Non-Visual Haptic Interaction Design - Guidelines and Applications

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Abstract

This dissertation has three cornerstones:

- Haptics
- Human-Computer Interaction (HCI)
- Blind Users

Haptics deals with controlling human movements and getting feedback through the sense of touch. A haptic interface transmits forces to a person's hand or fingers in a way that mimics the sensation of touching real objects. Virtual haptic touch can be particularly useful for people with visual impairments. It makes it possible for a blind person to touch virtual objects, corresponding to the way a sighted person can see objects on a computer screen.

The goal of this research was to carry out an unbiased investigation of the potential of this technology for blind people. The more specific aims were to:

- Investigate if and how blind people's computer usage can be improved by virtual haptics.
- Investigate the problems that arise with graphical user interfaces for blind people and how these problems can be managed with haptics.
- Develop new applications and find new areas in which virtual haptics can be applied for blind people.

The design process has been primarily influenced by theories of usability engineering and reflection in action/reflection on action, focusing on the role of the engineer-designer. A concerted effort is made to use technology as a language to communicate with the users.

Several haptic interface devices have been involved. The Phantom from SensAble Technologies has been used the most. It is a small robot with a thimble or stylus attached to the tip which supplies force feedback to the user. The others are the FEELit Mouse from Immersion and the force feedback joysticks from Logitech and Microsoft.

Eighteen test applications were developed over five years' time. They included games, curves, textures, drawings, menus, floor plans, and geometrical objects. Formal and informal user tests were performed on blind, blind-deaf and sighted people.

One of the key results presented are five guidelines for non-visual haptic interaction design for researchers, designers, testers, developers and users of such applications. The guidelines are:

- Elaborate a virtual object design of its own
- Facilitate navigation and overview
- Provide contextual information
- Utilize all available modalities
- Support the user in learning the interaction method and the specific environments and programs

These guidelines represent the filtered and condensed knowledge and experience that the Haptics Group at Certec has gained during the testing and development process. They are further delineated and are a complement to existing HCI guidelines.

This work shows that there is great potential in using haptic technology in applications for blind people. It is viable to translate both 2D and 3D graphical information and make it comprehensible via haptics. It has been demonstrated that a blind person can orientate and navigate in a virtual haptic environment and that these tasks can be further supported by using complementary information such as sound and Braille. It is also possible for a blind person to use knowledge gained in the virtual world for real life orientation.

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Preface

As long as I can remember I have been involved in these *total commitment projects* that take all of your time and sometimes even more. In the summer of 2000 my wife and I married after 10 years together. That was something special; the feeling is *really* overwhelming but it is also so much work. Anyone who has arranged a wedding knows how much planning it takes. In the summer of 2001 I was in the organizing team of a scout camp in Sweden with 26,500 participants from all over the world. That was huge. Try to imagine 26,500 people setting up camp in a gigantic field all in one day: from oceans of grass in the morning to thousands of tents in the evening. And then try to imagine arranging the daily program for all of these scouts. Such an experience stays with you for a long time. This summer I have basically used every moment of my waking hours to finish this dissertation. I keep saying to myself, "It will be better after…" but it hasn't happened yet. There is always a new project to jump into, and who wants to miss a once-in-a-lifetime experience? Not me anyway. I really wonder what I will be doing next summer…

I want to express my deepest and most sincere gratitude to my wife Marika. Your help and support on all levels has been totally essential.

I also want to thank my advisors Professor Bodil Jönsson and Assistant Professor Charlotte Magnusson.

My daily work would not have been at all the same without my colleagues Kirre Rassmus-Gröhn and Henrik Danielsson. Thank you both! And a special thanks to Henrik for your critical reading.

Thanks also to Peter Kitzing, MD for all your right-on-the-mark comments that helped to improve the text considerably.

And thanks to Eileen Deaner for *wonderful* help and cooperation with all the aspects of the English language.

Thanks to all of you who have assisted me in making this trip a unique experience.

I am also grateful to the organizations that have provided financial support for this research:

The vast majority of this work has been financed by project grants from The Swedish Transport and Communications Research Board (KFB).

The Enorasi Project user tests were financed by The European Union, Fifth Framework, IST.

A renewal of our haptics lab was financed by the Crafoord Foundation in Lund, Sweden.

The early work in haptics at Certec was financed by the following Swedish foundations and organizations:

- The Swedish Committee for Rehabilitation Foundation (Stiftelsen Svenska kommittén för rehabilitering) and the Helfrid and Lorentz Nilsson's Foundation.
- Swedish National Agency for Special Needs Education (Statens institut för handikappfrågor i skolan – SIH)
- Norrbacka-Eugenia Foundation via the Swedish Handicap Institute (Handikappinstitutet).
- Alfred and Ebba Piper's Fund.

Later work has been funded by Certec and Region Skåne (the county council of Skåne, the southernmost part of Sweden).

Summary

This dissertation has three cornerstones:

- Haptics
- Human-Computer Interaction (HCI)
- Blind Users

Certec is the Division of Rehabilitation Engineering Research, Department of Design Sciences, Lund Institute of Technology, Lund University, Sweden. Certec's research focuses on the meeting between the needs, wishes and dreams of people with disabilities on one hand and technological and educational concepts on the other. Normally we start with the person and try to find technical solutions that match his or her needs. In our work with haptics, though, it all started from the other direction: we were given the opportunity to work with virtual touch per se. But we quickly realized that this technology could be of great use and enjoyment for people with disabilities.

Certec started to work with the Phantom, a haptic interface device, from SensAble Technologies Inc. in early 1995, to gain experience in working with virtual haptic touch.

Our first concept of touch-enabled applications for disabled children was called Fantomaten®, in English "The Phantasticon". The purpose of developing the Phantasticon out of the Phantom was to give people, above all children with different disabilities, new touch sensations as a compensation for the deficiencies they had in seeing or touching things in other ways.

Haptics deals with controlling human movements and getting feedback through the sense of touch. A haptic interface transmits forces to a person's hand or fingers in a way that mimics the sensation of touching real objects. This makes it possible for the person to touch virtual objects, corresponding to the way a sighted person can see objects or pictures on a computer screen. Virtual haptic touch can be particularly useful for people with visual impairments. Graphical information and computer games can be made accessible for those who are blind via the sense of touch.

The overall goal of this research was to carry out an unbiased investigation of the potential of this technology for blind people. The more specific aims were to:

1. Investigate if and how blind people's computer usage can be improved by virtual haptics.
2. Investigate the problems that arise with graphical user interfaces for blind people and how these problems can be managed with haptics.
3. Develop new applications and find new areas in which virtual haptics can be applied for blind people.

I have used several different haptic interface devices: The Phantom from SensAble Technologies is the device that we have used the most at Certec but I have also used the FEELit Mouse from Immersion and force feedback joysticks from Logitech and Microsoft.

Technically the Phantom is a small robot with very low back drive friction. The standard A-model Phantom has three full degrees of freedom, i.e., three motors and three encoders. The tip of the robot is attached to a stylus or thimble via a passive gimbal that allows rotational movements. The normal use of the Phantom, however, is the opposite of a robot's: the user holds on to the stylus (or puts a finger in the thimble) in the end of the robot arm and moves it; the robot provides feedback to the user by applying forces via the stylus.

Two Software Development Kits (SDKs) for the Phantom have been commercially available for some time now. They are GHOST by SensAble Technologies Inc. (Boston, Massachusetts) and the Reachin API by Reachin AB (Stockholm). A third SDK for haptic development: e-Touch SDK by Novint Technologies (Albuquerque, New Mexico) is currently available as a beta version.

When we started our haptics work, none of these SDKs or APIs were available so we made our own simple object-oriented package to start with. We started using GHOST as soon as the first beta version was available (in 1997), and since 2001 we have also been using the Reachin API. All the APIs described here constitute a huge leap forward compared to the essentially force level programming that we had to carry out in the beginning.

Eighteen test applications have been developed and formal and informal user tests have been performed. The tests are:

Submarines

Haptic variant of the well-known battleship game.

Device:	The Phantom
Tests:	Tried out by at least 20 blind children, at least 5 deaf-blind persons and at least 50 sighted persons. No formal testing.

Paint with Your Fingers

Different colors are associated with different textures so that you can feel what you are painting.

Device:	The Phantom
Tests:	Tried out by at least 20 blind children and at least 50 sighted persons. No formal testing.

Early Mathematics Program

The program makes it possible to feel a mathematical curve with the Phantom.

Device:	The Phantom
Tests:	Tried out by at least 20 blind children and at least 50 sighted persons. No formal testing.

The Memory House

A combined haptic and audio memory game with 12 sound pairs and one "Old Maid".

Device:	The Phantom
Tests:	Tested by 9 blind persons and tried out by many more blind and sighted persons.

Haptics in Collaborative Virtual Environment

Shared haptic virtual environment with cubes that can be manipulated by one or two users together. Vision and speech communication were also used.

Device:	The Phantom
Tests:	Tested by 28 persons in 14 groups.

FEELit Desktop + Synthetic Speech and Braille

Program from Immersion that makes the objects on Windows desktop touchable. Combined with synthetic speech and Braille in these tests.

Device:	The FEELit Mouse
Tests:	Pilot testing with two blind persons. Tried out in informal tests as well.

Radial Haptic Menus

Program for testing radial haptic menus in a Windows-like environment using haptics and speech.

Device:	The FEELit Mouse
Tests:	Pilot testing with two blind persons. Tried out in informal tests as well.

Virtual Haptic Search Tools

Program for virtual haptic search tools in a Windows-like environment.

Device:	The FEELit Mouse
Tests:	Pilot testing with two blind persons. Tried out in informal tests as well.

Mathematics – Herbivores and Carnivores

Mathematic curve displaying program viewing simulation of herbivores and carnivores on an isolated island.

Device:	The Phantom
Tests:	Tested by 24 blind persons.

Textures

Simulations of real textures such as wood, corduroy fabric, sandpaper and linen cloth.

Device:	The Phantom
Tests:	Tested by 25 blind persons.

Line Drawings

Black and white line drawings represented as haptic reliefs.

Device:	The Phantom
Test:	Tested by 24 blind persons.

Floor Plans

Floor plans represented as haptic reliefs with sound labels.

Device:	The Phantom
Tests:	Tested by 23 blind persons.

Geometrical Objects

Recognition of geometrical objects, such as cubes, semi-cylinders and spheres.

Device:	The Phantom
Tests:	Tested by 25 blind persons.

VRML Objects

Recognition and discussion of virtual representation of real life objects.

Device:	The Phantom
Tests:	Tested by 24 blind persons.

Traffic Environment

Virtual training and game environment with houses, roads and cars.

Device:	The Phantom
Tests:	Tested by 21 blind persons.

Sound Memory Game

Two combined haptic and audio memory games with three and six sound pairs respectively.

Device:	The Phantom
Tests:	Tested by 25 blind persons.

Mathematical Surface

Mathematic graphing program. Equations are entered as text. The resulting surface is rendered haptically.

Device:	The Phantom
Tests:	Tested by 7 blind persons with interest and knowledge in mathematics.

Follow-up Experiments on Haptic Interaction Design Guidelines

Different variations of haptic/audio memory games with six sound pairs. Testing interface widget design, reference points and haptic grid as navigational help.

Device:	The Phantom
Tests:	Tested by 10 blindfolded sighted persons.

The design process that I have used during this haptics research can be described as being primarily influenced by the usability engineering described by Nielsen [1993] and the reflection in action/reflection on action as described by Schön in *The Reflective Practioner* [1983]. I try to work both as an artist-designer and an engineer-designer but my focus in the research for this dissertation is on the engineer-designer's role.

I try to use *technology as a language* to communicate with the users and most often experience the outcome of this to be more fruitful than ordinary questionnaires and lengthy product specifications on paper – this way the user and the engineer have a common fixed point in the technology.

The guidelines are one of the key results presented in this dissertation. The first version of the guidelines was presented in my licentiate thesis[1] in December 1999. Since then I have reworked and updated the guidelines and published them separately at CHI 2001 and ISSPA 2001. For this dissertation the guidelines have been reworked even further, on the basis of new material and new results.

To come up with the guidelines, I have filtered, condensed and processed the knowledge and experience that the Haptics Group at Certec has gained during the testing and development. The experience is backed up with reasoning taking observed problems as a starting point, results from other researchers and followup experiments.

The guidelines presented here are intended for use when designing haptics interfaces. It is important to note that principles that guide the design of traditional interfaces, such as Schneiderman's "Eight Golden Rules" [1998], Bruce Tognazzini's list of basic principles for interface design [2001] or Nielsen's "Ten Usability Heuristics" [2002], still apply. The guidelines I propose can in principle be used *in addition* to other HCI guidelines, not *in place* of them.

Since these are meant to be design guidelines, the target groups are researchers, designers, testers, developers and users of applications that use haptics in some form. The guidelines are presented here with key issues concerning each guideline:

Guideline 1: Elaborate a virtual object design of its own

- Avoid objects with small and scattered surfaces. Objects with large connected surfaces are easier to find and explore.
- Use rounded corners rather than sharp ones.
- Virtual objects in virtual worlds can be given virtual properties. Utilize them.
- Optimize your haptic interface widgets as well. Think about affordance.
- Make sure that the models are haptically accurate and work without vision.
- Be aware that orientation of the object matters.

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[1] A LICENTIATE IS A GRADUATE DEGREE NORMALLY REQUIRING 2-3 YEARS' GRADUATE WORK AND IS AN INTERMEDIATE STAGE BETWEEN A MASTER'S AND PH.D.

- Consider different representations to enhance different properties (negative relief emphasizes the line whereas positive relief emphasizes the contained surface).

Guideline 2: Facilitate navigation and overview

- Provide well defined and easy-to-find reference points in the environment.
- Avoid changing the reference system.
- Make any added reference points easy to find and to get back to. They should also provide an efficient pointer to whatever they are referring to.
- Utilize constraints and paths, but do so with care.
- Virtual search tools can also be used.

Guideline 3: Provide contextual information

- Provide contextual information from different starting points:
  - Present the haptic model or environment in its natural context.
  - Provide information about the purpose of the program.
  - Provide information about possibilities and pitfalls in the environment.
- Use a short text message such as a caption to an image or model, provided as speech or Braille. This can make a significant difference.
- Idea:
  Consider using an agent or virtual guide that introduces the user to the object and also gives additional information if requested.

Guideline 4: Utilize all available modalities

- Combine haptics with sound labels, a Braille display and/or synthetic speech for text output.
- Try environmental sound to aid in getting an overview.
- Use audio (both sound labels and environmental sound) to provide a context.
- Provide feedback to the user via any available sense.

Guideline 5: Support the user in learning the interaction method and the specific environments and programs

- Be consistent; limit the number of rules to remember.
- Give clear and timely feedback on the user’s actions.

- Facilitate imitating of other users and situations if possible.
- Develop elaborated exercises to make the handling of the interaction tools and methods automatic in the user.
- Idea:
  Consider using a virtual guide or remote users to help when a user comes to a new environment.

This work shows that there is a great potential in using haptic technology in applications for blind people. It is viable to translate both 2D and 3D graphical information (such as line drawings, VRML models, floor plans etc.) and to make it comprehensible via haptics. It has been demonstrated that it is possible for a blind person to orientate and navigate in a virtual haptic environment and that these tasks can be further supported by using complementary information such as sound and Braille text. It is also possible for a blind person to use knowledge gained in the virtual world for real life orientation. Taken together, this means that it is definitely possible to make both a Windows system and applications with multimodal haptic interfaces.

The potential for haptics is also great in the education of blind children: Our haptic mathematics viewer has attracted a large interest among the blind people who have tried it even though many of them did not think that mathematics was particularly interesting from the start. The application simply makes mathematics more fun (or for some, at least less boring). Multimodal haptic games such as Submarines can be used to make scientific concepts (like coordinate systems in that case) more interesting to blind children. With haptic technology it is possible to make completely new kinds of computer games for blind children, which can be used both for fun and learning. I am sure that the knowledge gained in this work along with a skilled low vision teacher would be an excellent foundation for many interesting applications including haptic technology that could really add something new to the education of blind children.

A multimodal haptic Internet browser would alleviate the problems of certain web pages, especially those that make heavy use of graphics. I present a suggestion for designing such a browser using the outcomes from this work.

This dissertation is based on the following articles, included as appendices:

The sense of touch provides new computer interaction techniques for disabled people
Calle Sjöström, Kirre Rassmus-Gröhn
Technology and Disability, Volume 10, No 1, pp 45-52, IOS Press, 1999.

Supporting Presence in Collaborative Multimodal Environments by Haptic Force Feedback
Eva-Lotta Sallnäs, Kirre Rassmus-Gröhn, Calle Sjöström
ACM Transactions on Computer-Human Interaction (To CHI), Volume 7 Issue 4, pp 461-476, ACM, 2000.

Designing Haptic Computer Interfaces For Blind People
Calle Sjöström
Proceedings of the Sixth IEEE International Symposium on Signal Processing and its Applications, Kuala Lumpur, Malaysia, August 13 – 16, 2001.

Haptic Representations of 2D Graphics for Blind Persons
Calle Sjöström, Henrik Danielsson, Charlotte Magnusson, Kirsten Rassmus-Gröhn
Submitted to Haptics-E, the Electronic Journal of Haptics Research, 2002.

Navigation and Recognition in Complex 3D Haptic Virtual Environments
Charlotte Magnusson, Calle Sjöström, Kirsten Rassmus-Gröhn, Henrik Danielsson
Submitted to Haptics-E, the Electronic Journal of Haptics Research, 2002.

