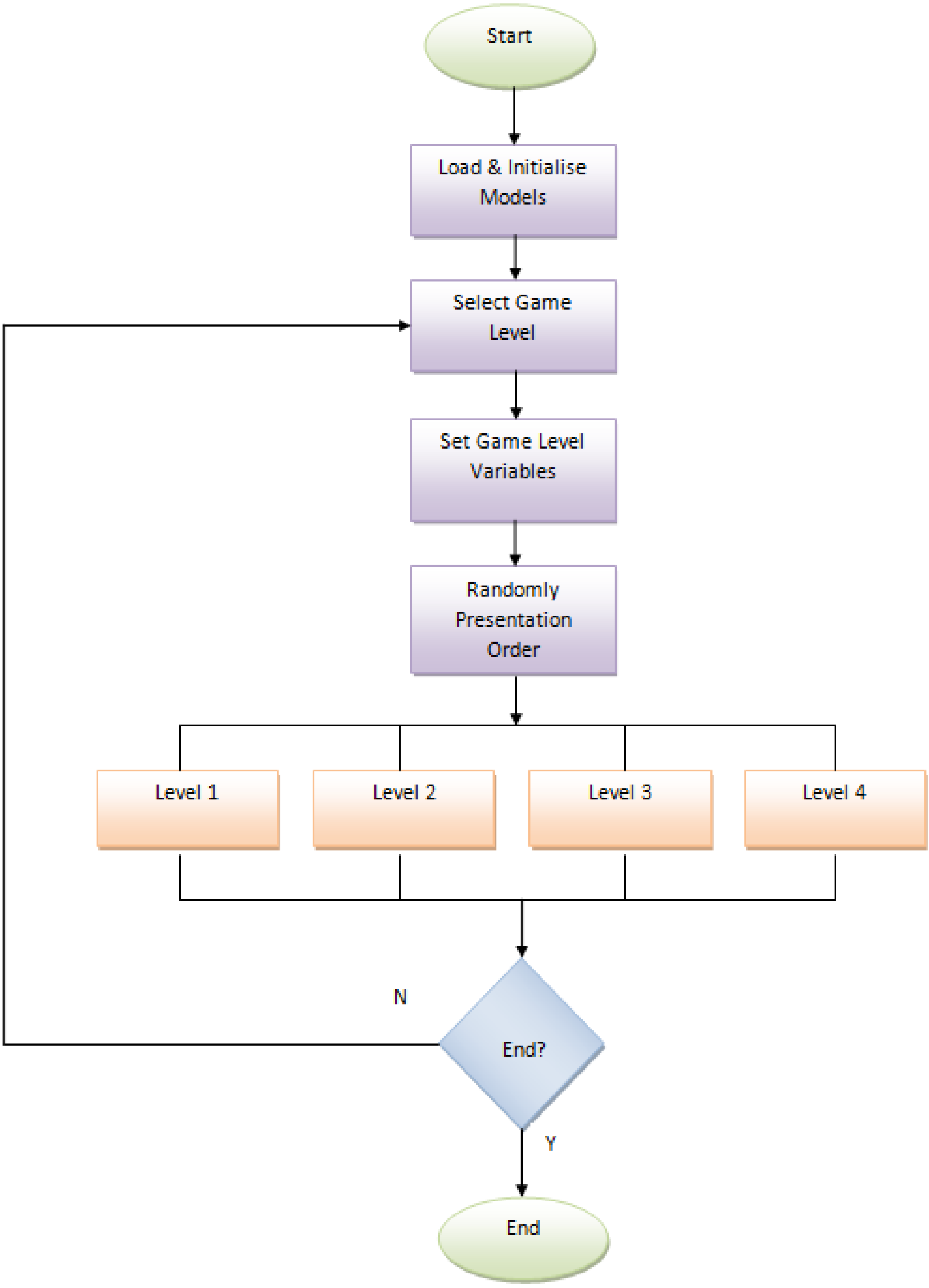
Bonus
Correct Answer
Quit

Appendix G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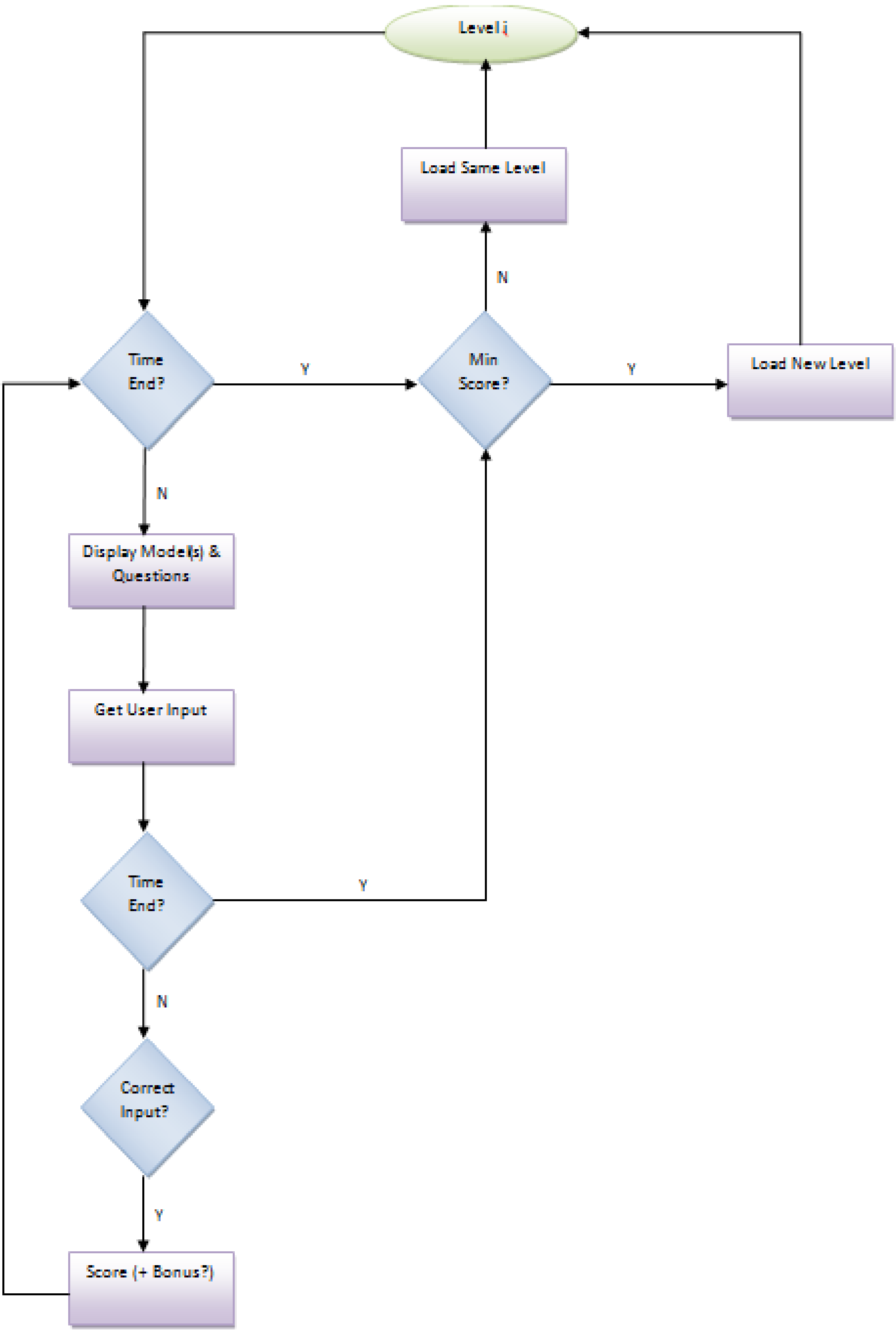
Load & Initialise Models
Select Game Level
Set Game Level Variables
Randomly Presentation Order
Level 1
Level 2
Level 3
Level 4
N
End?
Y
End


Level i
Load Same Level
N
Time
End?
Y
Min
Score?
Y
Load New Level
N
Display Model(s) &
Questions
Get User Input
Time
End?
Y
N
Correct
Input?
Y
Score (+ Bonus?)

Appendix H

Participants' Performance: Task 1

Participant A: He was instructed to find the object or the objects there were in the VLE and name them. Participant A was very familiar with the use of Novint's Falcon grip as he had been practising with it in his spare time at the School for Blind. In total, the time spent playing with the device was maximum 90 minutes. Therefore, he successfully managed to locate the object in 8 seconds and it took him another 10 seconds to recognise that it was a sphere. He commented that it was easy to locate the object as he had a perception of how big the VE was this time, therefore by moving the grip horizontally or vertically from one end of the screen to the other, he would have been able to sense the collision. As far as the identification, he was aware that as soon as he located the object he needed to remain on the object by doing small movements. He advised that the process could have been less difficult if there was an audio feedback of whether they are in the VE.

Participant B: Participant B had spent some time experiencing Novint's Falcon. His teacher mentioned that he was primarily interested in playing the games that come with the console and with help and instructions he really did well and enjoyed the play. In total he hadn't spent more than 60 minutes practising. He located the object in 6 seconds and he needed another 16 seconds to identify the object. His movements on the object were rather quick, so he easily lost control and position.

Participant C: He had spent around 60 minutes playing with the console during break between classes. He easily located the object in 10 seconds and identified it in 6 seconds. He was asked to explain how he managed to identify the object so quickly and what was the distinct characteristic he felt. He explained that he felt the collision surface to be rounded and slippery so there was no point in further investigating it. His answer was characterised more as lucky and he was prompted to tell how he could tell if it was a hemi-sphere. The participant again grasps the grip and performs a full 360 degrees of exploration just to re-confirm it was a sphere. He was advised that in future similar tests he should be more careful because there are lots of objects which look very similar at the first touch but in real content they are not.

Participant D: Participant D is late blind. She has never used the Novint's Falcon and according to her academic performance reports and teachers' feedback her knowledge in both Mathematics and Computer Science is average. Her school performance dramatically declined after her health problem. She was allowed 15 minutes to use the Novint's Falcon grip primarily by running the tutorials that come within the package. She experienced the different textures and also some time was given her to play pre-installed games, like tennis and golf. Observing and evaluating her level of successful interaction, show some positive results regarding controlling the grip and her movements within the VE. After the training, she proceeded to Task 1. She took 6 seconds to locate the object and 8 seconds to identify it. She commented that "everything is very fresh and new in my mind so I faced no difficulty to locate and identify the object". The fact that she had just tested the tutorials seemed to her as a repeating process.

Participant E: As a result of her visual impairment (<18/60) participant E faces some mobility and learning difficulties. Prior to the test, she was allowed 15 minutes to explore the game haptically and visually and received a brief explanation of what the research was aiming at and in what way she could help towards its completion. It was important to make her feel comfortable and assure her that her feedback and comments were significantly important and valuable. In contrast with the other 4 participants and primarily compared to participant D's performance, her results were rather disappointing. She couldbaely control the grip and it took her 3 minutes to identify that there was an object in the VE. After instructing her on the movements she needed to do in order to identify the object, she managed to isolate the characteristics of the object: a) it was tough b) slippery and c) rounded. Even then, she was not able to tell that it was a sphere. To help her more, two choices (sphere or cube) were given to her to choose from. Overall she needed 5 minutes to complete Level One.

Participant F: She had vision <20/60 and she was allowed to have visual contact with the screen display. Participant F had no mobility issues but faced some learning difficulties and her knowledge on mathematics was poor as her experience narrows down to basic algebra awareness. She faced the same difficulties as Participant E but she managed to locate and identify the object in 1 and 2 minutes less than the previous user.

Participants' Performance: Task 2

Student A: He needed only 3 seconds to locate the object and another 10 to identify it. He seemed very determined and confident on his movements. He believed that vibration can be confusing and that only a distinct texture may lead to more accurate conclusions.

Student B: Similarly to Student A, he took 4 seconds to locate and another 9 seconds to identify it. He was very accurate regarding the position of the grip and he thought that vibration can help him keep control of their movements and be immediately aware when he was away from the object.

Student C: He located the object in 10 seconds and it took him 68 seconds to identify it - more than it was expected. He justified the failure to identify it right away to the vibration which was really confusing and made him feel uncomfortable. He believed that the tough surface of the sphere worked perfectly well for him.

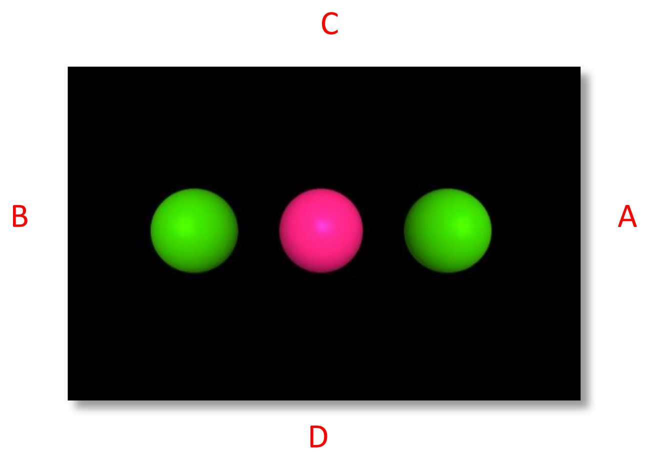
Student D: She managed to find it in 5 seconds and faced some problems to identify it (130 seconds). She didn't like the vibration and she insisted that tough surface is the best. She had some difficulties to successfully identify her position.

Student E: Vibration caused additional problems on controlling the grip. Student seemed to feel afraid of the vibrating grip and her movements were very restricted. With the help and instructions of the research team and the educators the user was able to tell when the grip was on the object. She was instructed to try to stabilize the grip on the object – something that was achieved – and with small and control movements along the surfaces to try and reach the first edge. She managed to locate the first edge quickly but she lost control when she had to locate and explore another surface. To make it easier for her, she was advised to brainstorm on what she sensed, so as to build a model based on the characteristics she haptically discovered. It took 10 minutes to build up a model of the cube.

Student F: In contrast with Student E, this user managed to keep control of the grip, she admitted that vibration was giving her enough stimulus to identify the object. She located the object in 2 minutes and by collecting the distinctive characteristics she managed to build up the model and tell it was a cube. She managed to identify the object in 4 minutes and she had a pretty good knowledge on which surface she was exploring. When she was asked whether she was using her vision she stated that her vision does not help her to see details and small scale objects. The only thing she could distinguish was the object existence.

Participants' Performance: Task 3

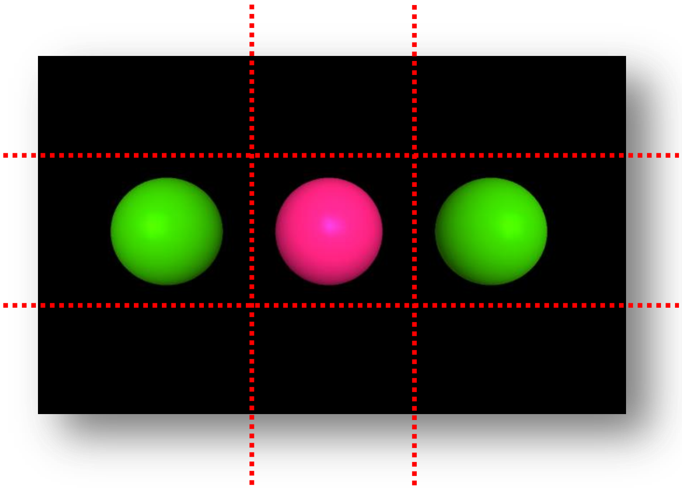
Student A: Starting of position A [See Task 3], student located the first object immediately. He recognised it to be a sphere and instantly he moved left to reach the second one. To be sure that it was actually a second object he moved backwards towards side A to double check the existence of the first object. Then he moved upwards toward side C searching for a new object. Then he moved to the centre (object 2) and then left to side B. Haptically he identified there was another object. He said that the objects are all of equal size, spheres and located on a straight line. Before submitting his final answer he wanted to check that there was not any other object randomly located in the VLE. It took him 4 minutes to complete the whole task. He commented that the objects were relatively small and that more complicated illustrations will be difficult to explore haptically.



Student B: He didn't follow a specific rule on how to move in the VLE. He managed to locate the first two objects easily but he was confused because he was expecting different objects and the fact that he was constantly colliding with a sphere slowed down the exploration. He personally believed that if every sphere had different texture then it would take less time and simplify the haptic exploration. He commented that "it is going to like colours for you (meaning the sighted people) that different colours make an object distinctive". He completed the task in 5 minutes 30 seconds.

Student C: Primarily he wanted to know where the grip's position was. He moved diagonally until an object was detected. He was randomly moving within the VLE. He was advised to construct a framework of movements in order to tell how many objects existed. He asked us to give him feedback on where he was in the VLE. His movement began to follow a model and he had more control. He completed the overall task in 7 minutes. The user pointed out that an audio feedback of his position on the VLE would simplify the process.

Student D: The first object she located was the one in the centre. Instantly she moved the grip to the right to reach the second sphere. Up until this point her performance was better compared to the previous users. She faced some difficulty to locate the third sphere. She spent some time exploring the VLE by splitting it into sections [See Level Three into sections] and exploring each one separately. She took 6 minutes to complete the process. Audio feedback and/or different texture would have speeded up the process, she explained.



Level Three into sections

Student E: She had actually explored all the three spheres but couldn't tell the number because every sphere seemed the same. One thing that was very supportive was that she seemed more comfortable and experienced in using the grip. It took her 10 minutes to reach all the three spheres.

Student F: She had the same issues as Student E completing the task in 10 minutes as well. She mentioned that there was not a medium to inform her when she was reaching a new object. She personally preferred to hear a different sound every time she reaches a new object.