1. Aim

The overall goal of this research was to carry out an unbiased investigation of the potential of haptic technology for blind people. The work on which this dissertation is based is intended to bridge the gap between traditional assistive technology for blind people and the area of haptics research. The more specific aims were to:

- Investigate if and how blind people's computer usage can be improved by virtual haptics.
- Investigate the problems that arise with graphical user interfaces for blind people and how these problems can be managed with haptics.
- Develop new applications and find new areas in which virtual haptics can be applied for blind people.

2. Background

Certec is the Division of Rehabilitation Engineering Research, Department of Design Sciences, Lund Institute of Technology, Lund University, Sweden. Certec's research focuses on the meeting between the needs, wishes and dreams of people with disabilities on the one hand and technological and educational concepts on the other. Normally we start with the person and try to find technical solutions that match his or her needs. In our work with haptics, though, it all started from the other direction: we were given the opportunity to work with virtual touch per se. But we quickly realized that this technology could be of great use and enjoyment for people with disabilities.

Our work with applications using virtual touch for blind persons started with games and educational programs especially for blind children. We also worked with the possibility of making graphical information and computer games accessible to blind persons via the sense of touch. A key issue is whether it is possible to obtain an overview of a virtual environment (for example a computer screen) via haptic interaction.

Certec started to work with the Phantom, a haptic interface device from SensAble Technologies Inc., in early 1995. Since then, a more or less formal group of researchers at Certec has been working with haptics for people with disabilities. My first work with the Phantom was a haptic battleship game, *Submarines,* that includes audio. The game was developed in the summer of 1995. I have been working with haptics since then, from 1997 as a Ph.D. student. Dr Charlotte Magnusson and Kirre Rassmus-Gröhn have also been active in the Haptics Group. In 2000/2001 we joined the EU Enorasi Project on haptic virtual environments for blind people. I was the Certec representative on the Enorasi Project Technical Committee and Dr Magnusson was the representative on the Project Policy Board. At that time we also expanded the Haptics Group to include Henrik Danielsson.

2.1 The Original Project Idea: "The Phantasticon"

In the summer of 1994 Karin Jönsson and Ulf Larsson, from HADAR in Malmö, Sweden who were working with computer adaptations for blind people were on a study tour in the United States. At MIT in Boston they tried out the Phantom, a haptic interface that transmits forces to your hand or fingers in a way mimicking the sensation of touching real objects. The Phantom makes it possible to touch virtual objects and for a blind person this can be compared to seeing the objects on a computer monitor.

Ulf Larsson and Karin Jönsson identified the Phantom as the device that they had been looking for to make multimedia applications for blind children. The Phantom could be purchased, but there was no software available for blind persons. With that in mind, they contacted Certec.

Figure 2.1. Marie was one of the first test users of the Phantom.

Our concept of touch-enabled applications for disabled children was called Fantomaten®, in English "The Phantasticon" to give a new twist to the name "Phantom" and "The Optacon", an optical reader that could present graphics on a buzzing tactile display.

The purpose of making a Phantasticon out of the Phantom was to give people, above all children, with different disabilities new touch sensations as a compensation for the deficiencies they had in seeing or touching things in other ways (Figure 2.1). We started out with three applications: a mathematics application for blind children, a painting program with textures associated to the color and a battleship game that was completely based on haptic and sound interaction.

Another original idea was that of *Touch Windows:* to make vital portions of the Windows graphical environment haptically accessible for people who are blind. A combination of haptics to get the positions and overview of the desktop and Braille or synthetic speech for information on the specific parts of the menus, buttons and other features could make all the difference.

All Windows systems, both current ones and those that were in use when the project started, are entirely based on the user being able to gain an overview and to create an internal image of the system through visual input. This has made computers much easier for sighted people to use, but for blind people, the graphical information is of very limited use.

2.2 Collaborative Virtual Environments with Haptics

Early on we discussed how haptics could be used at a distance, for example, in special education of blind children. In cooperation with Eva-Lotta Sallnäs from the Interaction and Presentation Laboratory (IPLab), Royal Institute of Technology (KTH), Stockholm, we carried out a study of the advantages of adding haptics to speech and images in a situation in which two people could collaborate in solving an assignment at a distance.

The purpose of the study was to determine how a distance working situation would be effected if the people involved could also make use of the sense of touch. Several different parameters were measured, among them time, security and how the test persons themselves experienced the results. The test was carried out with sighted subjects who worked in pairs. They were given different tasks to work on together in a virtual environment. They sat in different locations and communicated by means of the telephone as well as via the graphical and haptic interfaces.

The tests demonstrated that the users could solve these kinds of tasks significantly faster with haptics than without. They also experienced that their performance abilities were better with haptics than without. In addition, the tests showed that the users felt more "present" in the virtual environment when the haptics function was running. This work is presented in detail in Appendix 2.

2.3 The Phantom at Furuboda

Furuboda is a folk high school and resource center near Kristianstad, Sweden with considerable practical experience in rehabilitation efforts for people with cerebral palsy and acquired brain damage. It offers a broad range of educational programs primarily for people with physical disabilities. We worked with the INKOM (Innovation and Communication) division that arranges courses for students, relatives and therapists with contents involving pre-communication, communication and computers. The division's primary responsibility it to offer individual training in communication subjects for students participating in longer courses. These students often have a diagnosis of traumatic brain injury or cerebral palsy.

Furuboda was interested in testing the Phantom because they wanted to offer their students new experiences. Cooperation was established in which Certec was responsible for program development and technical aspects involved in the project. The test trials were carried out at Furuboda under the direction of Greger Lennartsson, with many of Certec's existing programs for games and experience as a basis, along with certain adapted programs for this purpose.

The results were good, especially among people with traumatic brain injury. Those with cerebral palsy, on the other hand, were much less successful in general due to difficulties with involuntary movements. A possible sequel for them would be to include tests that had a more robust haptics interface, programmed to stabilize and filter out the involuntary movements.

We also carried out experiments with Furuboda on how an assistive robot could be steered by the Phantom, using the device's programmable resistance as a means of overcoming the difficulties in maneuvering heavy objects. Small movements and little strength could be enough to be in control. However, this Phantom-robot connection was not completed due to lack of resources.

2.4 The Klara Cooperative and Mogård's Folk High School

The Klara Cooperative and Mogård's Folk High School in Finspång, Sweden, have a group of people who are deaf and blind in their programs and the group has on a few occasions tested all the parts of our haptics concept, that is, the Phantom, the FEELit Mouse and the Force Feedback (FF) joysticks.

No doubt, haptics could have a special potential for people who have both hearing and visual disabilities. One of their priorities was to design and develop a tool for working in spreadsheet programs such as Microsoft Excel.

2.5 The IT Potential of Haptics

On December 6, 1999, I presented my licentiate thesis, "The IT Potential of Haptics – Touch Access for People with Disabilities" [Sjöström 1999]. It summarizes much of my own and Certec's work with haptics up to that point, but also introduces a number of new concepts. This thesis presents three pilot tests of virtual haptics in computer interface.

The first pilot test was to make the Touch Windows idea reality. This could be done with the FEELit Desktop[2] from Immersion Corp. combined with a Braille display and synthetic speech. FEELit Desktop is based on exactly the same ideas as what we called Touch Windows. FEELit Desktop uses MSAA (Microsoft Active Accessibility, previously AXA) to access information about the interface objects in Windows.

Specialized programs were most likely required to facilitate navigating in Windows environments. Thus, as an addition to direct translation of graphics to haptics in Windows, in the second pilot test we developed the idea of using virtual tools that facilitate searching in unknown structural environments such as the desktop in Windows. These virtual tools were meant to coexist with FEELit Desktop, and similar platforms, or to be built into it. One variation of a virtual search tool, a search cross, was presented and tested in the licentiate thesis.

The third pilot test in the licentiate thesis was a test of radial haptic menus. These menus (i.e., round, sectional menus) are sometimes used in graphical interfaces and they have certain characteristics that make them well suited for haptic interfaces.

All three of these tests were carried out with the 2D device, FEELit Mouse, which is a much simpler device than the Phantom. The price was then about $100 US instead of over $10,000 US for the Phantom. The performance, of course, is not in the same class as the Phantom's, but the FEELit Mouse was an interesting alternative for certain applications. In connection with these tests we closely cooperated with Immersion in the areas of hardware, ideas and support with program development, just as we had done before with SensAble Technologies concerning the Phantom.

The licentiate thesis also dealt with another 2D device, a force feedback joystick. I tested the program Submarines in a version for Logitech's force feedback joystick. It did not work very well because the joystick only functions in two dimensions, not three, as does the Phantom. The submarine game is in principle a two-dimensional game, but the third dimension is used to transfer information and that channel proved to be so important that the program did not function without it.

Even if the FF joystick was not adequate in this case, there are other situations in which it can be of use for blind people. Our colleagues, Anders Johansson and Joakim Linde, in cooperation with us have developed a program that enables a person to feel his or her way through a maze with a FF joystick. The blind children who tested it liked it very much.

After these initial tests with 2D devices we went back to 3D. In my licentiate thesis I suggest a 2.5D device, but since no such device yet

[2] A UTILITY THAT ADDS TACTILE RESPONSES TO WINDOWS INTERFACE TO GIVE THE USER THE FEELING OF HANDLING PHYSICAL OBJECTS.

exists and we often need more than two dimensions, in our research projects we have been working with the Phantom since then.

During development and testing, we also started to structure our findings from haptics interaction to develop guidelines for virtual haptics in computer interfaces. These were first published in the licentiate thesis. During 2000, I continued refining these guidelines, which resulted in an article presented at the CHI 2001 Conference [Sjöström 2001] and served as a foundation for further work in the area. A follow-up to the CHI article was presented at a special session of a conference called ISSPA the same year. This article is found in Appendix 3.

2.6 Villa Haptica

The different haptic interfaces used in addition to the Phantom along with the need for utilizing other senses made us redefine our area of operations from "The Phantasticon" to "haptics and human-computer interaction" soon after the licentiate thesis was completed. The haptics-related projects at Certec became a part of the work being done on multimodal human-computer interaction (HCI). In addition to pure haptics, we worked with general HCI and combinations of haptics and sound in computer interfaces, for instance, with *Villa Haptica* as the result.

The mind map below (Figure 2.2) shows how different sub-projects contributed to Villa Haptica and Enorasi. The EU Enorasi Project merged the ideas from Villa Haptica into an even wider concept.

The intention behind Villa Haptica was to build a bridge between our previous program ideas and a new generation of programs. We did not use our old programs directly but we made better implementations of the same ideas. The entire program was based on the concept of a house where one, by entering the different rooms, was able to experience and learn different things. When you went through the front door of the house, you entered a hallway with doors to different rooms. The hallway also contained a floor plan of the house and additional information.

In the first stage, we had rooms for math, music and games. Later, we planned to add rooms for art, geography and more. We were also looking into the possibility of having several people active in the house at the same time in order to work together and learn from one another. Villa Haptica merged with our next project, Enorasi.

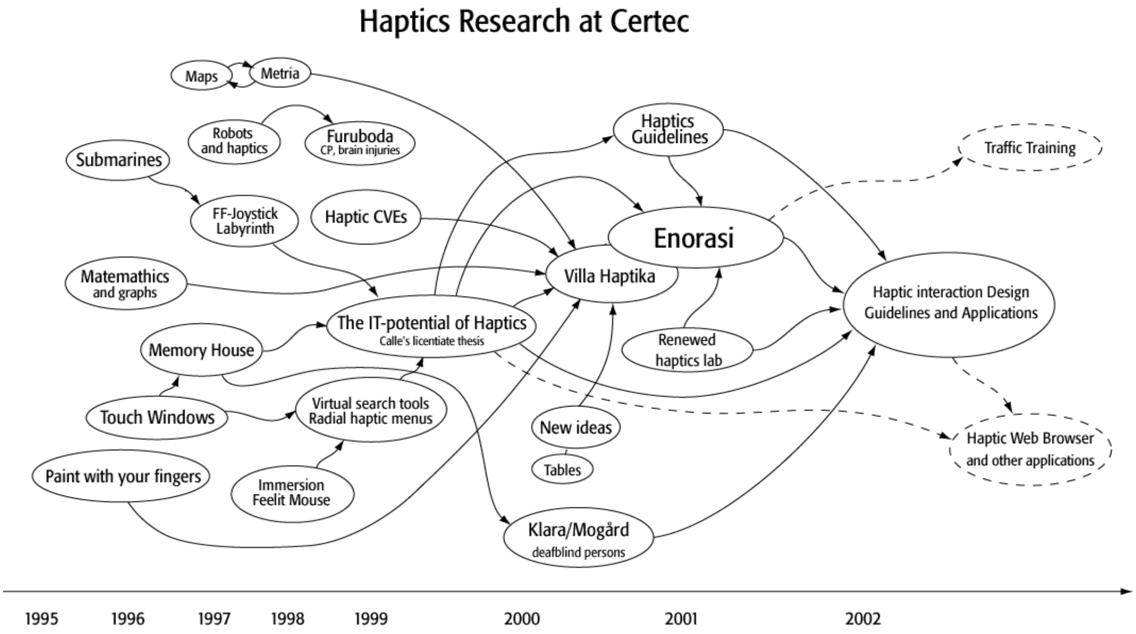

Figure 2.2. Haptics research projects at Certec

2.7 The EU Project Enorasi

We have also participated in the initial phase of a European Union Haptics project for blind people entitled *Enorasi*, which stands for "Virtual Environments for the Training of Visually Impaired". The thought behind Enorasi was to produce a basic haptics software program that would run on many types of hardware and to design and develop several different applications in the program especially for blind people. We also planned to implement virtual guides or agents in the system so that the user could get help in finding his way around complex environments. The idea was to make something like a virtual guide dog that helps its owner in different virtual environments. One category was new, improved versions of the game that we developed early on in our work with the Phantom. Another category was experiential environments such as going to a museum and feeling all the objects virtually.

We also planned to continue working on the program that aids blind people in feeling curves/graphs and in that way facilitates the learning of mathematics. Learning a coordinate system by means of playing the battleship game with a computer-generated sense of touch, for example, and other programs combines fun and learning with virtual touch.

Enorasi was an EU project coordinated by the Greek company Systema Informatics. The project consortium consisted of the following parties:

- Systema Informatics SA, Athens, Greece
- Center for Research and Technology Hellas/Informatics and Telematics Institute, Thessaloniki, Greece
- Fraunhofer Institute for Factory Operation and Automation, Magdeburg, Germany

- Certec, Lund University, Sweden
- Museo Marini, Florence, and the Italian Blind Union in Florence, Italy
- Czech Technical University in Prague, Czech Republic
- Universidad Politécnica de Valencia, Spain
- Local Union of Central Macedonia of the Pan Hellenic Association of the Blind, Thessaloniki, Greece

Our part of the Enorasi user studies tested:

- Recognition of geometrical objects, such as cubes, semi-cylinders and spheres.
- Recognition of and discussion of virtual representation of real life objects.
- A mathematic curve displaying program viewing simulation of herbivores and carnivores on an isolated island.
- A mathematic graphing program. 2D or 3D equations are entered as text. The resulting line or surface is rendered haptically.
- Simulations of real textures such as wood, corduroy fabric, sandpaper and linen cloth.
- Black and white line drawings represented as haptic reliefs.
- Floor plans represented as haptic reliefs with sound labels.
- A virtual training and game environment with houses, roads and cars.
- Two combined haptic and audio memory games with three and six sound pairs respectively.

That Certec was given the opportunity to participate was a direct result of our work in the Touch Windows project. For us it was a good opportunity to expand our efforts in the area of haptics.

The project was terminated after the initial user study, however, but many of the parts of Enorasi have continued as smaller projects in our laboratory.

2.8 Our Network

Certec's haptics network has expanded considerably over the years:

- Karin Jönsson and Ulf Larsson have always been important partners since they have daily contact with blind and visually disabled people in southern Sweden. Presently they run a private company, Horisont, based in Lund.
- SensAble Technologies that produces the Phantom and one of the inventors, Thomas Massie. We have both beta tested early versions of their software development kit GHOST and discussed the hardware issues with the early Phantoms.
- Immersion Corporation, the producers of the FEELit Mouse.
- The Department of Numerical Analysis and Computer Science (NADA) at the Royal Institute of Technology in Stockholm. The

common interest here is in how haptics can provide a feeling of being present at a distance. We have worked with Eva-Lotta Sallnäs at IPLab (The Interaction and Presentation Laboratory at NADA) since the autumn of 1998.

- Larry Scadden at the National Science Foundation in the USA. He was the opponent at my licentiate seminar and has provided valuable information about haptics and computer adaptations for blind people (among other things) from an American perspective.
- Furuboda Resource Center and Folk High School.
- The Klara Cooperative and Mogård's Folk High School.
- Reachin Technologies.
- The greatest expansion of our network came during the spring of 1999 when we were asked to participate in the EU Enorasi Project by ITI — the Informatics and Telematics Institute in Thessalonica, Greece.

3. Theory and Related Work

This chapter provides a brief theoretic background on the sense of touch, how it works in virtual haptic interaction and how it can be useful for blind people. It also positions my work and relates it to other researchers. In an area that is as new as that of virtual haptics, it is more or less the ongoing work that continuously forms the basis for and restructures the theories and methods.

3.1 Haptic Interaction and the Sense of Touch

Haptics refers to the modality of touch in combination with proprioception. Researchers in the field are concerned with the development and research of force feedback devices and software that permit users to feel and manipulate virtual objects with respect to features such as shape, weight, surface textures, etc.

The word "haptic" is derived from the Greek "haptesthai" meaning "to touch". Haptic sensing is defined as the use of motor behaviors in combination with touch to identify objects [Appelle 1991]. Many of the touch interfaces that have been developed in recent years use one-point haptic interaction with the virtual world. The effect is somewhat like tracing the outline of an object with your index finger in a thimble or holding a pen and recognizing it through this information alone.