Participants' Performance: Task 4

Student A: He correctly identified that there were gradient faces and a vertex. He then searched from the base and by putting all the pieces together he managed to tell in 3 minutes that it was an up-side-down pyramid. This student's performance was the best among all the users.

Student B: He spent some time examining all the surfaces. He managed to recognise it in 4:30 minutes.

Student C: He used the same investigation avenue as Student B. He completed the task in 4.50 minutes.

Student D: She faced some difficulties in putting all the characteristics together and therefore successfully naming the object. She received some guidance help from the research team's members. She did manage to get it right in 6.30 minutes.

Student E and F: Unfortunately, the last two participants didn't manage to name the object. Even when educators told them all the characteristics of the object they were unable to figure out the object. This shows the poor level of their mathematical knowledge and background.

Appendix I: Results – Level One

Student A: He overall did very well during Level One. He seemed excited and enjoyed the experience. He seemed to be in a very competitive mood as he wanted to find out what other fellow participants did. He said that the tactile feedback was helpful but at the beginning he had to be extremely focussed to decode the haptic feedback. He admitted that he started to feel more comfortable and relaxed as time was going by. He rated Level One with 4/5 as he believed that there is space for improvements. One of his recommendations was that he would have preferred the grip to be placed by default on the object instead of searching to locate it. Twice he found difficulties to name the object but he was able to link the specific virtual objects with a real object, e.g. cylinder to by a Coke can. He later explained that stress made him forget the name of the object. Locating and manipulating the object was quite easy for him and he rated both with 5/5 (very easy). He explained that as soon as he was on the virtual object he had to do small and controlled movements in order to stay in touch with it. He was primarily searching to detect edges; if none was discovered then the process was turning to be less difficult. He managed to find 3 correct answers, two of them in less than 10 seconds so he was awarded a total of 60 points.

Student B: He managed to move to the second level of the game from his first time. He was the user who showed the most positive and stress-free attitude. He spent approximately 10 seconds to locate the objects and he was in full control throughout the level. The fact that there was a verbal description of his location against the object caused him some confusion. He stated that *"instructional directions messing up my mental navigation plan".* He received the highest score. He gave a positive feedback to the current level. He would prefer to have a warning sound playing when the time is running out. He also advised that "it would be fun to have a song playing at the background and be able to make your own selection". He believed that these new haptic feedback interaction programs can be used in other subjects like geography and maybe physics. As an immediate future improvement of the current version of Level One, he wished to see a more challenging tasks, like more complex 3D objects to explore. In addition to the last one, he pointed out that future objects need to be much bigger that the current ones. He rated both locating and manipulation tasks very easy (5/5).

Student C: He needed an average of 10 seconds to locate the objects in VE. He felt very comfortable in using the grip and he reported that he spent quite some time playing games during breaks. He seemed very experienced primarily in using and controlling optimally the grip and furthermore exploring the object. He commented that he wanted to be more actively informed of the remaining time. Even though all participants were informed when 10 and 5 seconds remained, he said that there were too many verbal instructions that sometimes could be confusing. He would have preferred a sound that would become more intense closing to the end. He overall left a positive impression for Level One and 5/5 for locating and manipulating the object.

Student D: Compared to the previous three participants, student D had some obstacles in successfully locating the objects. She managed to find three objects but she failed to collect the minimum points to move on to the next level. During her first attempt she twice successfully located the object but instantly she moved away. She said that she couldn't tell that she had reached the object. Her movements were tight and her hand was shaking. She seemed very distressed. She later explained that she wanted to do well so stress took over and she panicked her. When asked how she evaluated the tactile cues and haptic feedback received, she was unsure to give an accurate answer. The second time around, the results were diametrically opposed. She seemed to have more control over her movements and navigate more quickly than the first time. She managed to find 3 correct answers plus 20 points of bonus. When she was informed that she moved on to the next stage she was really happy and relieved. She described her performance as stress-free and she said knew what to expect during second time. When she was asked again about the tactile feedback, she said that it was difficult sometimes to decode the cues and that she sometimes was not clear whether she was on the virtual object or not. She gave locating 3/5 and 4/5 for manipulation. Overall she was rated at Level One as average.

Student I: His exploration movements were slow. He was the only student that hadn't lost control of the object once it was located. His very slow and small movements helped him have full control over the manipulation process and not move away from the object. On the other hand, this caused him the fact that he didn't manage to collect the minimum points so he had to repeat the process. He managed to find 2 objects relatively quickly so an extra bonus of 20 points were collected. He seemed very relaxed and the fact that he failed at the first round didn't seem to put him off at all. He said he enjoyed the interaction and that this technology can be used in gaming. He had practised some of the games that come with the platform and he was really happy. He also added that, "*it can enable blind and sighted friends to play the same game".* Also, he wished to have this technology applied to art and painting and he could see lots of potential in this area. The second time around he managed to collect the minimum points by finding 3 objects this time plus 20 bonus points. He left a positive feedback for this level. He gave locating 4/5 and 5/5 for manipulating.

Student J: IT took him an average of 12.5 seconds to locate the object, meaning within the time he located 8 different shapes. He initially searched to reach the boundaries of the scene and then with random horizontal movements he located the object. As soon as he found it, he performed very organised and small movements on the object. He successfully found 3 objects, 2 within a period of 10 seconds. He proceeded to the next stage. He preferred the object to have a magnetic effect to help participants remain on the virtual object and therefore save time. He believed that 100 seconds is not enough time. He rated this level as Good. The navigation task was not difficult for him as he believed that the mechanism he used minimised the possibilities of missing out the object. He rated it with 5/5(very easy) and the exploration task with 3/5.

Student K: He was moving vertically in the scene. He managed to locate 11 different shapes and identify correctly four and receive 10 points as bonus. He looked really concentrated on the tasks and he asked the teacher to stop giving location instructions. He commented that the instructions were misleading for him. He expressed the following very interesting view, *"your (teacher's) statement 'Your are very close' does not necessary mean exactly the same thing to me. My very close can be 5 cm away whereas yours can be 1 cm away".* He wanted to have the remaining time notified by a sound. He left a positive rating by giving 5/5 to both navigation and exploration.

Student L: She had some difficulties in locating the object. Overall she managed to locate only 5 objects and correctly identify only 1. She repeated Level One but again she didn't' manage to collect the necessary points. She said that it was difficult for her to explore the object as it seemed to have a really tough surface. She found collision realistic enough and could recognise edges. She commented that 100 seconds was not enough. She could easily lose track of the grip without recognised it. Her exploration and navigation process was not characterised by a tactile pattern. Her feedback was neutral and she evaluated the navigation with 2/5 and exploration with 1/5.

Student M: She found difficulties in locating the object and every time she achieved it she could easily lose control. She didn't manage to locate any object within the allowed time. She had the level repeated but she didn't manage to meet the minimum requirements. She said that even though she could see the existence of the object she tried to rely more on her visual feedback rather than the haptic. Her sight level only allowed her to see that there was an object in VE but could not help her understand its shape. One of the mistakes she was making was the attempt to locate the virtual ball - that was the virtual position of the grip. She could not see any potentials for this testing but she commented that young participants might benefit from this.

She gave a negative feedback for it and she simply stated that she didn't like it. She evaluated navigation with 2/5 and exploration with 1/5.

Student N: He managed to locate 6 objects and identify correctly 2 and earned a bonus of 10 points. He moved within the VE very quickly and his movements were very well-ordered. He could keep control over the object exploration and he was able to tell what he was reaching (e.g. an edge, a face, a vertex etc). However he found it particularly difficult to name the object. He said that the tactile cues and haptic feedback were clear but yet he didn't feel excited. He overall rated it as average; for locating the object he gave 4/5 and exploration 3/5.

Student O: Very similar to student M. However, he managed to locate 2 objects and name 1. He repeated the level but again he failed to collect even the minimum points. He said that the tactile cues were clear for the rounded objects (sphere, hemi-sphere, cone). For the remaining objects it was difficult to keep control of his movements. He didn't see any potential so he gave a negative feedback.

Student P: He located a number of 7 objects in total, recognised 3 and earned 10 points as bonus. During the second trial he managed to successfully collect the required points. He said that tactile cues could be more helpful and meaningful if participant practised more. He again didn't need to have verbal instructions as when he was in VE. He left an average feedback and gave 4/5 and 3/5 for navigating and exploration respectively.

Appendix J: Results – Level Two

Student A: He found it very entertaining and he admitted that the experience he gained from Level One helped him during this level. He wanted it to have more playful sounds and be informed of the time remaining. He believed that this level was more challenging than the previous one, therefore it was more interesting. He reported no problems of moving between the 3D shape section and the 2D illustration section.

Student B: There was an increase in the number of objects located this time. He wanted to be aware of the time and to have a way of knowing how the other colleagues did on the specific tasks. He found it more interesting than the previous one and admitted that the experience gained from Level One was extremely useful and that even though the objects were smaller than in Level One, it was easy for him to identify the objects because he knew how *"an edge or a vertex feels"*. He didn't search to locate primarily the base but he rather starting exploring the surface that he came first in contact with. He collected the necessary characteristics and using the method of elimination he could recognise the object. He gave a positive feedback for this and he commented that even though it was more difficult from previous tasks he enjoyed it better. He also expressed the idea of having this level running on the internet so as to be able to compete with his friends who live in different cities.