The central function in haptic interaction is touch perception via movements, just as when perceiving an object via a tool or probe. It is the movement, the involvement of the kinesthetic and proprioceptive systems in combination with touch, that provide the information necessary for the perception of the model as an object. Tracing the outline of the virtual object will after some time give the user a notion of the shape of the object. The only skin receptors affected by the display are those that are in contact with the pen or thimble. Thus, haptic interaction does not primarily involve the skin receptors of the human tactile system. However, it is impossible to separate the systems completely. The skin receptors provide pressure and vibration information also present in a haptic system.

The human touch system consists of various skin receptors, muscles and tendon receptors, nerve fibers that transmit the touch signals to the touch center of the brain, as well as the control system for moving the body. Different receptors are sensitive to different types of stimuli: pressure, stretch of skin, location, vibration, temperature and pain [Burdea 1996]. In normal tactile exploration the receptors in the hairless skin play the dominant role but in virtual haptic interaction the focus is shifted towards the proprioceptive and kinesthetic touch systems.

A great deal of information provided by the kinesthetic system is used for force and motor control. The kinesthetic system enables force control and the control of body postures and motion. This system is closely linked to the proprioceptive system, which gives us the ability to sense the position of our body and limbs. Receptors connected to muscles and tendons provide the positional information. In virtual touch this information is absolutely necessary. Hand and arm movements become a more important part of the exploration since they are needed to gain information about the shape of the object. A large number of the tactile receptors also remain unused since the user has a firm grip on the interface stylus or thimble.

There is usually a distinction made between haptic and tactile interfaces. The tactile interface is one that provides information more specifically for the skin receptors, and thus does not necessarily require movement in the same way as a haptic interface does.

Another aspect of haptic touch is that the serial nature of the information flow makes it harder to interpret the raw input information into something that is useful. Understanding objects via haptic touch and coming up with a mental image of them is a cognitive process. Beginner users of virtual haptics in particular seem to handle this interpretation at a higher level of consciousness than when obtaining the corresponding information through normal touch.

3.2 Virtual Haptic Environments for Blind People

The studies in this dissertation of how blind people can use haptics concentrate on computer use. They aim at finding out the extent to which blind people, with the help of haptics, can better manage in the Windows environment, play computer games, recognize virtual objects, etc. However, we have not, as Jansson and associates at Uppsala University in Sweden, worked to distinguishing specific factors that can be discriminated with haptic perception. Neither have we to any larger extent worked as Colwell and colleagues at both the University of Hertfordshire and the Open University in the UK to identify possible differences between blind and sighted people's ability to create mental representation through haptics. Like us, though, Colwell and colleagues have also investigated whether blind users could recognize simulated real objects.

The starting point for Jansson and associates is their many years of research in experimental psychology, aimed at establishing blind people's different abilities. They have complemented their previous studies by also making use of the Phantom [Jansson et al. 1998; Jansson & Billberger 1999; Jansson 2000; Jansson & Ivås 2000].

Jansson establishes that haptic displays present a potential solution to the old problem of rendering pictorial information about 3D aspects of an object or scene to people with vision problems. However, the use of a Phantom without visual guidance, as is done by blind people, places heavier demands on haptics. Against this background, Jansson and Billberger [1999] set out to compare accuracy and speed in identifying small virtual 3D objects explored with the Phantom and analogous real objects explored naturally. Jansson and Billberger found that both speed and accuracy in shape identification were significantly poorer for the virtual objects. Speed in particular was affected by the fact that the natural shape exploratory procedures, involving grasping and manipulating with both hands, could not be emulated by the point interaction of the Phantom.

Jansson used a program called Enchanter [Jansson et al. 1998] to build virtual environments based on the haptic primitive objects provided by the GHOST SDK. Enchanter also has a texture mapper that can render sinusoidal, triangular, and rectangular and stochastic textures.

Jansson and Ivås [2000] investigated if short-term practice in exploration with a Phantom can improve performance. The results demonstrated that the performance for a majority improved during practice, but that there were large individual differences. A main conclusion is that there is a high risk that studies of haptic displays with users who have not practiced underestimates their usefulness.

Jansson is also involved in the EU PureForm Project [PureForm 2002]. The project consortium will acquire selected sculptures from the collections of partner museums in a network of European cultural institutions to create a digital database of works of art for haptic exploration. Visitors to the planned virtual exhibition can interact with these models via touch and sight.

Colwell has her background in experimental psychology (Sensory Disabilities, University of Hertfordshire) and in educational technology (Open University). Colwell and colleagues [1998a; 1998b] tested the potential of the Impulse Engine 3000 device from Immersion Corp. [Immersion 2002] for simulating real world objects and assisting in the navigation of virtual environments. The study included both virtual textures and simulated real objects. This study showed that the blind subjects were more discriminating than the sighted ones in their assessment of the roughness of the virtual textures. The subjects had severe difficulties in identifying virtual objects such as models of sofas and chairs, but could often feel the shape of the components of the models. The models in this study were made of simple shapes butted together and that gave rise to problems of slipping through the intersections between the parts of the objects. The authors neglect to mention to what degree this problem disturbed the users, but it is likely that these kinds of problems lower the performance for non-visual interaction significantly.

3.3 Static Versus Dynamic Touch Information

Tactile images normally provide a raised representation of the colored areas in the corresponding picture. It is possible to use microcapsule paper (a.k.a. swell paper) to convert a black and white image to a tactile version. This technique gives access to line drawings, maps, graphs and more in a permanent fashion. The main drawback is that it takes some time to produce these pictures, but in many applications this is not a big problem. These devices can be compared to the printers in computer systems for sighted people. Embossing thick paper as is normally done with Braille text can also produce static reliefs. By using vacuum formed plastic, it is possible to produce tactile pictures that are more robust than embossed paper.

What is much more difficult however, is to access graphical information that is variable, such as web graphics or graphical user interfaces. To access such information one needs an updateable touch display that can take the place of the monitor in a normal computer system. Several researchers have carried out investigations with updateable tactile pin arrays [Minagawa, Ohnishi, Sugie 1996; Shinohara, Shimizu, Mochizuki 1998]. The main problem with this technology is to get a sufficiently high resolution. The tactile pin arrays of today still have nowhere near the resolution that is available with embossed paper or vacuum formed plastic.

We have investigated different ways of accessing graphical information dynamically via the sense of touch and a haptic computer interface. The haptic interfaces that are available today have very high resolution and are becoming more and more robust. Haptic interfaces also can render dynamic touch sensations and variable environments. Haptic technology is thus a very interesting alternative for computer graphical access for people who are blind.

One of the problems that must be dealt with when working with haptic interfaces is that the technology limits the interaction to a discrete number of points at a time, as described above. Although this might appear to be a serious limitation, the problem should not be overestimated. It has been demonstrated by several independent research teams that haptic interfaces can be very effective in, for example, games, graph applications and for information access for blind persons [cf. Colwell et al. 1998a; 1998b; Fritz & Barner 1999; Holst 1999; Jansson et al. 1998; Sjöström 1999; Yu et al. 2000].

3.4 Mathematics and Graph Display Systems

In the field of computer-based simulations for the blind, haptic representations of mathematical curves have attracted special interest. One of Certec's first haptic programs was a mathematics viewer for the Phantom [Sjöström 1996; Sjöström, Jönsson 1997]. In this program the 2D functional graph was presented as a groove or a ridge on a flat surface. It turned out that this representation was quite effective and the program was appreciated even though it was not very flexible (for example, the functions could not be entered directly but had to be chosen from a list). The program could also handle 3D functional surfaces.

At about the same time, Fritz and Barner designed a haptic data visualization system to display different forms of lines and surfaces to a blind person. This work was presented later [Fritz & Barner 1999]. Instead of grooves or ridges, Fritz used a "virtual fixture" to let the user trace a line in 3D with the Phantom. This program and our original program are the first mathematics programs for the Phantom that we are aware of.

Later on, Van Scoy, Kawai, Darrah and Rash [2000] developed a mathematics program with a function parser that is very similar to our mathematics program but includes the ability to input the function via a text interface. The functional graphs are rendered haptically as a groove in the back wall, much as we did in our original program. However, the technical solution is quite another: in this program the surface and the groove are built with a polygon mesh that is generated from the input information.

Ramloll, Yu, Brewster et al. have also presented an ambitious work on a line graph display system with integrated auditory feedback as well as haptic feedback [Ramloll et al. 2000; Yu et al. 2000]. This program can make use of either the Phantom or Logitech Wingman Force Feedback Mouse. The haptic rendering is somewhat different for the different haptic interfaces: with the Phantom the line is rendered as a V-formed shape on a flat surface. With the Logitech mouse, which only has two dimensions of force feedback, the graph is instead rendered as a magnetic line (very similar to the virtual fixtures used by Fritz above).

Finally, Minagawa, Ohnishi and Sugie [1996] have used an updateable tactile display together with sound to display different kinds of diagrams for blind users.

All of these studies have shown that it is very feasible to use haptics (sometimes together with sound) to gain access to mathematical information. In our present mathematics program we chose to stick to the groove rendering method, which has been found very effective, but we changed our old implementation to a polygon mesh implementation that is more suited for today's haptic application programming interfaces. Moreover, we wanted to take the mathematics application closer to a real learning situation. Therefore, we have also developed an application that puts the functional graph into a context, namely an ecological system of an isolated island with herbivores and carnivores. This is, of course, only an example of what this technology can be used for, but still an important step forward towards usage in a real learning situation.

3.5 Textures

Most of the research that has been performed on haptic textures so far concentrates on the perception of roughness. Basic research on haptic perception of textures both for blind and sighted persons, has been carried out by Lederman et al. [1999], Jansson et al. [1998], Colwell et al. [1998a; 1998b] and Wall and Harwin [2000]. McGee et al. [2001] investigated multimodal perception of virtual roughness. A great deal of effort has been put into research on applied textures for blind and visually disabled persons, see Lederman, Kinch [1979] and Eriksson, Strucel [1994].

Different technical aspects of haptic texture simulation have been investigated by Minsky [1996], Siira and Pai [1996], Greene and Salisbury [1997], Fritz and Barner [1999] among others.

Compared to much of the research reviewed here, we are not interested in isolating the haptic aspects of textures but rather to include textures in multimodal virtual environments for blind and visually disabled persons. That means that we are interested not only in the roughness of the texture but also in other aspects of the texture. Therefore, we base the textures in our tests on real textures and do not mask out the sound information that is produced by the haptic interface when exploring the virtual textures. Most of the authors above use a stochastic or sinusoidal model for simulation of the textures. Although this model is very effective in simulating sandpaper it is not possible to use it for most real life textures. As is described in Appendix 4, we have thus chosen to use optically scanned images of real textures as the basis for our haptic textures instead.

3.6 Tactile and Haptic Maps and Images

In the two-part article "Automatic visual to tactile translation" Way and Barner [1997a; 1997b] describe the development of a visual-to-tactile translator called the TACTile Image Creation System (TACTICS). This system uses digital image processing technology to automatically simplify photographic images to make it possible to render them efficiently on swell paper. A newer image segmentation method that could be used within TACTICS has also been proposed by Hernandez and Barner [2000]. The Tactics system addresses many of the problems with manual tactile imaging but since it generates a static image relief it cannot be used for graphical user interface (GUI) access. Our program, described in Section 6.5.3, works very well with black and white line drawings, which is basically the output of the TACTICS system. This means that technology similar to this can be used in conjunction with the technology used in our experiments to make a very efficient haptic imaging system.

Eriksson, Tellgren and associates have presented several reports and practical work on how tactile images should be designed to be understandable by blind readers [Eriksson 1999; Tellgren et al. 1998]. Eriksson reports on the design of the tactile images themselves as well as how they can be described in words or by guiding the blind user.

Pai and Reissel [1997] have designed a system for haptic interaction with 2-dimensional image curves. This system uses wavelet transforms to display the image curves at different resolutions using a Pantograph haptic interface. Wavelets have also been used for image simplification by Siddique and Barner [1998] with tactile imaging in mind. Although the Pantograph is a haptic interface (like the Phantom) it has only 2 degrees of freedom. It is likely that the 3 degrees of freedom make the Phantom more fitted for image access (since lines can be rendered as grooves as described above) and it might also lower the need for image simplification.

Roth, Richoz, Petrucci and Puhn [2001] have carried out significant work on an audio haptic tool for non-visual image representation. The tool is based on combined image segmentation and object sonification. The system has a description tool and an exploration tool. The description tool is used by a moderator to adapt the image for non-visual representation and the exploration tool is used by the blind person to explore it. The blind user interacts with the system either via a graphics tablet or via a force feedback mouse. When we designed our image system described in Section 6.5.3 we wanted to have a system that could ultimately be handled by a blind person alone and that excludes a descriptor/explorer scheme.

Kurze [1997] has developed a guiding and exploration system with a device that uses vibrating elements to output directional information to a blind user. The stimulators in the device are arranged roughly like a circle and the idea is to give the user directional hints that he can choose to follow or not. Kurze [1998] has also developed a rendering method to create 2D images out of 3D models. The idea of an interface that can point to objects that are close to the user is quite interesting and can certainly help when exploring an unknown environment (a similar idea is our "virtual search tools" [Sjöström 1999]).

Shinohara, Shimizu and Mochizuki [1998] have developed a tactile display that can present tangible relief graphics for visually impaired persons. The tactile surface consists of a 64x64 arrangement of pins with 3 mm interspacing. The pins are aligned in a hexagonal, rather than a square formation to minimize the distance between the pins. Even though a tactile display can provide a slightly more natural interaction than haptic displays, we still think that the resolution of the tactile displays is far too low.

The Adaptive Technology Research Centre at the University of Toronto is running a project aimed at developing software applications that make it possible to deliver curriculum that can be touched, manipulated and heard via the Internet or an intranet [Treviranus & Petty 1999]. According to information provided by the Centre, software tools, as well as exemplary curriculum modules will be developed in the project. In relation to this, Treviranus [2000] has undertaken research to explore the expression of spatial concepts such as geography using several non-visual modalities including haptics, 3D real world sounds, and speech, and to determine the optimal assignment of the available modalities to different types of information.

A close similarity to our work with haptic images is an "image to haptic data converter" that was recently presented by Yu, Guffie and Brewster [2001]. This program converts scanned line drawings into a format that is interpretable by a haptic device. The system provides a method for blind or visually impaired people to access printed graphs. Currently, the graphs can be rendered on either the Phantom or Logitech's Wingman Force Feedback Mouse. This method has a simpler production process than the conventional raised paper method and the motivation and idea is pretty much the same as the one in our program for image access. However, Yu uses a technique that includes automatic image tracing which is not used in our program. Both methods have their strong and weak points, and we cannot say that one method is always better than the other. In the long run it could be good to let the user choose the rendering and simplification method depending on the kind of picture he or she wants to feel.

Much of the work done on tactile imaging can also be valid in the world of haptic interaction using programs similar to our program from the Enorasi tests. We have chosen to use a 3D haptic device because of its high resolution and its ability to easily render updateable graphics. The chosen rendering method is straightforward and enables a blind person to handle the system on her own.

3.7 Haptic Access to Graphical User Interfaces

To blind and nearly blind persons, computer access is severely restricted due to their inability to interpret graphical information. Access to graphical information is essential in work and social interaction for sighted persons. A blind person often accesses visual information through a process involving a sighted person who converts the visual image into a tactile or verbal form. This obviously creates a bottleneck for any blind person who wants access to visual information and it also generally limits his or her autonomy.

Access to graphical information is a key problem when it comes to computer access for people who are blind. All Windows computer systems are entirely based on the user being able to gain an overview of the system through visual input. The Windows interface is actually more difficult to use than the old text-based system. Still, Windows can be attractive for blind people due to the many computer programs available in that environment and the value of being able to use the same platform as others.

Another important problem associated with graphics for people who are blind is that it is often very difficult to perceive 3D aspects of 2D tactile pictures [cf. Jansson 1988]. This means that the ability to communicate 3D models that come with haptic interfaces like the Phantom could be much more important for blind people than what 3D graphics is for sighted people.

There have been many interesting research projects dealing with blind people's access to graphical user interfaces. Historically, most of the research has focused on access methods using sound and other non-haptic means of interaction see for example [Mynatt 1997; Petrie et al. 1995; Mynatt & Weber 1994; Winberg 2001]. However, haptic and tactile computer access is gaining ground and is now available in more than one version.

C Ramstein is one of the pioneers in haptic user interfaces for people with visual impairments [Ramstein et al. 1996]. His work involves multimodal interfaces in several ways. The haptic information is combined with both hearing and Braille technology. As a part of the "PC Access Project", Ramstein developed the Pantobraille, a combination of a 2D haptic interface called the Pantograph and a Braille cell [Ramstein 1996]. This device allows the user to place the pointer on a graphical interface and to perceive forms and textures using the sense of touch.

The Moose is another 2D haptic interface which was developed at Stanford [O'Modhrain & Gillespie 1998]. The software for the Moose reinterprets a Windows screen with force feedback such that icons, scroll bars and other screen elements like the edges of windows are rendered haptically, providing an alternative to the conventional graphical user interface. Even dynamic behavior is included in the software: drag-and-drop operations, for example, are realized by increasing or decreasing the apparent mass of the Moose's manipulandum.

Similar software has been developed for the Logitech Wingman, developed by Immersion Corporation and formerly known as the FEELit Mouse. Although not designed specifically with blind users in mind, the FEELit Desktop software renders the Windows screen haptically in two dimensions. The device works with the web as well, allowing the user to "snap to" hyperlinks or feel the "texture" of a textile using a FeeltheWeb ActiveX control. The Wingman mouse is now no longer commercially available, but has been replaced by an ungrounded haptic mouse called the TouchSense Mouse.