Student D: She felt uncomfortable at the beginning. She didn't seem to enjoy the process and she was really stressed. She failed to meet the minimum requirements so she had to repeat the level. When she asked why she looked more worried than during the first level, she explained that she preferred to be alone to complete the tasks and that the presence of the other people watching her made her feel really nervous. However, the second time she managed to collect the necessary points. Her final feedback for the software and the experience was positive as her stress was due to the environment and not the game itself.

Student I: He had a better performance compared to Level One. He managed to locate 10 objects and correctly match 5. He believed that objects should have been positioned at the same place every time. Also he believed that it would be more efficient and effective if there was voice recognition and users could answer verbally. He overall rated Level Two with a positive feedback and with 4/5 for the navigation task.

Student J: He had the highest performance (time to locate the object, number of correct matches, level of comfort) during this level showing an improvement tendency compared to his previous results. He had 6 correct matches and 10 bonus points. He preferred not to have audio instructions as to where he was in the VE. He left a positive feedback and gave full points to navigation tasks.

Student K: He managed to locate 13 objects and earned 80 points plus 20 as bonus. He expected more difficult tasks during this level even though he acknowledged that it was more challenging than the previous one. He believed that this level is an upgraded version of Level One but he would be very disappointed to find the same tasks repeated in future experiments. However, he also stated that without the experience and knowledge gained during the first level he wouldn't have been able to successfully complete that level within the time and score requirement.

Student L: Current level allowed her to engage better compared to previous testing. Even though her movements were tight and slow she had 50% success; she managed to locate 6 objects and effectively recognised 3. During her second trial she managed to collect the minimum points needed to move on to the next level. She gave a positive feedback for this level.

Student M: Her movements were very quick and even though she was reaching the object she couldn't sense the collision. With active help and very specific instructions she located 1 object and successfully recognised it. That object was a sphere. She didn't want to test it again and she said that she didn’t like it and couldn’t see any potential and any usefulness. She left a negative feedback for it.

Student N: Very similar tactic set of actions as student L. He preferred the objects to appear at the same position every time. He argued that locating and manipulating objects were tested during the previous testing. He preferred to have a sound informing him about the remaining time. He commented that this type of games could not be engaging for people of his age and he left an average feedback because he believed that it couldn’t be engaging, fun and educational for young participants. He added that he never enjoyed playing games and his interaction with video games was very limited.

Student O: With help from the teacher he managed to trace 3 objects within 140 seconds. He correctly identified 1 but said that he wished to quit. He left a negative feedback as he couldn’t see how this game could be beneficial to him.

Student P: Even though she said that haptic feedback was realistic and tactile cues easily interpreted she could not see how this game could improve her mathematical skills. She only tried it once without getting any points. She left a negative feedback.

Appendix K: Results – Level Three

Participants A, B, C, J and K: All 5 participants evaluated haptic interaction and tactile cues received as more accurate and meaningful during this level. They also stated that this feeling might have come from the fact that they were more experienced during this level and that knowledge gained played a catalytic role to successfully complete the tasks. When they were asked to express their opinion on the smaller workspace, they said that it was easier for them but did not have a huge impact on their performance. They suggested that adding sound indication when they move to another object could be one possible improvement to the current version. They all left a positive feedback for this level. They wanted to know how well other colleagues did and the first price was.

Student D: She found Level Three the most engaging. She faced some difficulties in re-locating the same object once she got away from it. She successfully managed to solve two scenes – spheres and cubes. She concluded that transferable knowledge and experience from previous levels helped her a lot.

Student I: He said that he felt comfortable and relaxed during the session. He preferred the smaller workspace because his movements were more controlled and so he didn't spend time looking for the object. He would have preferred the objects to have bigger surfaces to explore.

Student L: She spent most of the time searching for the "next shape". She seemed lost and unable to construct a model of the virtual scene. In the instruction "Locate a new object" she was constantly pointing at the same one and insisting she reached another object. She failed to complete the task and compared to previous performances that was not a logical and expected performance. She was asked to explain the reason she hadn't done well and she couldn't give a specific cause for her performance. The second time she ran Level Three she requested to be informed on which object she touched first (left-centre-right). She showed progressive knowledge of where she was and where she should go after. She managed to collect 20 points during second trial. She left a Good feedback and she commented that it would be helpful if users were allowed to know which object they reached first.

Participants M and O: Even though they managed to locate the 3 different objects they were unable to understand the difference in size. They commented that the difference in objects' sizes was very small and that it was significantly difficult for them to understand it. They left a negative feedback and they insisted on the statements they made on the previous levels. They didn't wish to proceed with a second trial.

Student N: He needed to know which object he reached first. He skipped objects with vertices and he searched to find the "easy" ones to explore. He managed to collect the necessary points by successfully completing the scene with spheres and cubes. He left an average feedback and he specified the need to help users to be aware of their position at the launch of the game. Also, he added that it would have been helpful and effective for participants to know when they reached a new object.

Student P: She managed to locate the objects fairly easily. She had some problems having a clear perception of the size of a new object and sometimes she needed to go back to the previous one to re-explore it. She successfully managed to meet the minimum requirements. She left a negative feedback as she said he didn't enjoy it and couldn't foresee any positive benefit for her.

Appendix L: Coding

(a)

```
// load an object file
bool fileload;
fileload=cone->
      loadFromFile(RESOURCE_PATH(
      "resources/models/camera/cone.3ds"));
```

(b)

```
// load an object file
bool fileload;
fileload=cone->
loadFromFile(RESOURCE_PATH("resources/models/camera/cone.3ds
"));
if (!fileload)
    {
        #if defined(_MSVC) //give the full path
        fileload = cone->
loadFromFile("../../../bin/resources/models/camera/cone.3ds"
);
        #endif
    }
    if (!fileload) //if object is not found
    {
        printf("Error - 3D Model failed to load
correctly.\n");
        close();
        return (-1);
    }
(...)
```

(c)

```
void selectLabel(int k)
{
      switch(k)
      {
      case CONE:
      titleLabel->m_string = "Find the Cone";
      break;
      (...)
}
```

To load and assign the audio file to the string:

```
void selectStream(int q)
{
    // Initialize sound device and create audio stream
```

```
    BASS_Init(1,44100,0,0,NULL);

    // Load the data from the specified file
    HSTREAM file_stream = 1;
    HSTREAM file_stream1 = 1;
    switch(q)
    {
    case CONE:file_stream=BASS_StreamCreateFile
   (FALSE,RESOURCE_PATH("resources/sounds/find the
cone.mp3"),0,0,BASS_STREAM_DECODE);
            break;

(...)
```

References

Akamatsu, M., Sato, S., & MacKenzie, I. (1994). Multimodal mouse: A mouse type device with tactile and force display. (pp. 73-80). Presence 3.

Aleman, A., Van Lee, L., Mantione, M., Verloijen, I., & de Haan, E. (2001). Visual Imagery without visual experience: Evidence from congenitally totally blind people. pp. 2601-2604.

Allen, M., Book, W., & Ebertuphoff, I. (2001). *Digital Clay for Shape Input and Display.*

Alseid, M. (2011). The Role of Earcons and Auditory Icons in the Usability of Avatar-Based E-Learning Interfaces. *Developments in E-systems Engineering (DeSE), 2011* (pp. 276-281). Dept. of Software Eng., Appl. Sci. Univ., Amman, Jordan: IEEE Xplore. doi:10.1109/DeSE.2011.34

Amedi, A., Malach, R., Hendler, T., Peled, S., & Zohary, E. (2001). Visuo-haptic object activation in the ventral visual pathway. *Nature Neuroscience, 4*, pp. 324–330.

Anderson, T. (2007). *Novint Inc*. Retrieved May 2012, from Novint - 3D Haptics Technology Software - Professional Use: http://www.novint.com/

Ballesteros, S., Bardisa, D., Millar, S., & Reales, J. (2005). The haptic test battery: A new instrument to test tactual abilities in blind and visually impaired and sighted children. *The British Journal of Visual Impairement*.

BANA, B. A. (2011). *The Evolution of Braille: Can the Past Help Plan the Future.* Braille Authority Org.

Barthelot, R., & Salin, M. (1998). The role of pupil's spatial knowledge in the elementary teaching of geometry. In *Perspectives on the Teaching of Geometry for the 21st Century* (pp. 71-78). Kluwer Academic Publishers.

Bereiter, C., & Scardamalia, M. (1993). *Surpassing Ourselves: An Inquiry Into the Nature and implications of expertise.* Chicago and La Salle: Open Court.

Borges, J., & Jansen, L. R. (1999). Blind people and the computer: an interaction that explores drawing potentials. *Proceedings of SEMENGE'99 –Seminário de Engenharia. Universidade Federal Fluminense*.

Bouaziz, S., Russier, S., & Magnan, A. (2005). The Copying of Complex Geometric Drawings by Sighted and Visually Impaired Children. *Journal of Visual Impairement and Blindness*, pp. 765-774.

Bowman, R. (1982). A Pac-Man theory of motivation. Tactical implications for classroom instruction. *Educational Technology, 22*(9), pp. 14-16.

Brewster, A., Wright, C., & Alistair, D. (1993). An evaluation of earcons for use in auditory human-computer interfaces. *Proceedings of the INTERCHI '93 conference on Human factors in computing systems*, pp. 222-227. doi:10.1145/169059.169179

Brewster, S. (1994). Providing a structured method for integrating non-speech audio into human-computer interface. PhD thesis Human Computer Interaction Group, Dept. of Computer Science. University of York, UK.

Brewster, S., Chohan, F., & Brown, L. (2007). Tactile feedback for mobile interactions. *Proceeding CHI '07 Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 159-162. doi:10.1145/1240624.1240649

Buchel, C. (1998). Functional Neuroimaging Studies of Braille Reading: Cross-modal Reorganization and Its Implications. *Brain , 121*, pp. 1193-1194.

Burdea, G. (1996). Force and Touch Feedback for Virtual Reality. Rutgers Univ., New Brunswick, NJ: John Wiley & Sons, Inc. New York, NY, USA ©1996.

Bussel, L. (2003). Touch Tiles: Elementary Geometry with a Haptic and Auditory Interface for Visually Impaired Children. *Eurohaptics*, (pp.512-515).

Chang, A., & O'Sullivan, C. (2005). Audio-haptic feedback in mobile. *Conference on Human Factors in Computing Systems* (pp. 1264–1267). NY, USA: ACM New York.

Clark, R. (1983). Reconsidering research on learning from media. *Review of Educational Research 53, 53*(4), 445-459.

Colenbrander, A. (2002). Visual standards: Aspects and ranges of vision loss. Report prepared for the 29th International Congress of the International Council of Ophthalmology, Sydney, Australia.

Colwell, C., Petrie, H., Kornbrot, D., Hardwick, A., & Furner, S. (1998). Haptic virtual reality for blind computer users. *Proc. 1998 3rd Inte. ACM Conf. Assistive Technol., ASSETS',98* (pp. 92-99). Marina del Rey CA USA: ACM, Inc.

Cornoldi, C., Fastame, M., & Vecchi, T. (2003). Congenitally blindness and spatial mental imagery. In a. Hatwell Y., & a. V. Streri A., *Congenitally blindness and spatial mental imagery* (pp. 173-187). Amsterdam/Philadelphia: John Benjamins Publishing Company.

Dagman, J., Karlsson, M., & Wikström, L. (2010). Investigating the haptic aspects of verbalised product experiences. *International Journal of Design, 4*, pp. 15–27.

D'Angiulli, S., & Maggi, S. (2003). Development of drawing abilities in a distince population: Depiction of perceptual principles by three children with congenital total blindness. *International Journal of Behavioral Develpment*, pp.193-200.

Daniels, P. (1996). Analog and Digital Writing. In *The World's Writing Systems* (p. 886).

de Aguilera, M., & Mendiz, A. (2003). Video games and education: (Education in the Face of a "Parallel School"). *Computers in Entertainment, 1 Issue 1*. doi:10.1145/950566.950583

Delus, T., Becker, T., Dupont, P., Jang, T., & R., H. (2001). Multichannel vibrotactile display for sensory subsitution during teleoperation. *In Proceedings of SPIE The International Society for Optical Engineering, p. 4570*.

Dickey, D. (2005). Engaging By Design: How Engagement Strategies in Popular Computer and Video Games Can Inform Instructional Design. *53(2), pp. 67-83*.

Dix, A., Finlay, J., Abowd, G., & Beale, R. (2003). *Human-Computer Interaction.* Prentice Hall International.

Dostmohamed, H., & Hayward, V. (2005). Investigation of Elementary Haptic Cues Necessary for Tactile Perception of Shape. *Poster at the 15th Annual Canadian Conference on Intelligent Systems (IS2005).* Quebec City, QC, Canada.

Edman, P. (1992). *Tactile Graphics.* American Foundation for the Blind,.

Edwards, A., McCartney, H., & Fogarolo, F. (2006). Lambda:: a multimodal approach to making mathematics accessible to blind students. *Proceedings of the 8th international ACM SIGACCESS conference on Computers and accessibility. ISBN:1-59593-290-9* . New York City: ACM New York, NY, USA ©2006. doi:10.1145/1168987.1168997

Erwin, E., Perkins, T., Ayala, J., Fine, M., & Rubin, E. (2001). You don't have to be sighted to be a Scientiest, Do you?Issues and Outcomes in Science Education. *Journal of Visual Impairment and Blindness*, pp. 338-352.

EST. (2009). *EST - Engineering Systems Technologies GmbH & Co. KG*. Retrieved October 2009, from CyberGlove Specifications: http://www.est-kl.com/products/data-gloves/cyberglove-systems/cyberglove.html

Evett, L., Brown, D., Battersby, S., Ridley, A., & Smith, P. (2008). Accessible virtual environments for people who are blind - creating an intelligent virtual cane using the Nintendo Wii controller. *Seventh International Conference on Disability, Virtual Reality and Associated Technologies, Nottingham Trent University*, (pp. 271-278). Nottingham.

Fenn, N., McSweeney, M., Silva, C., & Hagy, K. (2009). Educational Computer and Video Games. Towson Univeristy.

Fisher, R., Perkins, S., Walker, A., & Wolfart, E. (2003). *Image Synthesis*. Retrieved November 17, 2008, from Image Processing, Learning Resources: http://homepages.inf.ed.ac.uk/rbf/HIPR2/snthops.htm

Fleming, P., Ball, L., Collins, A., & Ormerod, T. C. (2010). Spatial Representation and Processing in the Congenitally Blind. In S. Ballesteros, & M. Heller, *Touch, blindness, and neuroscience.* Madrid,Spain: UNED Press.

Foley, J. D., van Dam, A., Feiner, S. K., & Hughes, J. F. (1990). *Computer Graphics: Principles and Practice .* Addison-Wesley Professional.

Gardner, J., Suzuki, M., & Yamaguchi, K. (2010). Using two audio-accessible math applications: ChattyInfty and Audio Graphing Calculator. *25th Annual International Technology & Persons with Disabilities .* Northridge, CA.

Gargus, J., Kim, B., Llamas, I., Rossignac, J., & Shaw, C. (2002). *Finger Sculpting with Digital Clay.* Georgia Institute of Technology: Tech. Rep. GIT-GVU-02-22, Center and College of Computing.

Gaver, W. (1994). Using and Creating Auditory Icons. Im G.Kramer (Ed.), Auditory Display - Sonification, Audification and Auditory Interfaces. (pp.417-446). Addison-Wesley.

Gee, J. P. (2004). *What Video Games Have to Teach Us About Learning and Literacy* (Vol. 1). Palgrave Macmillan ©2004.

Gee, J. P. (2004). *Situated Language and Learning: A Critique of Traditional Schooling.* London: Routledge.

Gee, J. P. (2005). *Why Video Games Are Good For Your Soul: Pleasure and Learning.* Melbourne: Common Ground Publishing Pty Ltd.

Gee, J. P. (2007). *Good Video Games and Good Learning: Collected Essays on Video Games, Learning and Literacy.* Tashia Morgridge Professor of Reading, University of Wisconsin-Madison: Peter Lang Publishing.

Gee, J. P., Hull, G., & Lankshear, C. (1996). *The New Work Order: Behind the Language of the New Capitalism.* Allen & Unwin (St. Leonards, NSW).

Gentaz, E., & Hatwell, Y. (2003). Haptic Processing of spatial and material object properties. In A. S. Y. Hatwell, *Touching for knowing* (pp. 123-159). Amsterdam/Philadelphia: John Benjamins Publishing Company.

Gillepse, R., & O'Modhrain, S. (1995). The Moose: A haptic User Interface for Blind Persons with Application to the Digital Sound Studio. *Proc. 3rd WWW6 Conference*, (pp. 37 - 42). Stanford University Department of Music.

Gipson, J. (1966). *The senses considered as perceptual systems.* Boston: Houghton Mifflin.

Gould, J., & Lewis, C. (1985, March). Designing for Usability: Key Principles and What Designers Think. *Communications of the ACM, 28*(3), pp. 300-311. doi:10.1145/3166.3170

Green, D., & Salisbury, J. (1997). Texture Sensing and Simulation Using the PHANToM: Towards Remote Sensing of Soil Properties. *2nd PHANToM Users Group Workshop.* Cambridge Massachusetts Institute of Technology.

Grohn, K. (2008). *User-Centered Design of Non-Visual Audio-Haptics.* Doctoral Thesis, Certec,Rehabiliation Engineering Research, Department of Design Sciences , Lund.