A relative newcomer in touch-based Windows access is the VirTouch Mouse from Virtual Touch Systems in Israel [VirTouch 2002]. The VirTouch Mouse is a "screen scanner-mouse", containing three tactile displays each incorporating 32 rounded pins arranged in a four by eight matrix. These pins respond vertically through the cursor to computer graphics, pixel by pixel. Using three fingers, the blind and visually impaired can understand the curvature and shading of the scanned screen pixels presented through the structure of pin height. Each pin moves up and down.

All these systems are directly related to my suggested system Touch Windows. I started out with a Phantom, which is a 3D device, instead of the 2D devices used in the above-mentioned projects but the main idea is still the same. In my licentiate thesis [Sjöström 1999] I argue that the optimal device for haptic Windows access might be a "2.5D device". Such a device would allow movements of say 80 mm in two dimensions and about 10 mm along the third axis. With such a setup, it is possible to use two dimensions for navigation and the third for added information.

3.8 Haptic Collaborative Virtual Environments

Collaborative haptic environments has been an area where research and art, in many cases, seem to be quite intertwined. Many experiments with haptic distance collaboration have been carried out with specialized hardware of different kinds. An early communicative haptic device was the Telephonic Arm Wrestling [White & Back 1986] which was an art exhibit consisting of a pair of spatially separated robot arms which allowed two remote users to arm wrestle with one another.

InTouch, a haptic device developed by Brave and his colleagues at the MIT Media Lab [Brave et al. 1998], also functions in an area that is somewhere between performance art and research. The device consists of three rollers. Moving a roller causes a coupled movement in a similar remote device. InTouch has been implemented in three steps where step one uses a mechanical coupling to create a first prototype. Step two uses two electronic devices connected to the same computer and step three uses the same kind of electronic devices but connected to two different computers communicating over a local area network.

Another device in this area is HandJive [Fogg et al. 1998], a device for "interpersonal haptic entertainment". It consisted of a pair of cylinders, joined together at the center. Each cylinder could rotate around this joint to lock into one of five positions. A change in position of the device was reflected in other coupled devices. HandJive differs from inTouch in that HandJive allows discrete articulation positions (as opposed to a continuous range of motions). The authors suggest that the HandJive interaction could be something like social dance, jazz improvisation and conversation.

There have also been a few studies of haptic cooperation/collaboration between users with standard haptic devices: Basdogan, Ho, Durlach, Slater and their colleagues [Basdogan et al. 1998; Ho et al. 1998; Basdogan et al. 2000; Durlach & Slater 1998], have developed a multimodal shared virtual environment and performed a set of experiments to study the role of haptic feedback in collaborative tasks and whether haptic communication through force feedback can facilitate a sense of being together and collaborating with a remote partner. The studies concern a scenario where two participants at remote sites must cooperate to perform a joint task in a collaborative virtual environment. The experiments involved tasks such as moving a ring back and forth along a wire while minimizing contact with the wire. The experiments were conducted with visual feedback only, and with both visual and haptic feedback. Both performance and feelings of togetherness were enhanced in the dual modality condition.

Oakley, Brewster and Gray have experimented with haptic communication in a shared editor [Oakley et al. 2000]. In their experiment, the user's pointers are considered as haptic avatars and interactions such as haptically pushing and pulling each other are afforded. The authors suggest three working modes to limit the intrusive part of the haptic communication. The modes are: working, communication and observation. In the working mode a user can interact with the canvas and can create content, but cannot be haptically influenced by another user. In the communication mode, users cannot interact with the canvas but have access to the haptic communication. In the observation mode, users can neither communicate haptically nor access the canvas. In the program, these three modes are mapped to the z-axis of the device. The system is not evaluated in the referenced article.

Adding haptics to multi-user environments creates additional demand for frequent position sampling and fast update. Latencies in the connecting computer networks must also be kept under control to allow a stable interaction. Architectures for distributed haptic collaboration addressing such problems have been suggested by Buttolo, Oboe, Hannaford and colleagues [Buttolo, Oboe, Hannaford et al. 1997] and also by Hespanha, McLaughlin, and Sukhatme in a chapter of *Touch in Virtual Environments: Haptics and the Design of Interactive Systems* [Hespanha, McLaughlin, Sukhatme 2002].

Haptic communication in collaborative virtual environments is a growing research area with many different aspects, both technical and behavioral scientific. Our work with collaborative haptic environments is described in Appendix 2. Our results are broadly in line with results from similar tests for example by Basdogan and colleagues [Basdogan et al. 1998; 2000] and the means of communication in our programs bear significant resemblance to the system implemented by Oakley and colleagues [2000]. What I would like to see more of in the future is haptic communication for learning and guiding in virtual environments for both sighted and blind people.

3.9 Guidelines for Haptic and Tactile Interfaces

The guidelines presented in this dissertation are intended for use when designing haptics interfaces. It is important to note that principles that guide the design of traditional interfaces, such as Schneiderman's "Eight Golden Rules" [1998], Tognazzini's list of basic principles for interface design [2001] or Nielsen's "Ten Usability Heuristics" [2002], still apply. The guidelines I propose can in principle be used in addition to other HCI guidelines, not in place of them. Apart from general HCI guidelines, the guidelines for accessible interfaces, such as the W3C Web Accessibility Initiative (WAI) guidelines [W3C 1999], are also important and should be taken into account.

Guidelines or recommendations for haptic and tactile interfaces have been presented in a number of articles. The background is both haptic interaction for blind people and haptics combined with other senses.

Colwell and associates have done a series of tests with haptic virtual environments for blind people. This work is closely related to my work even though we have different backgrounds. The article "The use of a haptic device by blind and sighted people: perception of virtual textures and objects" [Colwell et al. 1998b] contains a section with "guidelines for the design of haptic interfaces and VEs". These guidelines mainly cover haptic textures and haptic virtual objects and they are generally in line with mine that cover the same areas (as cited in the reasoning behind my guidelines).

Challis and Edward have presented a set of design principles for tactile interaction [Challis & Edwards 2000]. Since these principles are developed for static tactile interaction with, for instance, a touchpad and a tactile overlay, these guidelines cannot be used directly for haptic interaction. However there are parts that are also relevant for the dynamic interaction provided by a haptic interface.

Miller and Zeleznik have made haptic enhancement to the X-windows system and subsequently gone even further in designing 3D haptic interface widgets. [Miller & Zeleznik 1998; 1999] Their work is to a large extent grounded in 3D interaction with both haptics and vision but their discussion and proposed widgets are really interesting even in a non-visual context.

I have also found inspiration for the guidelines in Lederman and Klatzky [2001], Jacko and Sears [1998], Kurze [1994], Ramstein [1996], Ramstein and colleagues [1996], Kamel and Landay [2000] as well as Jansson and associates [1999; 2000], among others.

4. Devices and Software

Several different haptic interface devices have been used in this research: the Phantom from SensAble Technologies is the device that we have used the most at Certec but I have also used the FEELit Mouse from Immersion and force feedback joysticks from Logitech and Microsoft.

Two Software Development Kits (SDKs) for the Phantom have been commercially available for some time now. They are GHOST by SensAble Technologies Inc. (Boston, Massachusetts) and the Reachin API[3] by Reachin AB (Stockholm). A third SDK for haptic development: e-Touch SDK by Novint Technologies (Albuquerque, New Mexico) is currently available as a beta version.

When we started our haptics work, none of these SDKs or APIs were available so we made our own simple object-oriented package to start with. This package handled basic, necessary steps in haptic programming such as communication with the haptics hardware, coordinate system conversions, temperature and force tracking, basic shape geometry and also sinusoidal textures. We started using GHOST as soon as the first beta version was available (in 1997), and since 2001 we have also been using the Reachin API. All the APIs described here constitute a huge leap forward compared to the essentially force level programming that we had to do in the beginning.

4.1 The Phantom

Technically the Phantom is a small robot with very low back drive friction. The standard A-model Phantom has three full degrees of freedom, i.e., three motors and three encoders. The tip of the robot is attached to a stylus or thimble via a passive gimbal that allows rotational movements (Figure 4.1). The normal use of the Phantom, however, is the opposite of a robot: the user holds on to the stylus (or puts a finger in the thimble) at the end of the robot arm and moves it and the robot provides feedback to the user by applying forces via the stylus.

[3] API STANDS FOR APPLICATION PROGRAMMER'S INTERFACE.

Figure 4.1 The Phantom 1.0, a haptic interface with a close-up of the motors.

The basic principle of the haptic rendering is simple: every millisecond, the computer that controls the Phantom reads the position of the stylus. It then compares this position to the boundaries of the objects in the virtual environment. If the user is not near any of the virtual objects, no current is sent to the motors and the user is free to move the stylus around. However, if the system detects a collision between the stylus and one of the virtual objects, it drives the motors to exert a force on the user's hand (via the stylus) to push the user's hand back to the surface of the virtual object. In practice, the user is prevented from penetrating the virtual object just as if the stylus collided with a real object (Figure 4.2).

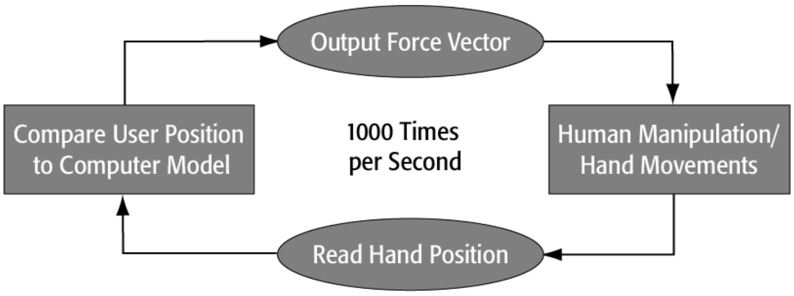

Figure 4.2. The basic haptic rendering control loop.

Other haptic devices — such as Immersion Corporation's Impulse Engine or CyberGrasp — use the same principle but with different mechanical systems for force generation and sometimes more than one point of interaction.

4.2 The FEELit Mouse

The FEELit Mouse is a 2D haptic device intended as a mass-market product, and as such it needs to be inexpensive. It has a smaller work area than the other devices and can only exert a fraction of the force that can be felt with many other devices. Immersion justified force feedback for the mass market by emphasizing benefits such as increased targeting speed in Windows and better ergonomical factors. The commercial version of the FEELit Mouse was the Logitech Wingman Force Feedback Mouse (Figure 4.3) mainly marketed as a device that gives an added dimension to computer games.

Figure 4.3. Logitech Wingman Force Feedback Mouse, the commercial version of the FEELit Mouse

4.3 Force Feedback Joysticks

These are intended to be used as gaming devices with a home user price tag. However it is possible to make special programs for force feedback joysticks that can be both educational and fun for blind children [Johansson & Linde 1998]. I have used force feedback joysticks from Microsoft (Figure 4.4) and Logitech.

Figure 4.4. The Microsoft SideWinder Force Feedback Pro Joystick.

4.4 GHOST

The General Haptics Open Software Toolkit (GHOST SDK) from SensAble Technologies is a C++ object-oriented toolkit that represents the haptic environment as a hierarchical collection of geometric objects and spatial effects. The GHOST SDK provides an abstraction that allows application developers to concentrate on the generation of haptic scenes, manipulation of the properties of the scene and objects within the scene and control of the resulting effects on or by one or more haptic interaction devices.

Using GHOST, developers can specify object geometry and properties, or global haptic effects using a haptic scene graph. A scene graph is a hierarchical collection (tree) of nodes. The internal nodes of the tree provide a means for grouping objects, orienting and scaling the subtree relative to the parent node, and adding dynamic properties to their subtrees. The terminal nodes (leaves) of the tree represent actual geometries or interfaces. Leaves also contain an orientation and scale relative to their parent nodes.

The GHOST SDK does not generate visual representations of objects within the haptic scene graph. The GHOST SDK does, however, provide graphical callback mechanisms to facilitate integration between the haptic and graphic domains. SensAble also provides a graphics toolkit called GhostGL that works with GHOST. GhostGL is a library that can render any GHOST SDK scene using OpenGL. It provides an easy way to add graphics to any GHOST SDK application. Once a GHOST SDK scene graph has been created it can be passed to the GhostGL routines that traverse and render a graphical representation of each node in the scene [SensAble 2001; 2002].

Key features of the GHOST SDK include the ability to:

- Model haptic environments and models using a hierarchical haptic scene graph.
- Specify the surface properties (for example, compliance and friction) of the geometric models.
- Use behavioral nodes that can encapsulate either stereotypical behaviors or full free body dynamics.
- Use an event callback mechanism to synchronize the haptics and graphics processes.
- Extend the functionality through the subclassing metaphor. Application developers can extend, modify or replace all object classes.

4.5 Reachin API

The Reachin API (formerly known as Magma) is an object oriented C++ application programming interface for creating touch. Reachin API lets the developer create haptic applications by means of a node concept: to let the user sense different forms, one creates geometric nodes; to let the user sense different surface qualities one defines surface property nodes, etc. The Reachin API includes an extensible library of shape nodes, surface property nodes, simulation and scripting nodes, and control nodes for the different haptic and tracking devices.

The Reachin API also makes heavy use of a VRML loader. This means that many haptic environments can be built without having to go into C++ coding. Reachin uses an extended version of VRML97 that supports touch properties on the objects in addition to the standard visual properties. More complicated behavior can also be programmed without C++ by adding “script-nodes”. These are small programs written in Python (an object oriented programming language suitable for scripting) that can connect and manipulate states and properties of different nodes in the scene. Reachin VRML uses a field network approach to event handling: Instead of defining callback procedures (as in GHOST), the developer uses “field routing” to make a direct connection between the fields of different nodes or within a single node. This way, for example, the “pressed” field (a state property) of a virtual button node can be connected to the “playing” field (an activation property) of a sound node to make a sound when the button is pressed [Reachin 2001; 2002].

The Reachin API features:

- A high frequency loop (1-5 kHz) for time critical force calculations and a slower loop for prediction, force interpolation and dynamic scene graph updates.
- Haptic environments and models using a hierarchical haptic scene graph.
- Touching modeled objects with a finite ball stylus tip, which makes edges feel more realistic and prevents fall-through.
- Haptic texture algorithms on a 3D oriented volume or in free space.
- Surface friction and damping.
- Additional tool kits for NURBS, soft tissues, etc.

4.6 E-Touch

E-Touch is a 3D, multi-sensory (sight, touch and hearing) software package from Novint Technologies (Albuquerque, New Mexico). It is the first software that has been developed and delivered as an Open Module system, which is an outgrowth of the Open Source movement.

The e-Touch SDK is a modular, multi-process system that allows multi-sensory programming. With the e-Touch SDK, programmers can build 3D applications that enable use of the senses of sight, touch, and hearing. The e-Touch SDK includes programming tools for creating 3D tools, navigation techniques, 3D models, and a full set of user interface tools including an extensive API [Novint 2002].

5. Methods

This chapter describes my work as an engineer, designer, tester, software developer and researcher. Different usability methods are compared and I discuss how they have affected my work. I also try to explain how we utilize *technology as a language* to communicate with potential future users.

5.1 Design Processes and Usability

Design is concerned with the interaction between needs, ideas, visualization, form, environment, financing, planning, production, user trials, end use, and utilization of experience. Design involves both the process – an iterative and to a large extent non-sequential interplay between the individual and the evolving artifact – and the results of the design process and their effects on the individual during the use phase. Rehabilitation engineering research has a great deal in common with, and can be seen as a subset of, design research [Jönsson & Anderberg 1999]. Its focus is on design for *usability and useworthiness* in a (re)habilitation context [Eftring 1999].

The design process simply cannot be described as a straight path from vision to a final product. Instead a typical feature of a design process is the constant shift between different levels and activities. Donald Schön in his classic book *The Reflective Practitioner* [Schön 1983] talks about *reflection in action*. Terry Winograd defines it as "the shift that happens when a designer is surprised during the flow of skilled, practiced performance, and shifts to a more conscious mode of analysis while continuing to act" [Winograd 1996, p. 172]. There are, of course, instances of design where the usability of the artifact produced is of little importance, but in our projects we are concerned with design that leads to a product that the intended users find usable. Thus the user and the use have to enter into this process of reflection and action.

However, it is not enough to start a design process by just asking users what they want. Confronted with the question, "What do you want?" most people will answer, "What can I get?" It is also very difficult to know exactly what one wants in a specific situation without being able to try it out. Furthermore, the situation of use will change in the presence of a new artifact. Thus the users have to be involved all along in the design process. Different stages must be made accessible as models, mock-ups, prototypes, etc. In this context it must be pointed out that even if a computer prototype in many cases is necessary, as much work as possible during the early stages should be performed using low fidelity (lo-fi) prototypes. Lo-fi prototypes allow the designer to spend more time thinking about the design then implementing the prototype [Rettig 1994].

If you attempt to group different methods for obtaining better usability by their degree of user involvement (starting with the highest) in the design process, you come up with the following list (the names of the different levels are taken from Löwgren [1993], but the levels are of a general nature):

Participatory design, which may be described as a mutual learning process between the designer(s) and the users. Not only should the users participate in the design process but also the designers should participate in the work/use situations where the product is to be used.

Contextual design means that the designers spend time in the users' environment, watching what happens. They discuss with the users and the system is designed with the users, who also test it.

Usability engineering is a method where you start by analyzing the users, what they do and what they need/want. From this study (and in cooperation with the users) a set of usability goals are formulated. These goals should be such that usability testing can be applied to them. Prototypes are then generated and tested until the usability goals are met. It is usually better to perform more tests with few users (3-5 are often said to be an optimum) than to secure good statistics in a few extensive tests – the cost of the extensive testing is seldom justified by the benefit.