Habgood, M., Ainsworth, S., & Benford, S. (2003). Endogenous Fantasy and Learning in Digital Games. *Simulation & Gaming*, *36*, pp. 483-498.

Haihong, Z., & Wayne, J. (2002). Control Concepts For Digital Clay. *in 2003 IFAC Symposium on Robot Control (SyRoCo),* Georgia Institute of Technology, Atlanta.

Hasser, C., Goldenberg, K., & Rosenberf, L. (1998). User Performance in a gui pointing task with a low-cost force-feedback computer mouse. *In Proceedings of the Asme Dynamic Systems and Control Division: Presented at the 1998 Asme International Mechanical Engineering Congress and Exposition.*

Hatwell, Y., & Martinez-Sarrochi, F. (2003). The tactile reading of maps and drawings and the access of blind people to work of art. In Y. H.-S. F., *Touching for Knowing* (p. 320). Amsterdam/Philadelphia: John Benjamins Publishing Company.

Hatwell, Y., Streri, A., & Gentaz, E. (2003). Congenitally Blindness and Spatial Mental Imagery. In a. Cornoldi C., a. Vecchi T., & M-C, *Touching for Knowing* (pp. 173-187). Amsterdam/Philadelphia: John Benjamins Publishing Company.

Hayward, V., & Robles-De-Lap Torre, G. (2000). Virtual Surfaces and Haptic Shape Perception. *Proc. of the Haptic Interfaces for Virtual Environment abd Teleoperator Systems Symposium, ASME International Mechanical Engineering Congress & Exposition.* Orlando, Florida: USA.

Heller, M., McCarthy, M., & Clark, A. (2005). Pattern Perception and Pictures for the Blind. *Psicológica, 26*, (pp. 161-171).

Herz, J. (1997). *Joystick Nation. How Videogames Are Our Quarters, Won Our Hearts and Rewired Our Minds.* Boston: Little, Brown & Co. Inc.

Immersion, C. (2011). *Immersion*. Retrieved from The Value of Haptics : http://www.immersion.com/docs/Value-of-Haptics_Jun10-v2.pdf

Ittyerah, M., & Marks, L. (2007). Memory for curvature of objects: Haptic touch vs. vision. *British Journal of Psychology, 98*(4), pp. 589–610. doi:10.1348/000712606X171531

Iwata, H. (1990). Artificial Reality with Force-feedback:Development of Desktop Virtual Space with Compact Master Manipulator. *ACM SIGGRAPH, Computer Graphics*.

Iwata, H., Hiroaki, Y., Fumitaka, N., & Ryo K. (2001). Project FEELEX: Adding Haptic Surface to Graphics. *Proc. 28th Ann. Conf. Computer Graphics and Interactive Techniques* (pp. 469-476). Los Angeles, CA: IEEE.

Jackson, G. (1968). *Mathematics at a Grammar School for the Blind.* In Fletcher R.C. (ed) Teaching of Maths and Sciences to the blind. RNIB, London. Retrieved from http://www.rni.org.uk/xpedio/groups/public/documents/visugate/public_teachsci.hscp

Jansson, G., Fanger, J., Konig, H., & Billberger, K. (1998). Visually Impaired Persons' Use of the PHANToM for Information about Texture and 3D form of Virtual Objects. *Proceedings of the Third PHANToM Users Group Workshop*.

Jansson, G., Petrie, H., Colwell, C., Kornbrot, D., Fänger, J., König, H., Billberger,K., Hardwick, A., Furner, S. (1999). Haptic Virtual Environments For Blind People: Exploratory Experiments with Two Devices. International Journal of Virtual Reality, 4, pp. 10-20.

Jessica, R. (2003, April 2). *Haptic technology simulates the sense of touch -- via computer*. Retrieved June 17, 2009, from Stanford University: http://news.stanford.edu/news/2003/april2/haptics-42.html

Jonassen, D. (1988). Integrating learning strategies into courseware to facilitate deeper processing. *In D. Jonassen (Ed.) Instrucional Desings for Microcomputer Courseware*, pp. 151-181.

Kafai, Y. (2001). *The Educational Potential of Electronic Games:From Games–To–Teach to Games–To–Learn*. Retrieved 05 01, 2012, from http://culturalpolicy.uchicago.edu/papers/2001-video-games/kafai.html

Kamuro, S., Minamizawa, K., Kawakami, N., & S., T. (2009). *Pen de Touch*. Retrieved October 2009, from Tachi Lab - Virtual Reality and Telexistence: http://tachilab.org/

Kataria, M., & Tapudum. (2010). Haptics : The Story of Touch. *Electrical Dept. Technical Newspaper, IIT Bombay*.

Kennedy, J. (1993). *Drawing and the Blind: Pictures to Touch.* New Haven, Connecticut: Yale University Press.

Kennedy, J. (1997). How the Blind Draw. *Scientific American*(276), pp. 60-65.

Kennedy, J., & Tipps, S. (1994). Guiding Children's Learning of Mathematics. In 7. Edition. Belmont, California: Wadsworth Publishing Company.

Khatib, O., Brock, O., Chang, K., Ruspini, D., Sentis, L., & Viji, S. (2003). Robots for the Human and Interactive Simulations. *Proceedings of the 11th World Congress in Mechanism and Machine Science.* Tianjin, China: China Machinery Press, edited by Tian Huang.

Klatzky, R. L., & Lederman, S. J. (2000). The haptic identification of common objects. In I. Y. (Eds.) (Ed.), *Touching for Knowing* (pp. 109-128). Paris: Presses Universitaires de France.

Klatzky, R. L., Lederman, S. J., & Metzger, V. (1985). Identifying objects by touch: an 'expert system'. *Perception & Psychophysics, 37*, pp. 299 –302. doi:10.3758/BF03211351

Klatzky, R., & Lederman, S. (2003). The haptic identification of everyday life objects. In Y. Hatwell, A. Streri, & E. Gentaz, *Touching for knowing: cognitive psychology of haptic manual perception*, Vol.53, (pp. 105-121). Amsterdam: John Benhamins Publishing Company.

Klatzky, R., Lederman, S., & Metzger, V. (1985). Identifying objects by touch: An "expert system." Perception & Psychophysics. *Perception and Psychophysics, 37*, pp. 299-302.

Klatzky, R., Lederman, S., & Reed, C. (1987). There's More to Touch Than Meets the Eye: The Salience of Object Attributes for Haptics With and Without Vision. *Journal of Experimental Psychology: General, 116*(4), pp. 356-369.

Klatzky, R., Loomis, J., Lederman, S., Wake, H., & Fujita, N. (1993). Haptic identification of objects and their depictions. *Perception & Psychophysics, 54*, pp. 170-178.

Klingenberg, G. (2007). Geometry: Educational Implications for Children with Visual Impairment. *Norwegian University of Science and Technology*.

Knuth, D. (1984). *The TeX book.* Stanford University: MA:Addison-Wesley.

Kornbrot, D., Penn, P., Petrie, H., Furner, S., & Hardwick, A. (2007). Roughness perception in haptic virtual reality for sighted and blind people. *Perception and Psychophysics, 69*(4), pp. 502-512.

Kramer, G. (1994). An introduction to Auditory Display. *In G.Kramer (Ed.), Auditory Display: Sonification, Audification and Auditory Interfaces* (pp. 1-77). Addison-Wesley.

Kurze, M. (. (1996). TDraw: A Computer-based Tactile Drawing Tool for Blind People. *Proceedings of the Second Annual ACM Conference on Assistive Technologies*, (pp. 131-138). Vancouver, British Columbia, Canada. doi:10.1145/228347.228368

Kurze, M. (1997). Rendering Drawings for the Interactive Haptic Perception. *Proceedings of the SIGCHI Conference on Human factors in Computing Systems* (pp. 423-430). Atlanta, Georgia USA: Proceedings CHI 97. doi:10.1145/258549.258826

Lahav, O. (2006). Using Virtual Environment to Improve Spatial Perception by People Who Are Blind. (doi:10.1089/cpb.2006.9.174., Ed.) *CyberPsychology & Behavior, 9*(2), pp. 174-177.

Lakatos, S., & Marks, L. (1999). Haptic form perception: Relative salience of local and global features. . *Perception and Psychophysics, 61*, pp. 895–908.

Lamport, J. (1985). *Latex: A document Preparation System - Users Guide and Reference Manual.* Reading: MA:Addison-Wesley.

Landau, S., & Gourgey, K. (2003). : A New Approach to Interactive Audio/Tactile Computing: The Talking Tactile Tablet. (C. S. Northridge, Ed.) *Center On Disabilities Technology And Persons With Disabilities Conference*.

Larsen, K. (2005). PHANTOM Desktop and FreeFormModeling System Selected by CADENCE. *Recognition Awarded for Innovative Touch-Based Capabilities in 3D Modeling*.

Lawson, R., & Bracken, S. (2011). Haptic object recognition: how important are depth cues and plane orientation? *Perception, 40*, pp. 576-597.