Theory based design, finally, is a way of describing approaches where one tries to find the general theories and guidelines that define good design. This was historically the first approach to usability, and although some results generated are useful, this is not enough for the designer who wants to create usable designs.

5.2 Usability Engineering

Usability engineering can be defined in several different ways. Perhaps the most well-known description is to be found in Jacob Nielsen's book that bears the straightforward title *Usability Engineering* [Nielsen 1993]. Here Nielsen describes the process in a hands-on manner that is very suitable for inclusion in an engineering design process.

Nielsen also describes a simplified version of the process, "Discount Usability Engineering", which is based on four simple yet effective techniques:

- User and task observation
- Scenarios
- Simplified thinking aloud
- Heuristic evaluation

These uncomplicated methods may not be the best way of ensuring that the end product is usable, but a design that has gone through this process stands a much higher chance of being used at all. I often use these methods at an early stage in my development and research work.

5.3 Design Processes in the Present Work

In reality, there is a certain amount of overlap between the different methods when it comes to the practical work, and I have thus included elements from all the design methods above. The design process that I have used during my haptics research can be described as being primarily influenced by the usability engineering described by Nielsen and the reflection in action/reflection on action as described by Schön in *The Reflective Practioner* [Schön 1983]. In some cases, I have moved quite far away from standard usability engineering to achieve a more research-oriented process. I have, for instance, done most of my user testing with more than the 3 to 5 persons common when looking for design problems in usability engineering. I try to work both as an artist-designer and an engineer-designer [cf. Winograd 1996, p. 41], but my focus in the research for this dissertation is on the engineer-designer's role.

In the design process, early prototypes may be used in the communication with the test persons in order to get information that is relevant. Using technology this way means using a prototype as a partner that contains an emerging version of the functional specifications of the product under development. The first prototypes are often simple but still very useful. The prototype can be used both to communicate ideas to other people and to aid in understanding what is good and what is bad in the design. In some cases the prototype is made to prove a point but the more interesting results normally come when the prototype is used as a platform for a design dialogue. I figuratively try to use *technology as a language* to communicate with the users and most often experience the outcome of this to be more fruitful than ordinary questionnaires and lengthy product specifications on paper – this way the user and the engineer have a common fixed point in the technology.

6. Programs and Tests

Since 1995 I have designed and developed a multitude of demo and research applications and tested them with blind and sighted people. A main result from this work is the set of guidelines that is presented later in this dissertation.

This chapter is a compilation of the work I have been involved in. Each study is described more thoroughly either in the articles in the appendices or in my licentiate thesis [Sjöström 1999].

In short, this is what I have done or been part of:

- Tested ideas on how virtual haptics can be of use and enjoyment for blind people.
- Investigated how orientation and navigation work in a virtual haptic environment, above all for blind people.
- Investigated how graphical user interfaces can be made accessible for blind persons using virtual haptics.
- Investigated collaborative virtual environments with haptics.
- Investigated how other graphical information such as maps, floor plans and pictures can be made accessible using virtual haptics.
- Formulated guidelines for haptic interaction design.

To provide a quick overview for the reader, each test is introduced in a short formalized format describing the program, telling what haptic device was used and in what section of the dissertation more information can be found.

Submarines

Haptic variant of the well-known battleship game.

Device:	The Phantom
Tests:	Tried out by at least 20 blind children, at least 5 deaf-blind persons and at least 50 sighted persons. No formal testing.
See further:	Section 6.1.1 and Appendix 1.

Paint with Your Fingers

Different colors are associated with different textures so that you can feel what you are painting.

Device:	The Phantom
Tests:	Tried out by at least 20 blind children and at least 50 sighted persons. No formal testing.
See further:	Section 6.1.2 and Appendix 1.

Early Mathematics Program

The program makes it possible to feel a mathematical curve with the Phantom.

Device:	The Phantom
Tests:	Tried out by at least 20 blind children and at least 50 sighted persons. No formal testing.
See further:	Section 6.1.3 and Appendix 1.

The Memory House

A combined haptic and audio memory game with 12 sound pairs and one "Old Maid".

Device:	The Phantom
Tests:	Tested by 9 blind persons and tried out by many more blind and sighted persons.
See further:	Section 6.2 and Appendix 1.

Haptics in Collaborative Virtual Environment

Shared haptic virtual environment with cubes that can be manipulated by one or two users together. Vision and speech communication were also used.

Device:	The Phantom
Tests:	Tested by 28 persons in 14 groups.
See further:	Section 6.3 and Appendix 2.

FEELit Desktop + Synthetic Speech and Braille

Program from Immersion that makes the objects on Windows desktop touchable. Combined with synthetic speech and Braille in these tests.

Device:	The FEELit Mouse
Tests:	Pilot testing with two blind persons. Tried out in informal tests as well.
See further:	Section 6.4.1 and my licentiate thesis.

Radial Haptic Menus

Program for testing radial haptic menus in a Windows-like environment using haptics and speech.

Device:	The FEELit Mouse
Tests:	Pilot testing with two blind persons. Tried out in informal tests as well.
See further:	Section 6.4.2 and my licentiate thesis.

Virtual Haptic Search Tools

Program for virtual haptic search tools in a Windows-like environment.

Device:	The FEELit Mouse
Tests:	Pilot testing with two blind persons. Tried out in informal tests as well.

See further:	Section 6.4.3 and my licentiate thesis.

Mathematics – Herbivores and Carnivores

Mathematic curve displaying program viewing simulation of herbivores and carnivores on an isolated island.

Device:	The Phantom
Tests:	Tested by 24 blind persons.
See further:	Section 6.5.1 and Appendix 4.

Textures

Simulations of real textures such as wood, corduroy fabric, sandpaper and linen cloth.

Device:	The Phantom
Tests:	Tested by 25 blind persons.
See further:	Section 6.5.2 and Appendix 4.

Line Drawings

Black and white line drawings represented as haptic reliefs.

Device:	The Phantom
Test:	Tested by 24 blind persons.
See further:	Section 6.5.3 and Appendix 4.

Floor Plans

Floor plans represented as haptic reliefs with sound labels.

Device:	The Phantom
Tests:	Tested by 23 blind persons.
See further:	Section 6.5.4 and Appendix 4.

Geometrical Objects

Recognition of geometrical objects, such as cubes, semi-cylinders and spheres.

Device:	The Phantom
Tests:	Tested by 25 blind persons.
See further:	Section 6.5.5 and Appendix 5.

VRML Objects

Recognition and discussion of virtual representation of real life objects.

Device:	The Phantom
Tests:	Tested by 24 blind persons.
See further:	Section 6.5.6 and Appendix 5.

Traffic Environment

Virtual training and game environment with houses, roads and cars.

Device:	The Phantom
Tests:	Tested by 21 blind persons.
See further:	Section 6.5.7 and Appendix 5.

Sound Memory Game

Two combined haptic and audio memory games with three and six sound pairs respectively.

Device:	The Phantom
Tests:	Tested by 25 blind persons.
See further:	Section 6.5.8 and Appendix 5.

Mathematical Surface

Mathematic graphing program. Equations are entered as text. The resulting surface is rendered haptically.

Device:	The Phantom
Tests:	Tested by 7 blind persons with interest and knowledge in mathematics.
See further:	Section 6.5.9 and Appendix 5.

Follow-up Experiments on Haptic Interaction Design Guidelines

Different variations of haptic/audio memory games with six sound pairs. Testing interface widget design, reference points and haptic grid as navigational help.

Device:	The Phantom
Tests:	Tested by 10 blindfolded sighted persons.
See further:	Section 6.6, Chapter 7 and Appendix 6.

6.1 Programs for Learning and Fun

The haptics work at Certec started out with developing programs for learning and fun for blind children. The first steps resulted in three programs. These programs have not been formally tested, but they have been demonstrated at exhibitions and conferences to both sighted and blind visitors. There have also been many test sessions at Certec with blind children and adults, as well as with a group of deaf-blind persons.

6.1.1 SUBMARINES

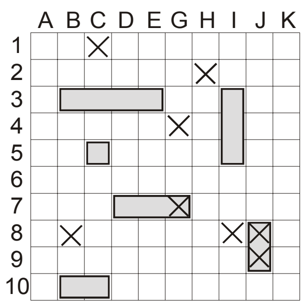

Figure 6.1. A paper-based battleship game

Submarines is a haptic variant of the well-known battleship game. The ordinary pen-and-paper based battleship game (Figure 6.1) has been used to give school children an initial idea of what coordinate systems can be used for. With Submarines it is possible for a blind child to have even more fun with coordinate systems.

The player feels 10x10 squares in a coordinate system. In the game, your finger in the Phantom is a helicopter that is hunting submarines with depth charge bombs. If you put your finger on the “surface of the water” you can feel smooth waves moving up and down. The surface feels different after you have dropped a bomb, and it also feels different if a submarine has been sunk. There are four different states for a square with associated haptic feedback:

- Not yet bombed – calm waves
- Bombed, but missed – no waves (flat water surface)
- Bombed, hit part of a submarine – vibrations (the submarine starts its motors and tries to flee)
- Bombed, hit entire submarine – small waves (like bubbles from the wreck)

This computer game uses the Phantom, the screen, and the keyboard in the interaction with the user. It also uses sound effects as most games do nowadays. Many people – both sighted and blind – have tested it. They have all had a lot of fun with it.

Submarines has also been tried by a group of deaf-blind persons. Since the different conditions of the squares are provided as haptic feedback, our hypothesis was that it should work well for deaf-blind users too. As it turned out, it seems like the haptic feedback of the game was sufficient, in all but one case. In the game, the space key is used to drop the bomb in the water, and while the bomb falls, a hearing person hears the sound of the falling bomb in the speakers. It is not until the bomb has reached the water that the user gets haptic feedback to indicate if it was a hit or not. Since there was no haptic feedback for the falling bomb, this confused the deaf-blind users.

6.1.2 PAINT WITH YOUR FINGERS

The first Phantom program at Certec was a painting program for blind children, *Paint with Your Fingers*. With the Phantom, the user chooses a color from a palette. Each color on the palette has an associated texture that the user feels when painting with it. The harder you push with your finger, the thicker becomes the line. By changing program mode the user can feel the whole painting, and also print the painting on a color printer. (Original software developed by Niclas Melin.)

6.1.3 MATHEMATICAL CURVES AND SURFACES

Early in our work we also developed a simple mathematics program. People who try to explain mathematics to blind persons often notice that to some extent it is a visual subject. A haptic interface helps blind persons to understand equations in terms of curves and surfaces. Our program makes it possible to feel a mathematical curve or surface with the Phantom. (Original software developed by Charlotte Magnusson.)

6.2 Touch Windows and the Memory House

Computers have become everyday technology for many people. They have also opened up many doors for disabled people. For example, it is now fairly easy for a blind person to access written text. Any text in a computer can be read either with a one-row Braille display or a speech synthesizer. It is, however, still not easy for a blind person to access computer graphics that are common on the web, in documents and in graphical user interfaces like Windows. With this problem in mind, we started the Touch Windows project.

In the haptic Windows system that we suggested, we wanted to use haptic interaction mainly to provide an alternative image of the graphical parts of the system. The idea was to make window frames, buttons, menus, icons and more touchable via the haptic interface, which should provide the overall information in a similar way as the graphical widgets do in the standard Windows system. The text on the screen was meant to be made accessible with more specialized techniques like speech synthesis and/or Braille displays.

With a system like this it would be possible to translate the up, down, left and right of the Windows system on the screen into a touchable environment with the same construction and metaphors. It is a big advantage if blind and sighted users have the same inner image of the system. Then they can talk about the system and help each other from a common ground. Suddenly, a simple statement like, "The START button is in the lower left corner," takes on a much greater significance.

As a first step towards Touch Windows, I created a program called The Memory House (Figure 6.2). The aim was to find out if it is possible to understand and control such a complicated system as Windows with only haptic information. The Memory House [Sjöström 1997] was a combined haptic and audio memory game. The game consisted of 25 push buttons that produced a sound when pressed. There were 12 sound pairs, and one "Old Maid" or odd sound out. The buttons disappeared when the player pressed two buttons with the same sound in sequence and the game was finished when all pairs were gone.

In the Memory House the buttons were placed in five different rows. Between each row of buttons the user could feel a thin wall that helped him to stay within one set of buttons. It was possible to move from one floor to another anywhere; there was no staircase or elevator. The user only had to push a little harder on the floor or ceiling to slip through it. To make navigation among the rows easier there was a voice that read the number of the floor each time the user moved from one floor to another. Many of the blind users liked this feature and used it for reference, but some of them found the voice annoying rather than helpful.

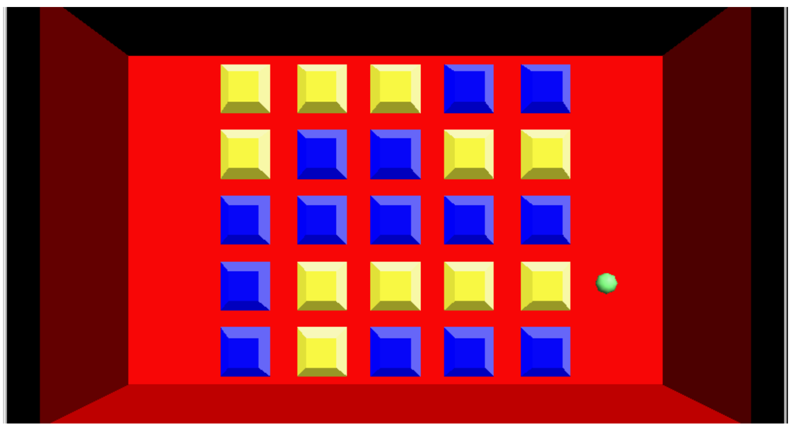

Figure 6.2. The Memory House

This program has been tested in a study comparing sighted and blind people. The sighted testers used a regular mouse and pictures or sounds, while the blind testers used the Phantom and sounds.

The test results show that it is possible for almost any blind user to navigate among the sounds and buttons in the game. Of the nine blind persons in our initial test only two were unable to finish the game (although they managed to find a few pairs). The other seven users managed to find all the pairs and many of them finished the game using about the same number of button pushes as the sighted testers. However, most of the blind testers needed more time than their seeing counterparts.

Perhaps the most interesting result was that our tests showed that it is actually possible for a blind person to use virtual touch and audio to create an inner picture of rather complex environments.

6.3 Haptics in Collaborative Virtual Environments

Haptic feedback is a natural ingredient in communication between people. One example is when a person hands over a precious artifact to another person; in such a situation, people tend to rely heavily on haptic perception to make sure that the object has been securely transferred to the receiver.

In the Haptics Group we have discussed how haptics could be used at a distance since we started our work. For example, we discussed using haptic interfaces at a distance in special education of blind children. That way it would be possible to let blind children from the whole country receive special education instruction from skilled low vision teachers without needing to move to a special school for blind pupils.

In 1998-1999 we had the opportunity to team up with Eva-Lotta Sallnäs from the Interaction and Presentation Laboratory (IPLab) at the Royal Institute of Technology (KTH), Stockholm, to conduct a study on presence in multimodal collaborative virtual environments with haptics. Eva-Lotta Sallnäs's interest was in collaborative virtual environments (CVEs) and our joint overall hypothesis was that haptics could be an interesting addition to the visual and auditory collaborative environments. This work is presented in detail in Appendix 2.

We performed an experimental study to test the hypotheses that a distributed CVE supporting the touch modality will increase perceived virtual presence and social presence, improve task performance and increase perceived task performance. The independent variable in this experiment was the interface condition in two variations: visual-voice haptic and visual-voice only. The test subjects were instructed to perform five tasks that involved lifting and moving eight cubes in the shared virtual environment. The tasks were to build different specific constructions with the virtual cubes. Half the test pairs performed the tasks with touch feedback and the other half without. Twenty-eight test subjects, all students at Lund

University, participated in the test. The subjective measures were obtained through questionnaires. The objective measures of task performance were obtained by measuring the time required to perform the five tasks.

The haptic devices used in the tests were two Phantoms (one T-model 1.0 and one A-model 1.0). In the first condition that included haptic force feedback, the subjects obtained haptic force feedback from the dynamic objects, the static walls and the other person in the virtual environment. The two subjects in each pair sat at haptic workstations at different locations. The program developed for this test enables two individuals in different locations to simultaneously feel and manipulate dynamic objects in the shared virtual environment. The objects in the virtual environment are cubes with form, mass, damping, and surface friction (Figure 6.3).

The subjects could simultaneously manipulate the dynamic objects that were modeled to simulate real cubes with form, mass, damping and surface friction. The subjects could also hold on to each other by pushing the button on the Phantom stylus. In the second condition the subjects had no haptic force feedback and could not hold on to each other. The haptic device then functioned as a 3D mouse. Voice communication in both conditions was provided through a telephone connection using headsets. Task performance was measured by the total time it took the pairs of subjects to perform the five tasks, and also by the frequency of failure to lift cubes together, which was used as a measure of precision.