Lederman, S. J. (1981). Perception of surface roughness by active and passive touch. *Bulletin of the Psychonomic Society, 18*(5), pp. 253-255.

Lederman, S. J., & Klatzky, R. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology, 19*, pp. 342-368.

Lederman, S. J., & Klatzky, R. (1997). Relative availability of surface and object properties during early haptic processing. *Journal of Experimental Psychology: Human Perception & Performance, 23*, pp. 1680-1707.

Lederman, S. J., & Klatzky, R. (2004). Haptic identification of common objects:Effects of constraining the manual exploration process. *Perception & Psychophysics, 66* (4), pp. 618–628.

Lederman, S. J., & Klatzky, R. (2009). Haptic perception: A tutorial. *Attention, Perception, and Psychophysics , 71*(7), pp. 1439–1459.

Lederman, S. J., & Taylor, M. (1972). Fingertip force, surface geometry and the perception of roughness by active touch. *Perception and Psychophysics, 12*(5), pp. 401-408.

Lederman, S. J., Klatzky, R., Chataway, C., & Summers, C. (1990). Visual mediation and the haptic recognition of two-dimensional pictures of common objects. *Perception & Psychophysics,, 47*, pp 54-64.

Lepper, M., & Malone, T. (1987). Intrinsic Motivation and Instructional Effectiveness in Computer-Based Education. *Aptitude, Learning and Instruction: III. Conative and affective process analyses* (pp. 255-286). In R. E. Snow & M. J. Farr (Eds.),Hilsdale, NJ: Erlbaum.

Liu, C., & Kennedy, J. (1993). Symbolic Forms and Cognition. *14(2)*, pp. 441–456.

Loftus, G., & Loftus, E. (1983). Mind at play. The psychology of video games. New York:Basic Books.

Loomis, J. (1990). A model of character recognition and legibility. *Journal of Experimental Psychology: Human Perception & Performance, 16*, pp. 106-120.

Lotzsch, J. (1994). Computer-Aided Access to Tactile Graphics for the Blind. *4th International Conference on Computers for Handicapped Persons (ICCHP)* (pp. 575-581). Vienna: Berllin: Springer (Lecture Notes in Computer Science 860).

Magee, L., & Kennedy, J. (1980). Exploring pictures tactually. *Nature, 283*, pp. 287-288.

Magnusson, C., & Gröhn, K. (2005). Audio haptic tools for navigation in non visual environments. *Proceedings of ENACTIVE05, 2nd International Conference on Enactive Interfaces.*

Magnusson, C., Rassmus- Gröhn, K., Sjostrom, K., & Danielsson, H. (2002). Navigation and Recognition in Complex Haptic Virtual Environments - Report form an Extensive Study with Blind Users. *,Eurohaptics.* Edinburgh, UK: In S.A. Wall, B.Riedel, A. Crossan & M.R.McGee (Eds.).

Malone, T. (1980). *What makes things fun to learn? A study of intrinsically motivating computer games.* Palo Altao, CA: Xerox Palo Alto Research Center: Report CIS-7.

Malone, T. (1981). Towards a theory of intrinsically motivating instruction. *Cognitive Science, 4*, pp. 333-369.

Malone, T., & Lepper, M. (1987). Making Learning fun: A taxonomy of intrinsic motivations for learning. *Aptitute, learning and instruction: III. Conative and affective process analyses* (pp. 223-253). In R.E. Snow & M.J.Farr(Eds.), Hilsdale, NJ:Lawrence Erlbaum.

Massie, T., & Salisbury, K. (1994). The PHANToM Haptic Interface: A Device for Probing Virtual Objects. *ASME Winter Annual Meeting, DSC-Vol. 55-1, ASME. 55 (1)*, pp. 295-300. Chicago: In Dynamic Systems and Control 1994.

McGee, M. (2003). *Investigating a multimodal solution for improving force feedback generated textures.* The Univeristy of Glasgow: Doctoral Thesis, Department of Computing Science.

Miguel, A., Otaduy, N., Avneesh, S., & Ming, C. L. (2004). Haptic Display of Interaction between Textured Models. *Proc. of IEEE Visualization*, pp. 297–304.

Millar, S. (1997). *Reading by Touch.* London: Routledge.

Millen, L., Hawkins, T., Cobb, S., Zancanaro, M., Glover, T., Weiss, L., & Gal, E. (2011). Collaborative technologies for children with autism. *IDC '11 Proceedings of the 10th International Conference on Interaction Design and Children* (pp. 246-249). ACM New York, NY, USA ©2011 . doi:10.1145/1999030.1999073

Monkman, G. (1992). An Electrorheological Tactile Display. *Presence (Journal of Teleoperators and Virtual Environments), MIT Press, 1*(2), 219-228.

Morelli, A. (2010). Haptic/Audio Based Exergaming for Visually Impaired Idividuals. (96),pp. 50- 53. doi:10.1145/1731849.1731859

Navy, C. (1993). *The History of the Nemeth Code: An Interview with Dr. Abraham Nemeth.* Retrieved 03 02, 2013, from National Federation of the Blind, Voice of Nation's Blind. Issue '93, Raised Dot Computing Newsletter: https://nfb.org/images/nfb/publications/fr/fr28/fr280110.htm

Nikolakis, G., Tzovaras, D., & M.G., S. (2005). Object Recognition for the Blind. *Informatics and Telematics Institute, Centre for Research and Technology Hellas*.

Nikolakis, G., Tzovaras, D., Moustakidis, S., & Strintzis, G. (2004). CyberGrasp and PHANTOM Integration: Enhanced Haptic Access for Visually Impaired Users. *SPECOM'2004: 9th Conference Speech and Computer.* St. Petersburg, Russia.

Norman, J., Dawson, T., & Raines, S. (2000). The perception and recognition of natural object shape from deforming and static shadows. *Perception, 29*, pp. 135–148.

Norman, J., Norman, H., Clayton, A., Lianekhammy, J., & Zielke, G. (2004). The visual and haptic perception of natural object shape. *Perception and Psychophysics, 66*, pp. 342–357.

Novint Technologies Inc. (2008). *Novint Falcon*. Retrieved May 2010, from http://home.novint.com/products/novint_falcon.php

O'Modhrain, S., & Gillespie, E. (1997). The Moose: A Haptic User Interface for Blind Persons. *In Third WWW6 Conference*, (pp. 37-42).

Ostad, S. (1989). *Mathematics through the fingertips. Basic mathematics for the blind pupil: Development and empirical testing of tactile representations.,.* University of Oslo, Oslo.: Norwegian Institute of Special Education.

Pakkanen, T., & Raisamo, R. (2004). Perception strategies in modal-redistributed. *Proc. World Haptics 2005* (pp. 641-644). Pisa, Italy: IEEE Press.

Paterson, M. (2006). Seeing with the hands: Blindness, touch and the Enlightment spatial imagery. *The British Journal of Visual Impairement*, pp. 52-59.

Penn, P., Petrie, H., Colwell, C., Kornbrot, D., Furner, S., & Hardwick, A. (2000). The perception of texture, object size, and angularity by touch in virtual environments with two haptic devices. *Proc. Haptic Human-Computer Interaction Workshop*, (pp. 92 -97).

Petridou, M., Alabbadi, R., & Blanchfield, P. (2011). The Development of Educational Interactive Virtual Environments for Children with Low or No Vision. *Interactive Technologies and Games: Education, Health and Disability.* Nottingham, UK.

Petridou, M., Blanchfield, P., Alabadi R., & Brailsford, T. (2011). User Centred Design and Development of an Educational Force Feedback Haptic Game for Blind Students. *Proceedings of ECGBL 2011 The 5th European Conference on Games Based Learning.* Athens: ACI.

Petridou, M., Brailsford, T., & Blanchfield, P. (2011). Involving the User with Low or No Vision in the Design of an Audio-Haptic Learning Environment for Learning about 3D Shapes. *Computer Science and Electronic Engineering Conference (CEEC 2011)* (pp. 29-34). Essex UK: IEEE.

Petrie, H., Kornbrot, D., Hardwick, A., & Furner, S. (1998). Haptic Virtual Reality for Blind Computer Users. *Proceedings 1998 3rd Internationl ACM Conference Assistive Technologies* (pp. 92-99). ASSETS '98.

Petrie, H., O'Neill, A., & Colwell, C. (2002). Computer Access by Visually Impaired People. In (Eds.)A. Kent, & J. Williams, *Encyclopedia of Microcomputers* (Vol. 28). New York: Marcel Dekker.

Plant, T. (1995). Game over! Let’s get on with the real work, in Ability. *Journal of the British Computer Society Disability Group*(15), pp. 17-18.

Prensky, M. (2001). *Digital game-based learning.* New York: McGraw-Hill.

Presley, I., & D’Andrea, F. M. (2008). *Assistive Technology for Students Who Are Blind or Visually Impaired.* New York: AFB Press.

Provenzo, E. (1992). What do video games teach? *Education Digest*, 58(4), 56-58.