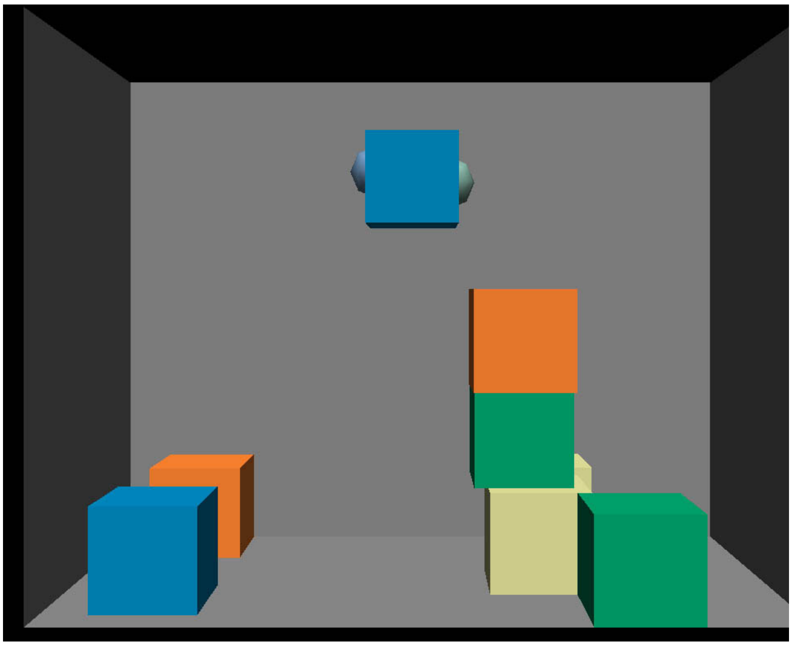

Figure 6.3. The collaborative desktop virtual environment consists of a room with eight cubes. The two small spheres represent the users. Here they are lifting a cube together.

The results show that haptic force feedback significantly increased task performance, which means that the tasks were completed in less time in the haptic force feedback condition. The subjects used an average of 24 minutes to perform five tasks in the haptic force feedback condition as opposed to 35 minutes in the condition with no haptic force feedback. An analysis of frequencies of failures to lift cubes together as a measure of precision in task performance demonstrated that it is significantly more difficult to coordinate actions with the aim of lifting objects in a three-dimensional desktop virtual environment without haptic force feedback. In the haptic force feedback condition, the subjects failed to lift cubes on average 4 times when building a cube and 7 times when constructing two piles. In the condition without haptic force feedback, subjects failed to lift cubes on average 12 times when building a cube and 30 times when constructing two piles. Thus a major part of the difference of the time between conditions can be explained by the fact that the subjects' precision when lifting cubes without haptic force feedback is lower.

We used a questionnaire to measure the subjects' perceived performance in the different virtual environments. The questionnaire showed that the subjects in the haptic force feedback condition perceived themselves to be performing the tasks significantly better. The mean value for each question on a scale from 1 to 7 (7 being the highest rating) showed that subjects perceived their task performance to be higher in the three-dimensional visual/voice/haptic condition (5.9) than in the three-dimensional visual/voice only condition (5.1). Supporting haptic force feedback in a distributed collaborative environment makes manipulation of common objects both faster and more precise. There are clear connections between the ease with which people manipulate objects together and how long it takes to complete the tasks. The results also show that haptic force feedback in a collaborative environment makes task performance more efficient.

The analysis of data from the virtual presence questionnaire shows that the conditions differ significantly. The subjects' mean rating of perceived virtual presence was higher in the three-dimensional visual/voice/haptic condition (5.4) than in the three-dimensional visual/voice only condition (4.4). Haptic force feedback thus adds significantly to people's perceived virtual presence even in an environment that supports voice communication. An example of this is the observation that the emotional expressions of failure were much fewer in the non-haptic environment when people did not manage to lift the cubes. People seemed to be more disappointed when failing to lift the cubes in the haptic environment.

In this study Eva-Lotta Sallnäs had the main responsibility for the experimental layout and questions. Kirsten Rassmus-Gröhn and I designed and programmed the software for the collaborative environment and did most of the technical setup.

6.4 Experiments with the FEELit Mouse - Haptics in Graphical Computer Interfaces

The Phantom is a high performance force feedback device with many benefits, but the drawback for the end user is its high cost. Consequently, we started to transfer our experience from the Phantom to new and less expensive devices. A force feedback mouse like Immersion's FEELit Mouse, for example seemed to be a good platform for a haptic user interface with much of the functionality of the more expensive devices but at a significantly lower cost [cf. Hasser et al. 1998].

My licentiate thesis [Sjöström 1999] contains a study where three pilot programs were tested:

1. Combining FEELit Desktop from Immersion with synthetic speech for general Windows access
2. Developing "radial haptic menus"
3. Constructing a set of virtual haptic tools that can be used as aids in searching for disordered virtual objects like icons on the desktop.

Of these, the first is an example of direct translation from graphics to haptics. The other two are examples of what can be done when using haptics on its own terms.

6.4.1 HAPTICS AS A DIRECT TRANSLATION – FEELIT DESKTOP

FEELit Desktop is a program that directly translates many graphical interface objects into corresponding haptic ones. It is a serious attempt to make a major part of Windows touchable. Almost all objects in the user interface produce something that can be felt. FEELit Desktop uses Microsoft Active Accessibility - MSAA [see Microsoft 2002], which means that many objects in application programs become touchable in the same way as the system objects. If one combines FEELit Desktop with speech and/or Braille output the result is a possible solution that will help a blind user to discover, manipulate and understand the spatial dimension of Windows. My work in this case has been to try to find out how well FEELit Desktop can compensate for things that are not made accessible by the speech synthesizer. In this context, interesting aspects are support for:

- Direct manipulation of objects
- Communication of spatial properties
- Free exploration of the interface

These are central (and widely accepted) properties of graphical user interfaces, which ensure that many people will find them easier to use than a text-based interface (e.g., MS-DOS). It is a very challenging thought that the visual interfaces which created so many opportunities for sighted people, but so many drawbacks for those who are blind, could now be complemented with haptics.

However, a direct translation of a system that was originally optimized for visual use is not the best way of implementing haptics. Consequently, I am trying to create a haptic interface which is very similar to Windows but which goes a bit further in using haptics as haptics and not merely as a replacement for graphics.

6.4.2 HAPTICS ON ITS OWN TERMS – RADIAL HAPTIC MENUS

Radial menus are ones in which each choice is indicated as a ray pointing out from the center instead of having the choices arranged in a column as ordinary linear menus. A radial menu can be likened to a pie or a clock (Figure 6.4). I have used a radial menu with 12 choices in each menu, making it very easy to use a clock analogy (e.g., "copy is at three o'clock").

There is a virtual spring that pulls the user to a line from the center of the clock to each menu choice. There is also a small virtual spring that pulls the user towards the center. My hypothesis is that radial haptic menus can work better than linear ones for three reasons:

- It is possible to tell which choice is the active one by reading an angle instead of reading an absolute position.
- The user has a well-defined and easily accessible reference point in the center of the menu.
- It is easy for the user to adjust the menu to her own needs by moving the mouse in a circle at a greater or smaller distance from the center. Away from the center, greater force and larger movements are required to get from one menu choice to another. Conversely, it is possible to change the active choice using only a small movement and almost no force at all when moving closer to the center. In other words, the navigational precision increases the closer one moves to the center.

Moreover, radial menus are generally considered to be efficient because they allow the user to select from a number of possibilities without moving very far and the number of choices is relatively large.

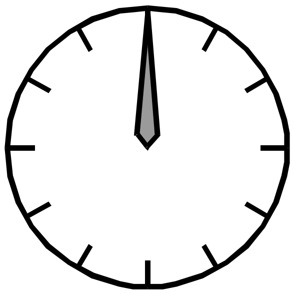

Figure 6.4 Clock metaphor of a haptic radial menu

The "snap-to-centerlines" is a useful approach for creating haptic menus. I have tried thin walls but they do not work very well. It is very easy to move across one menu item without noticing it even if the distance to the next wall is fairly large.

In the case of a radial menu, the snap-to-centerline idea is even better since it makes it easy to feel the angle of the current selection. If you instead design the menu with a wedge-shaped area with thin walls to the next selection it is much harder to feel the direction you are moving in. And since the distances are very small in this type of menu, it is a very good idea to use direction as much as possible. It is also quite hard to remember/identify exact positions in a haptic environment; movement is absolutely necessary and that means that we want to use directions rather than positions as much as possible.

In any virtual environment it is important to provide good reference points for the user. Tests with the Memory House showed that the subjects who actively used reference points in the rooms performed much better than those who did not. The only well-defined natural reference points on a haptic display are the corners. The fact that radial menus have a well-defined reference point in the center is therefore of great importance.

To test radial menus I developed a special program that shows a mock menu system similar to a standard word processor's. This program uses sampled words to indicate the imagined function of each menu choice.

6.4.3 HAPTICS ON ITS OWN TERMS – VIRTUAL HAPTIC SEARCH TOOLS

Menus can be very useful when the information is ordered and fits in a linear-hierarchical structure. The opposite is the case when objects are scattered over an area with no special pattern. For a blind person, locating an object with a point probe in a 2D space can be as hard as finding a needle in a haystack. Even if you get as close as 0.1 millimeter from the object, you still do not feel anything at all until you touch it. This is a problem since it is necessary to be able to locate objects if one is to understand someone else's Windows desktop.

To help the user in cases like this, I propose three virtual search tools that can be used as a complement to the standard point probe interaction:

- A cross that makes it possible to feel when you are lined up with an object horizontally or vertically (Figure 6.5).
- A magnet that pulls the user towards the nearest object.
- A ball that makes it possible to feel objects at a distance but with less detail.

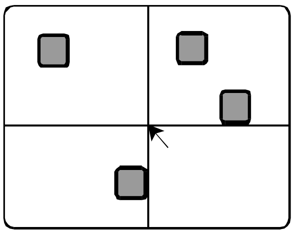

Figure 6.5. The cross touching two objects on a simulated desktop

I have developed a program to test the cross tool for finding objects in an unknown environment. The magnet and the ball were saved for future studies. (Today, the Reachin API uses a finite sphere instead of a point for user interaction, which is essentially the same thing as the ball tool.)

With these tools it is possible to feel objects without touching them directly. It is similar to when a blind person uses a white cane to avoid running into things. In this case, though, both the tools and the objects are virtual.

Since all of these tools distort the sensation, it is important to make it easy to switch between the different tools and no tool at all. In my test program the user can turn the cross on and off by clicking the right mouse button. The test does not take the tools into the real Windows environment. It is a straightforward search task for testing purposes only.

A variant of the cross that could also be useful is a half cross – a vertical or horizontal bar. Both the cross and the bars reduce the 2D search task to 1D. The user can move along a line in order to feel if there are any objects. If a bar hits something, the user can move along the bar to feel what is there.

Locating objects is very important in all user interface work and, naturally, it is also important when the user is discovering a new or unfamiliar environment. Several things could be done to make it easier for a blind user to find objects. It is also important to help the user be certain that there is no object for her to feel. With clean point probe interaction it can be very hard to be sure that all the objects are gone. With the cross, the problem of determining when there are no objects at all is almost eliminated since it is very easy to scan the whole screen using a one-dimensional movement.

6.5 Enorasi User Tests

The tests in this section were conducted as part of the Enorasi Project. Twenty-five blind test users, 14 from Italy and 11 from Sweden, carried out the tests. Nine of them were female; 13 were blind from birth. Their ages varied from 12 to 85 years with a mean of 39 and standard deviation of 19. They had varying professional backgrounds, but there were more students and telephone operators than in an average population. For time reasons, not all test users participated in all of the tests. All of the test users had limited or no experience in using the Phantom. All were blind.

The programs were developed with either the GHOST SDK from SensAble Technologies (geometrical objects, both mathematics programs and the sound memory games) or the Reachin API (textures, line drawings, floor plans, traffic environment and the complex objects).

The hardware that we used for haptic interaction was the Phantom from SensAble Technologies. We used two Phantoms in parallel for the tests, one was equipped with a thimble and the other was equipped with a pen as manipulandum. Twelve of the users used the Phantom with a thimble, 8 with a pen and 5 users switched between the tests so that they used both the thimble and the pen.

The tests are described in detail in two articles submitted to Haptics-E, both available as appendices to this dissertation. See Appendix 4 for representation of 2D haptics (Section 6.5.1-6.5.4) and Appendix 5 for 3D haptic virtual environments (Section 6.5.5-6.5.9).

6.5.1 MATHEMATICS – HERBIVORES AND CARNIVORES

This virtual environment was a dynamic one with a curve displaying information from a simulation of an ecological system with imaginary carnivores ("mega-crocodiles") and herbivores ("super pigs") on an isolated island (Figure 6.6). A slider in the environment could be moved to adjust the fertility of the herbivores, or in mathematical terms change a parameter of the differential equation that represents the number of animals on the island. In order to recalculate the curve, a button had to be pressed after the slider had been moved to a new position.

The tasks in these tests varied from simply feeling the curve and describing it to finding the smallest value of herbivore fertility that produced a system where the animal strains do not die out.

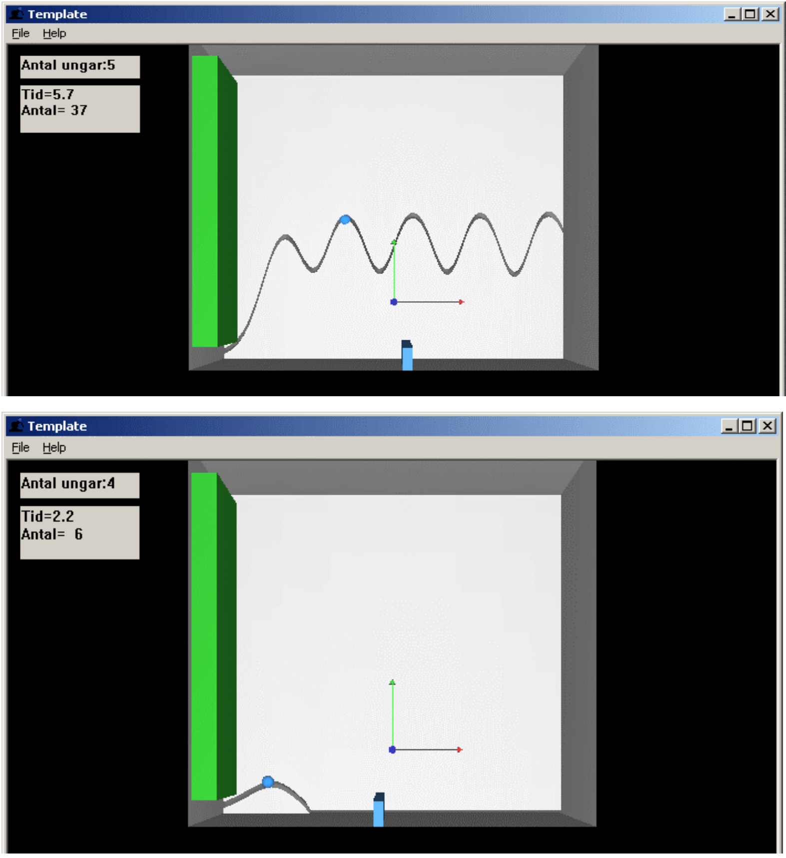

Figure 6.6. The mathematical environment with herbivore fertility set to 5 respectively 4 births per time unit.

The graph in the system is rendered as a groove in the back wall of the room. The user was instructed to sweep the back plane until he or she fell into the groove, then the user could choose to trace the curve or to move to another place on the curve without following it. The left wall and the floor also represent the coordinate axes (only positive time values and positive number of animals). The user could place the cursor at any place on the curve and press the space bar on the keyboard to get exact information about a value. The X and Y values were then displayed in text that could be accessed, for instance, via synthetic speech or Braille. Synthetic speech in this test was simulated by letting a human read the values on screen as they changed.

6.5.2 TEXTURES

The virtual environment in these tests consisted of a room with simulated textures on squares on the back wall. In the first test, one square with corduroy fabric was used. The user was also given a thin piece of wood mounted with the real corduroy texture. The task was to explore the virtual texture and then orient the real texture sample in the same way as the one in the virtual environment.

In the second test, the virtual environment consisted of four different textures (Figure 6.7). The user was given five different real textures, mounted on wood, and the task was to choose four of them that corresponded to the textures in the virtual world and then to spatially arrange them in the same way as in the virtual world. The simulated textures included grinded wood, fine sandpaper, coarse

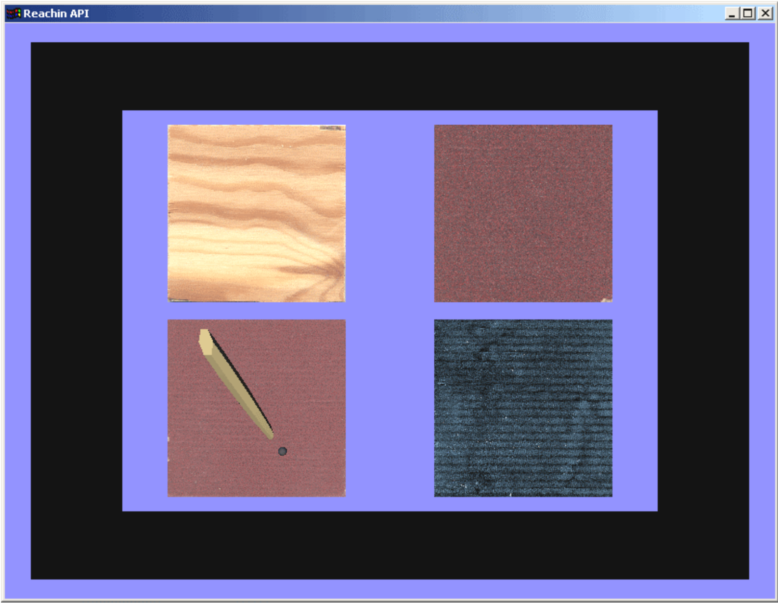

Figure 6.7. The virtual environments for the second texture tests.

sandpaper and the same corduroy as in the first test. The fifth real sample, which was not simulated, was a semi-coarse linen type cloth.