Reed, C., Klatzky, R., & Halgren, E. (2006). What" vs. "Where" in Touch: An fMRI study. *NeuroImage*, pp. 672–680.

Reiber, L., & Matzko, M. (2001). Serious design of serious play in physics. *Educational Technology, 41(1)*, pp. 14-24.

Riener, R., & Harders, M. (2012). Auditory Aspects. In *Virtual Reality in Medicine* (pp. 131-147). Springer London. doi:10.1007/978-1-4471-4011-5_5

Rouzier, S., Hennion, B., Perez, S., & Chene, D. (2004). Touching Geometry for Blind Pupils. *Proceedings of EuroHaptics 2004*, (pp. 697-704). Munich Germany.

Ruspini, D. (2003). Beyond the looking glass: the haptic exploration of virtual environments. California, USA: PhD Thesis Dept. Computer Science, Stanford University.

Salisbury, J., & Mandayam, A. (1997, September). Phantom-Based Haptic Interaction with Virtual Objects. *IEEE Computer Graphics and Applications, 17*, 6-10. doi:10.1109/MCG.1997.1626171

Sarama, J., & Douglas, H. C. (2002). Design of Microworlds in Mathematics and Science Education. *Journal of Educational Computing Research, 27*(1), pp. 1-5.

Savery, J., & Duffy, T. (1995). Problem Based Learning: An instructional model and its constructivist framework. *Educational Technology, 35*(5), pp. 31-37.

Schmitz, B., & Ertl, T. (2012). Interactively Displaying Maps on a Tactile Graphics Display. *Proceedings of the international Workshop on Spatial Knowledge Acquisition with Limited Information Displays (SKALID).* Institute for Visualization and Interactive Systems, Universitat Stuttgart.

Serafin, C., Heers, R., Tschirhart, M., Ullrich, C., & Ramstein, S. (2007). User Experience in the US and Germany of in-vehicle touch screens. SAE World Congress 2007.

Sharp, H., Rogers, Y., & Preece, J. (2002). *Interaction Design: Beyond Human-Computer Interaction* . John Wiley and sons.

Shimizu, Y., Saida, S., & Shimura, H. (1993). Tactile Pattern Recognition by Graphic Display: Importance of 3-D Information for Haptic Perception of Familiar Objects. *Perception and Psychophysics*, pp. 43-48.

Sinclair, J., Hingston, P., & Masek, M. (2007). Considerations for the design of exergames. In W. A. In GRAPHITE 2007 (Perth (Ed.), *Proceeding GRAPHITE '07 Proceedings of the 5th international conference on Computer graphics and interactive techniques in Australia and Southeast Asia* (pp. 289-295). ACM New York, NY, USA ©2007 . doi:10.1145/1321261.1321313

Sjoberg, H., & Ylinenpaa, O. (2009). *Collision Detection for Haptic Rendering.* Umea University, Sweden: Master's Thesis.

Sjöström, C. (1997). The Phantasicon - Haptic Interfaces Give New Possibilities for Blind People. Master's Thesis. Certec, Lund University Sweden.

Sjöström, C. (1999). *The IT Potential of Haptics – Touch Access for People with Disabilities.* Sweden: Licentiate Thesis, Certec, Lund University.

Sjöström, C. (2000). Designing Haptic Computer Interfaces for Blind People. *Proceedings of the Sixth IEEE International Symposium on Signal Processing and its Applications.* Kuala Lumpur, Malaysia: IEEE.

Sjöström, C. (2001). Designing Haptic Computer Interfaces for Blind People. *Certec Lund University*.

Sjöström, C. (2001). Using Haptics in Computer Interfaces for Blind People. *ACM SIGCHI Conference on Human Factors in Computing Systems.* Seatle, USA: CHI 2001.

Sjöström, C., & Jönsson, B. (1997). To Use the Sense of Touch Control a Computer and the World Around You. *Proc. of the AAATE conference.* Thessalonica,Greece.

Sjöström, C., Danielsson, H., Magnusson, C., & Rassmus-Grohn, K. (2003). Phantom-based haptic line graphics for blind persons. *Visual Impairment Research, 5*(1), pp. 13-32.

Squire, K. (2002). Cultural Framing of Computer/Video Games. *The International Journal of Computer Game Research, 2*(1). Retrieved from Available: http://www.gamestudies.org/0102/squire/

Squire, K. (2003). Video Games and Education: Designing learning systems for an interactive age. *International Journal of Intelligent Simulations and Gaming, 2(1)*, pp.49-62.

Stedmon, A., Sharples, S., & Cobb, S. (2007). *Sound And Tangible Interfaces for Novel product design.* University of Nottingham, UK, Politecnico di Milano It, Technische Universiteit Eindhoven NL, Nottingham.

Stevens, R., Alistair, D., & Harling, P. (1996, April 11-12). Access to mathematics for visually disabled students through multimodal interaction. *Proceedings of the second annual ACM conference on Assistive technology, 12*(1), pp. 64-71. doi:10.1207/s15327051hci1201&2_3

Szymkiewicz, K., Magnusson, C., Gröhn, K., & Karic, E. (2008). Avatar Control and World Interaction in a Non-Visual 3D Gaming Environment. *ENACTIVE 08.* Pisa,Italy.

Tachi, S., Maeda, T., Hirata, R., & Hoshino H. (1994). A construction method of virtual haptic space. *Proc. of International Conference on Artificial Reality and Tele-existence*, (pp.131-138). Tokyo.

Tanti, M. (2007). Teaching Mathematics to a Blind Student - A Case Study. (P. Ernest, Ed.) *Philosophy of Mathematics Education Journal No. 20*.

Thompson, L., & Chronicle, E. (2006). Beyond visual conventions: Rethinking the design of tactile diagrams. *The British Journal of Visual Impairement*, pp. 76-82.

Toro-Troconis, M., Meeran, K., Higham, J., Mellström, U., & Partridge, M. (2010). Design and Delivery of Game-Based Learning for Virtual Patients in Second Life: Initial Findings. In K. M. Maria Toro-Troconis, *Researching Learning in Virtual Worlds* (pp. 111-138). Springer Link. doi:10.1007/978-1-84996-047-2_7

Tsung-Yen, C., & Wei-Fan, C. (2007). Digital Games for Cognitive Learning: A Pilot Study. *Journal of Scientific and Technological Studies, 41*(1), pp. 17-27.

Tzovaras, D. (2008). *Multimodal User Interfaces: From Signals to Interaction.* Thessaloniki Greece: Springer . doi:10.1007/978--3-540-78345-9

Ulfvengren, P. (2003). Desing of natural warning sounds in human-machine systems.PhD Thesis Man-Machine Systems. Industrial Economics and Management, KTH Sweden.

Ungerleider, L., & Mishkin, M. (1982). Two cortical visual systems. In M. Press (Ed.), *Analysis of visual behavior* (pp. 549-586). Cambridge, MA: MIT Press: In D.J. Ingle, M.A. Goodale, & R.J.W. Mansfield (Eds.).

Van, E., Jan, B., Hendrik, A., Van, V., Jansen, C., & Trevor, D. (2005). Waypoint Navigation with a Vibrotactile Waist Belt. *ACM: Transactions on Applied Perception (TAP). 2*, pp. 106-117. 2. doi:10.1145/1060581.1060585

Vanderheiden, G. (1996). Use of audio-haptic interface techniques to allow nonvisual access to touchscreen appliances. *In Human Factors and Ergonomics Society Annual Conference Proceedings*, *40*, p. 1266.

Vandewater, E., Shim, M., & A, C. (2004). Linking obesity and activity level with children's television and video game use. *In The Journal of Adolescence, 27*(1), pp. 71--85.

Veltman, K. (1997). Frontiers in electronic media. *Interactions, 4*(4), pp. 32-64. doi:10.1145/259330.259353

Wikipedia. (2011). *Novint*. Retrieved May 5, 2011, from Novint: http://en.wikipedia.org/wiki/Novint

Winberg, F., & Hellstrom, S. (2003). Designing Accessible Auditory Drag and Drop. *Proceedings of the the 2003 Conference on Universal Usability (CUU2003).* Vancouver, Canada.

Wood, J., Magennis, M., Arias, E., Gutierrez, T., Graupp, H., & Bergamasco, M. (2003). the Design and Evaluation of a Computer Game for the Blind in the GRAB Haptic Audio Virtual Environment. *In Proceedings of Eurohaptics 2003 .* Dublin, UK.

Ye, G., Corso, J., Hager, G., Allison, M., & Okamura, A. (2003). Vishap: Augmented reality combining haptics and vision. *In Proceedings of IEEE International Conference on Systems, Man and Cybernetics*, (pp. 3425–3431).

Yu, W., Ramloll, R., & Brewster S.A. (2000). Haptic Graphs for Blind Computer Users. *Proceedings of the First International Workshop on Haptic Human-Computer Interaction*, pp. 41-51.

Zyga, L. (2009). *Touchable Hologram Becomes Reality (w/ Video)*. Retrieved 03 02, 2013, from http://phys.org/news168797748.html