6.5.3 LINE DRAWINGS

The virtual environment consisted of a room with a relief line drawing of a stick man or an elephant (Figure 6.8 and 6.9). The relief for the stick man was positive (lines as ridges), while the relief for the elephant was negative (lines as valleys). The picture was placed on a square representing a piece of paper that was a few mm thick and placed in front of the back wall. The first task was to explore the line drawing, describe it to the test leader and also guess what it represented. The users that did not manage the first task were told what was depicted. The second task was to identify a part of the drawing, such as a foot.

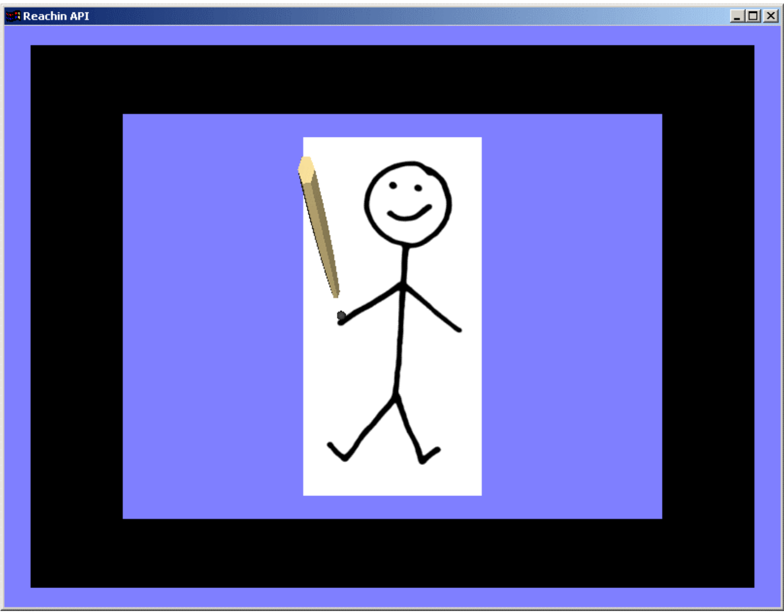

Figure 6.8. A stick man. One of the two line drawings used in the test. (The pen on the pictures shows the position of the user interaction point.)

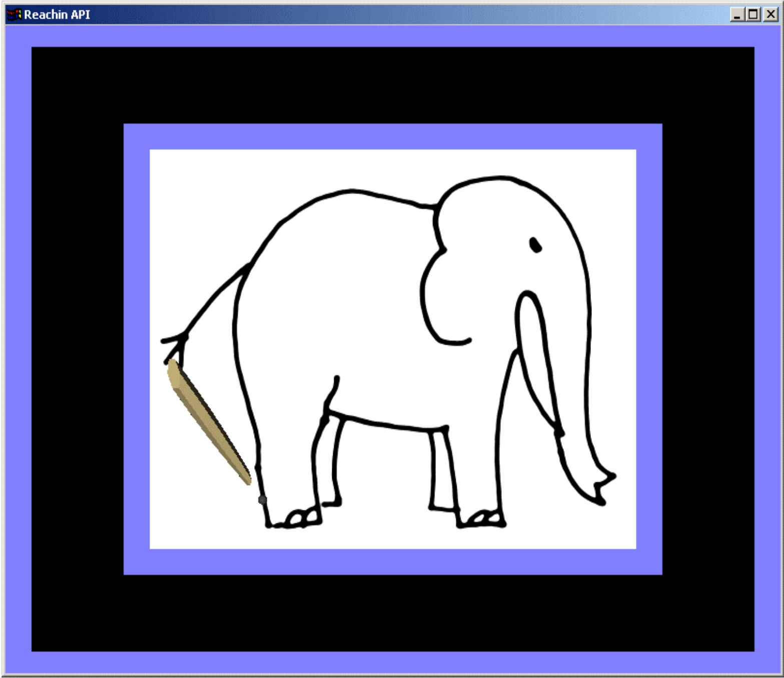

Figure 6.9. An elephant. The second of the two line drawings used in the test.

The haptic relief was rendered from scanned black and white images. The scanned image was slightly blurred and rendered haptically as a height map where dark areas corresponded to high or low areas depending on if the lines were represented as lines or valleys.

6.5.4 FLOOR PLANS

The virtual environment consisted of a positive relief map. Walls were thus shown as ridges. To avoid moving through the doors without noticing it, the door openings had a threshold that was simulated as a very low ridge. The walls and thresholds were designed to make it possible to move around the rooms to feel the size and form of the room without accidentally falling through the door. At the same time it was important to make it easy to distinguish walls from door openings even when tracing the wall and to make it easy to move between two rooms when that was desired. To make all this possible, the thresholds were made thinner than the walls and only a few millimeters high. The walls were rendered 25 mm high, which is more than what is normal in tactile reliefs but it works very well in haptic reliefs. To move between the rooms, the user could either stay close to the floor and move in and out through the doors, or "jump" over the walls and move directly from room to room. Both strategies were used by the test users.

The rooms and areas in the floor plans had sound labels on them to identify each room. The label sound was invoked by pressing the floor in the room and the sound stopped immediately when the user lifted his or her finger. The sound was repeated with about a second of delay as long as the floor was pressed down.

The test included two floor plans (Figure 6.10): one of a 6-room imaginary apartment and one of a real 18-room corridor (plus additional spaces) at Certec in Sweden. In the apartment test the user was asked to explore the apartment to gain an overview of it. The task was to count the rooms and locate a specified room in the virtual environment. In the corridor test the user was asked to locate a treasure on the map represented as the room with a different texture on the floor (only performed in Sweden). They were then asked to physically locate the room with the treasure in the real corridor.

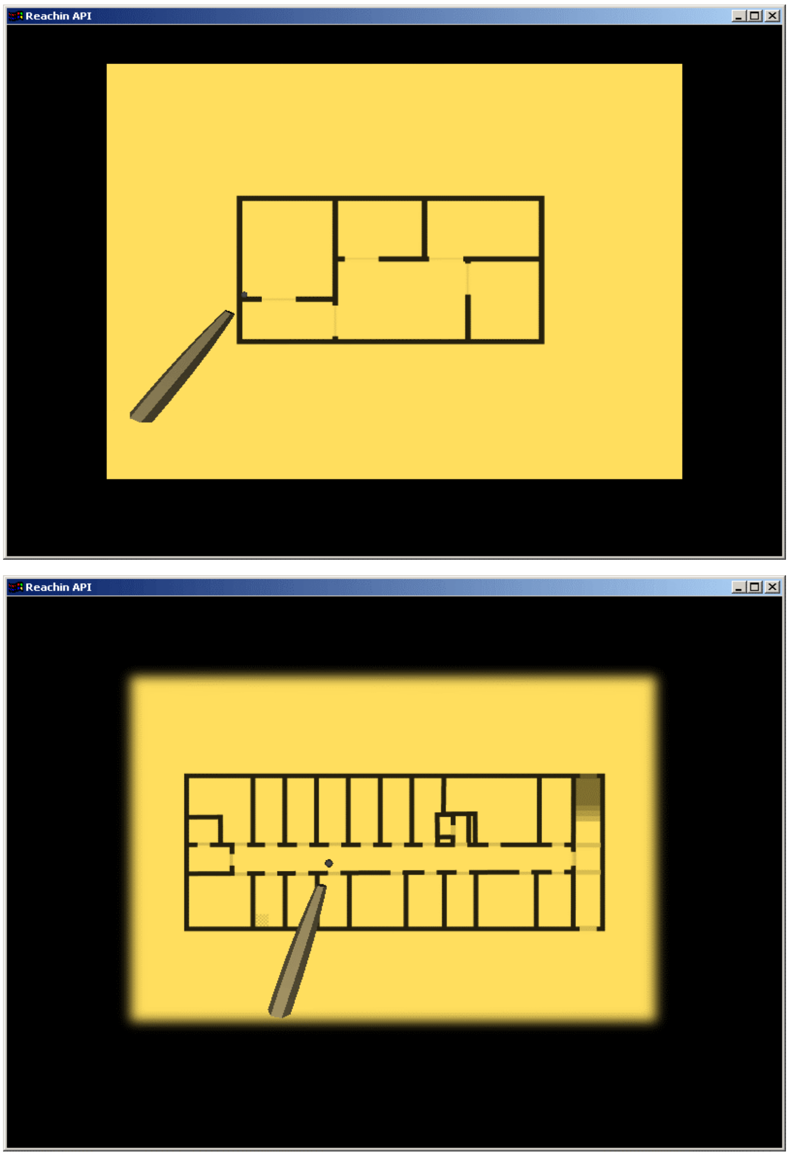

Figure 6.10. The two different floor plan environments used in the test.

6.5.5 GEOMETRICAL OBJECTS TEST

In this test, the first environment that was tested consisted of a room with a single geometrical object (Figure 6.11). On the desk, there were two boxes. In one, there were a number of physical models of different geometrical objects, similar to children's building blocks. The other box was empty. The user was instructed to explore the virtual model, and then to pick out the object that matched from the physical models. The real objects had the following shapes: rectangular parallelepiped (4 with different proportions were included), cylinder,

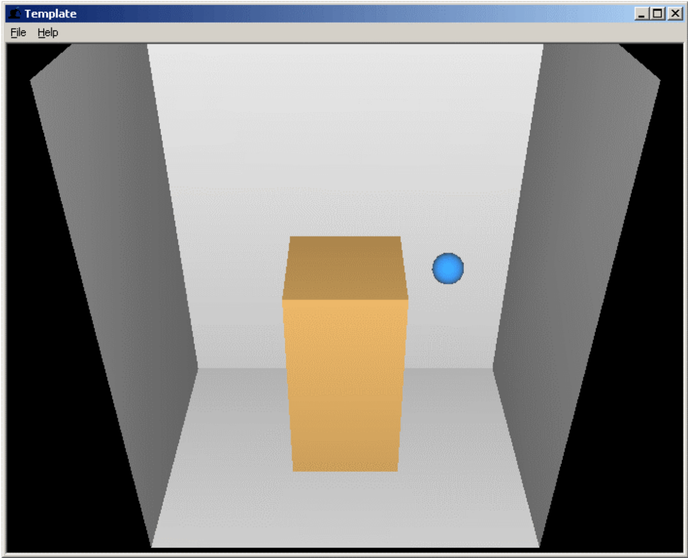

Figure 6.11. Virtual room for single object test. The blue sphere shows the user interaction point.

roof, semi-cylinder and sphere (Figure 6.12). The virtual object was a double cube, a cylinder or a roof.

Figure 6.12. Real object models for single object test.

The second test environment consisted of a similar room but with three geometrical objects placed in a grid made of small ridges on the floor. On the desk, there were two boxes. In one, there were a number of physical representations of different geometrical objects. The other box contained a wooden grid but no geometrical objects. The user was again instructed to explore the virtual environment and make a copy of it with the wooden models.

6.5.6 VRML OBJECTS

In this test, the user was to feel different VRML models of objects from real life and discuss their physical properties with the test leader.

VRML vase model

A single object was positioned on the floor in the room (Figure 6.13). The user was instructed to explore the object and describe its shape. The user was also supposed to guess what the virtual object represented. Any answer that suggested that the user understood that the object was vase shaped was considered correct for the analysis.

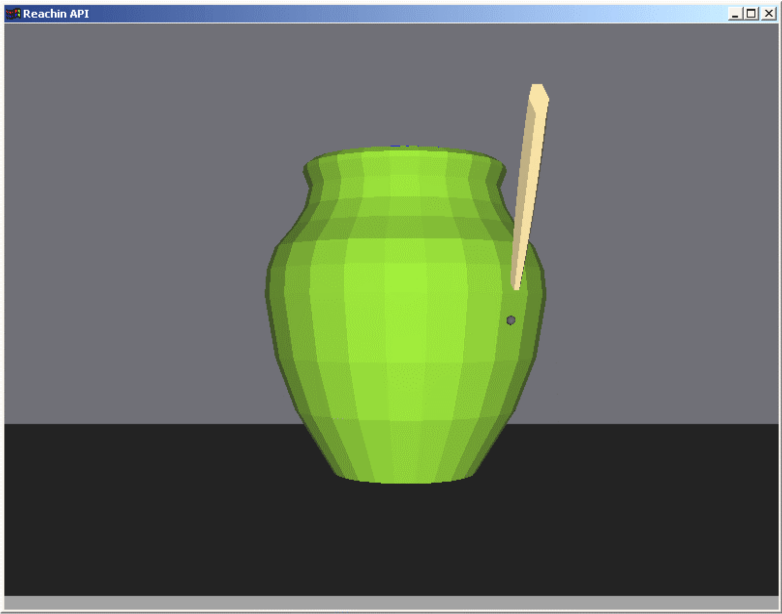

Figure 6.13. VRML model screen dump: a vase. The pen and the small sphere at its tip show the user interaction point.

VRML grand piano model

The virtual room had two objects standing on the floor – a grand piano and a stool (Figure 6.14). The user was told what the virtual room contained. The task was to explore the room and identify the grand piano and the stool and also describe the shapes. The test person and test leader talked about different physical properties and the user was asked to identify parts of the grand piano, such as the keyboard, the lid, etc.

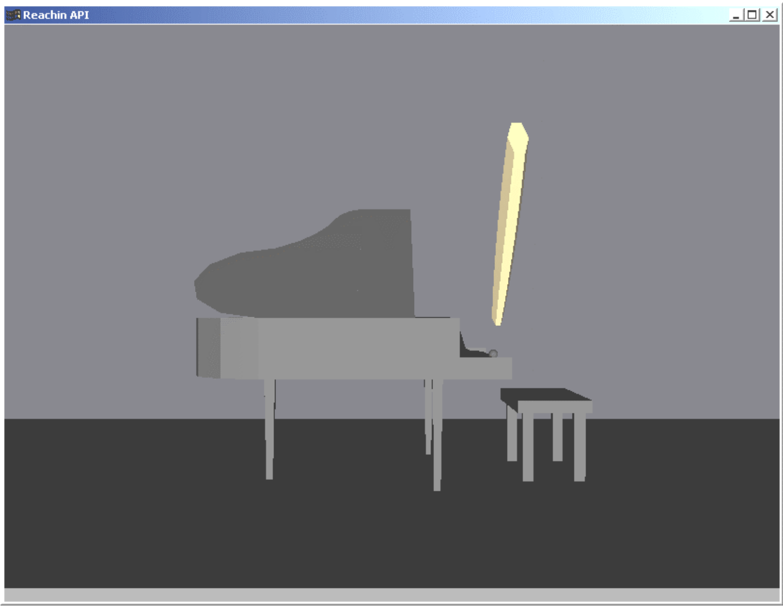

Figure 6.14. VRML model screen dump: a grand piano and a stool.

VRML satellite model

The virtual environment consisted of a satellite in space (Figure 6.15). The user was told what the virtual room contained and was supposed to find, explore and describe the different parts of the object (both solar panels and the main body).

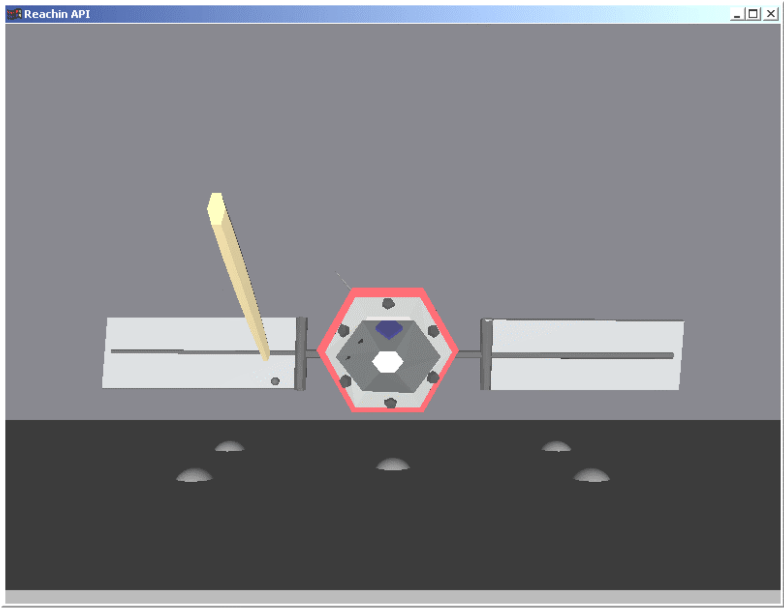

Figure 6.15. VRML model screen dump: a satellite.

6.5.7 TRAFFIC ENVIRONMENT

The virtual environment consisted of 6 houses (2 rows, 3 columns) with roads in between (Figure 6.16). The roads, sidewalks and houses had different surface properties. The task was to explore the environment and to describe the surface on the sidewalks, the road and the houses. Then, the user was asked to find the shortest route from house A to house B while staying on the sidewalks as much as possible. The houses emitted a sound when pressed.

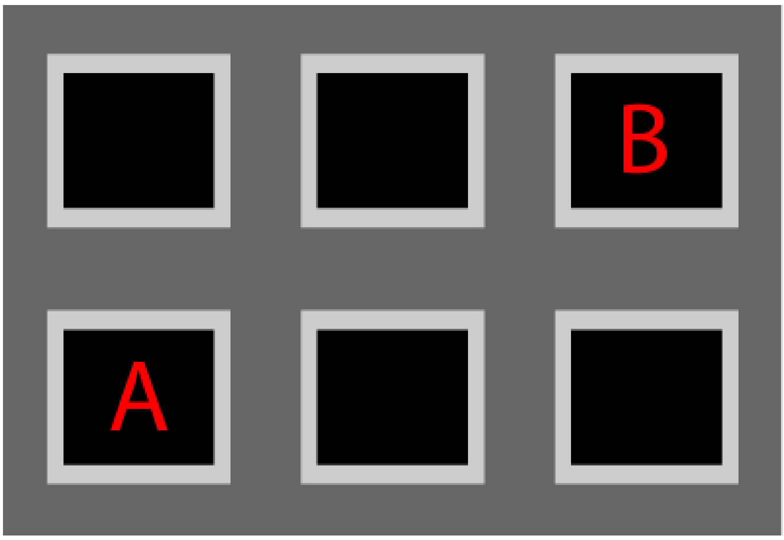

Figure 6.16. Bird's eye view of the traffic environment

Environment with cars

The virtual environment was the same as in the previous test, but some cars were added to the scene (the green and red blocks in Figure 6.17). The cars moved back and forth on the roads. The task was again to travel from house A to house B, but this time there was a risk of being hit by a car. Depending on the user's interest, more than one attempt was made to reach the destination and sometimes the test leader would act as a traffic light and tell the user when it was safe to cross in the reattempts.

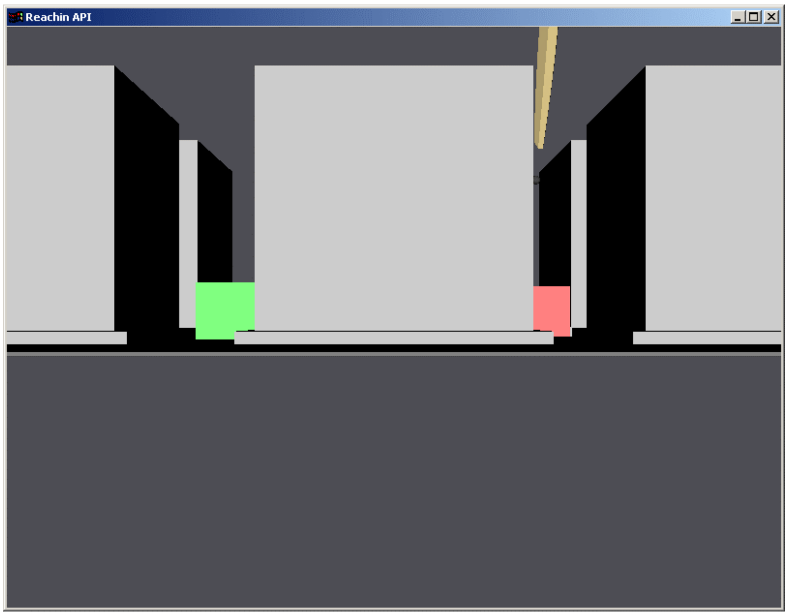

Figure 6.17. Screen dump of the traffic environment. The cars are the small colored cubes between the houses. The three cars move back and forth on the roads.

6.5.8 SOUND MEMORY GAME

This test was a memory game with virtual buttons that played sounds when pressed. The test environment consisted of a room with 6 or 12 cubic buttons attached to the back wall. Every button played a sound when pressed. Every sound appeared twice and the buttons with the same sounds were to be pressed in succession – directly after one another. This made a pair. It did not matter how long it took between pressing the buttons with the same sound, as long as no other button was pressed in between. When a pair was found the buttons disappeared (Figure 6.18).

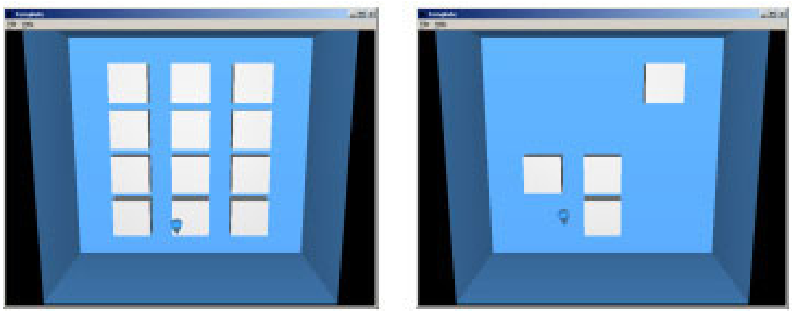

Figure 6.18. The initial memory environment (left) and how the environment looked after some pairs had been found (right).

6.5.9 MATHEMATICAL SURFACE

For this test we used our recently redesigned curve display program (Figure 6.19). This program makes it possible to submit an equation corresponding to a mathematical surface and obtain a haptic rendering of it. The program can render functions of both one and two variables. If the function has only one input variable, the output is a line rendered as a groove that can be traced with one finger on the back wall of the virtual room. If the function has two input variables, the output is instead a haptic representation of the functional surface defined as z=f(x,y). The users were asked to feel and describe the surface.

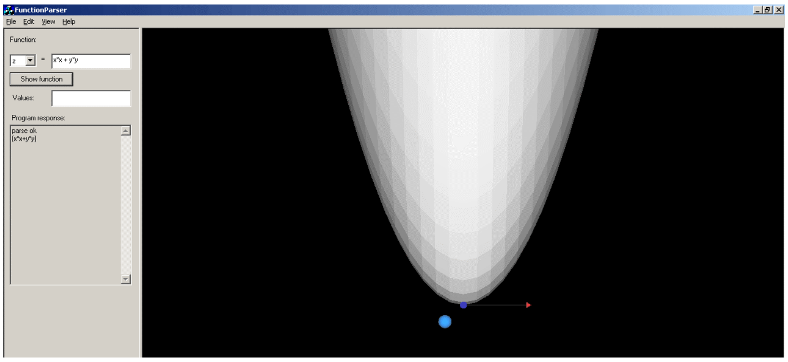

Figure 6.19. Mathematical surface.

6.5.10 RESULTS AND DISCUSSION ENORASI TESTS

For the 2D tests we can conclude that it is rather difficult to identify a haptic image without any contextual information. However, it seems that having a general idea of what is represented makes the image understanding much easier. The importance of contextual information has been noted before by Ramloll and colleagues [2001] and by Alty and Rigas [1998]. It has also been shown that training can improve results in haptic interaction substantially [Jansson & Ivås 2000].

Haptically represented applied mathematics apparently functions quite well. The sliders and buttons in the current program are rudimentary, an improvement of which should make the results even better. The floor plans worked very well for a majority of the test persons. It is also apparent that the knowledge gained from this kind of map can be used in real life. We received several positive comments from the users about the maps. We can see several important uses of this technology in the future, for example:

- Haptic web browsers
- Interactive multimodal simulations of applied mathematical problems
- Automatic visual-to-haptic image conversion
- Haptic representation of public map databases.

The outcomes of the 3D tests show that blind users are also able to handle and understand quite complex objects and environments. Sometimes a realistic virtual environment even appears easier to handle than more abstract but simpler test environments.

In our tests, the subjects recognized rather complex VRML models of real objects better than the environment with 3 geometrical objects in a grid. We conclude that the contextual information made part of the difference, but to some extent it may just reflect the test setup. Further tests to resolve this issue should be performed.

The importance of context highlights the importance of multimodal interaction such as sound. Another factor observed to be important is haptic scanning strategy, which is also described as "exploratory procedures" by Lederman & Klatzky [2001].

It has been shown that for the objects included in this test, the blind users were not greatly disturbed by the VRML approximation. What does disturb the illusion, however, is if the model is not haptically accurate. A similar problem has been noticed by Colwell and colleagues [1998a].

When it comes to the mathematical surfaces, all seven users could feel and describe them. They had no problem with the fact that the surface was made out of flat triangles. The users reported that this kind of mathematical information is not easily accessible for blind people in general and that this application provides them with a practical way of making it available.

The last tasks tested did not bother the test persons. All users could identify the main objects (houses, sidewalks and roads) in the traffic environment tests. The test task was not found to be very difficult, and was considered quite fun. Finally, all users managed to complete both versions of the sound memory game.

6.6 Follow-up Experiments on Haptic Interaction Design Guidelines

When working with the guidelines in this dissertation, it turned out to be necessary to complement the experiments already carried out with some new ones. All guidelines are based on observations made during user tests, but for some of the guidelines more formalized tests were needed to enable us to either support or reject a suggested guideline.

A complete account of these follow-up experiments is available in Appendix 6. In the next chapter, where I report on and discuss the guidelines, I also discuss the results from these final experiments.

7. Guidelines

This chapter summarizes my experience from working with non-visual haptic interfaces in guideline form. The experience is backed up by results from other researchers, followup experiments and reasoning, taking observed problems as a starting point. The guidelines are meant to be design guidelines, the target groups being researchers, designers, testers, developers and users of applications that use haptics in some form. The guidelines should be particularly useful for three purposes:

1. To come up with an initial design that is as good (usable, efficient, learnable, user acceptable, etc.) as possible
2. For the heuristic evaluation of an existing design
3. To facilitate users investigating haptic interfaces and to empower them in providing feedback from their experiences.

No guidelines can eliminate the need for trials with real users. An appropriate set of guidelines can only increase the chances of devising a better design with which to begin testing and it could probably save many tribulations for both test users and designers. Still, it is very likely that user tests will reveal some problems that were overlooked in both the initial design and a heuristic evaluation.

The vast majority of the tests and observations were carried out in situations with haptic interaction without vision. Many of the problems that need to be dealt with in haptic interaction are alleviated when combining haptics and vision but since this thesis is about haptic interaction design primarily for blind people, I have concentrated completely on how haptics works without vision.

The guideline headings are:

1. Elaborate a virtual object design of its own
2. Facilitate navigation and overview
3. Provide contextual information
4. Utilize all available modalities
5. Support the user in learning the interaction method and the specific environments and programs

7.1 Problems of Non-Visual Haptic Interaction

To classify and explain the information in the guidelines, the starting point will be the prerequisites and possible problems in non-visual haptic interaction. The five prerequisites divide the interaction into five different layers, each possessing its own specific, possible problems. This division is also suitable for the guidelines.

I have identified the following five basic prerequisites for being able to work efficiently in a virtual environment.

- To be able to explore, understand and manipulate the objects in the environment
- To navigate and to gain an overview
- To understand the context
- To use all modalities that are normally used
- To learn the interaction method and the specific environments/programs

The problems in turn have been divided into three groups depending on their background. I have chosen the following groups:

- Problems related to (isolated) touch interaction. This can be in real life and in virtual reality, also compared to other senses.
- Problems related to virtual interaction of any kind
- Problems related to discrete point interaction haptics

In this presentation, the classification of the problems of non-visual haptic interaction (Table 7.1) serves as the first step towards the guidelines (Table 7.2). In the underlying work however, I have gone back and forth between the identified problems and the preliminary guidelines and Table 7.1 was actually not ready until Table 7.2 was also completed.

Table 7.1 Problem classification of haptic interaction design.

	Objects	**Navigation and Overview**
Problems related to (isolated) touch interaction in real life and in virtual reality	Too many details on tactile images, for example, can make the objects hard to grasp. Objects may need to be simplified. The orientation of the objects is important. An orientation that does not correspond to the user's mental image of the object can make it hard to understand.	Overview will not come automatically. Reference points are necessary. Changes in the reference system can confuse the user. It is hard to move one's finger on a straight line in free space without feedback.
Problems related to virtual interaction of any kind		Many of the natural navigation methods that can be used in real life will not work in virtual reality.
Problems related to discrete point interaction	Active scanning is necessary to feel anything at all. Small and thin objects are hard to find and explore. Proportions are hard to judge. There are limits to what can be simulated. Some textures are hard to distinguish when haptically simulated.	Objects can be hard to find, especially if they are suspended in free space. The user's finger does not have any size/volume in the virtual environment.

Context	Multimodality	Learning
Object identification and understanding can be difficult without context since there are very rare cases in real life that force a person to recognize a random object without knowing its context. Context is normally gained via other senses than the sense of touch.	Blind persons are used to compensating for lack of vision with all other senses. A single sense does not provide as much information as could be used. Information transfer via the sense of touch is slow compared to other senses.	Learning and awareness are closely interwoven and take place only to a limited extent unless you are provided with an overview, the context, possibilities to navigate and to utilize more than one sense.
Virtual interaction can isolate the object or environment from its context.		Inconsistencies in the interaction or feedback make the tool and program more difficult to learn.
Object information can take considerable time to gather with point interaction haptics only. The context normally takes considerably longer to understand if no additional senses are available.	Discrete point interaction is even slower than ordinary touch interaction since it uses only a subset of the whole sense of touch.	Beginner’s problems related to the specifics of point interaction are common. 2D and 3D properties of objects can be misunderstood, especially by new users. Learning is limited through reduced opportunities for interaction and shared experience between student and teacher.

7.1.1 ELABORATING ON THE PROBLEMS TABLE

The span from object to learning covers a wide spectrum of problems that can arise in the haptic interaction. In many cases it is clear that a problem belongs under one of the headings, but often there is a sliding scale and a problem can belong partly under one heading and partly under another. This is especially true among the context/multimodality/learning headings. It is also the case that many problems can be seen from two sides so that they could be placed in different problem columns. For example, "Object information can take a considerable time to gather with point interaction haptics only." In that case I have simply placed the piece of information where the solution to the problem is most likely to be.

Objects

On the object level, only two problems related to touch interaction have been included. This is mostly a reflection that touch based object interaction works quite well if the user is allowed to use both hands. The size of the object is of course a factor: feeling the shape of a full scale house is not very easy, for example. In some cases there is a need for simplifications, especially when using tactile images (which I maintain is a special case of object interaction). In this case the details tend to clutter the image to an extent that makes the whole picture unreadable. However, there are many cases in which the details do provide extra information about an object.

There are examples in which objects that are not oriented the way people expect them to be are confusing to users. It is likely that this problem is greater if the user cannot touch the whole object at the same time and that would make the problem worse when using point interaction haptics. An example of this problem, a model of a grand piano, is discussed under Further Reasoning, Section 7.3.1.

When it comes to point interaction related problems, the most prominent property is that active scanning movements are needed to feel anything at all. Movement is used in all kinds of touching, even in the real world, but in virtual point interaction haptics, movement is even more important because without movement the information transfer is limited to a single force vector.

The normal way of modeling the user within the virtual environment is as a point and that makes it hard both to find and explore small and thin objects. The small objects are unlikely to catch the user's movement and that is what makes them hard to find when scanning. Small or thin objects are also easy to lose contact with in a scanning movement, making them difficult to explore too. A good example is a Windsor-style chair compared to an armchair: the first would be very hard to identify using one-point haptics with all its spindles but the latter would be much easier since it is basically all one big piece.

Furthermore, proportions have proven to be hard to judge using virtual haptic point interaction (in our Enorasi 3D objects test, for example, see Appendix 5). This is at least in part dependent on the variety of movements required to explore the object in different directions: back and forth exploration can be done with only finger movements, whereas up and down exploration requires hand movements.

The point interaction method also has some limitations in what can be simulated. Think of it as touching objects or textures with a tool or a thimble on your finger, which limits what you can feel of some textures in particular.

Navigation and overview

A leading feature of the visual sense is that it can provide an overview of a scene at a glance. It is almost automatic. In comparison, the sense of touch requires movement and time to gain an overview. This problem occurs both in real and virtual touch but again there is a scaling factor involved. Point based interaction often requires more scanning since you cannot use the whole hand.

All kinds of navigation require reference points. But when using touch, only the reference points need to be within reach to be useful. (A person with intact hearing would combine the touch based reference points with auditory ones that are also useful, even at a distance.) Reference points are necessary in virtual environments as well as in real life. Changes in the reference system can confuse the user.

Many of the natural navigation methods that can be used in real life will not work in virtual reality. This is a problem not only in haptic virtual environments, but in all virtual reality and has been the subject of considerable research in recent years.

As has already been stated, the user's finger in point interaction does not have any size in the virtual environment thus making objects harder to find, especially if they are suspended in free space. This also makes navigation among the objects more difficult.

Context

The context of an object is often determined by the situation. Take as an example going to a market to buy fruit: In this case a roundish thing with a slightly rough surface is likely to be an orange. In another context, the same object could have been a model of the sun. The virtual interaction can isolate the object or environment from its context since it is not automatically provided. As with most laws of nature (gravitation for example), the context must be recreated in the virtual environment because the interface itself does not apply context or laws of nature to the environment it is mediating.

Object identification and understanding can be difficult without context, especially if the object is unfamiliar. Context can make all the difference between understanding what the object is and not understanding it at all. Since most people are not used to handling objects via virtual haptics, the situation in which the object is not immediately recognizable is even more likely to occur; in that case it is almost always beneficial to supply the context as extra information.

Multimodality

Blind people are used to compensating for their lack of vision with all other senses. Object identification, navigation, overview and contextual understanding are all normally accomplished with a combination of touch, auditory information, smell, etc. Even the taste buds are often used to determine the quality of certain food products (even though we normally do not rely on the sense of taste as much as babies of a certain age do).

Information transfer via the sense of touch is slow compared to other senses. Discrete point interaction is even slower than ordinary touch interaction since it uses only a subset of the whole sense of touch.

Learning

Learning and awareness are closely interwoven and take place only to a limited extent unless you have an overview, context, opportunities to navigate and to utilize more than one sense. Beginner's problems related to the specifics of point interaction are common. The learning issues are important not least of all in the initial phase of getting acquainted with the interaction method of a haptic interface.

The learning situation in haptic-human computer interaction is somewhat contradictive: On the one hand there is a need for everyone to have his or her own experiences of haptic interaction. It is hard, if not impossible, to explain what it feels like to use a haptic interface for someone who has not tried it. On the other hand, there are many things that a new user of a haptic interface can learn from the experienced users when he or she starts using a haptic device like the Phantom.

The pitfall to avoid here is ending up in a catch 22 situation: an urgent need for guidance but at the same time limited communication between the guide and the student since most haptic interfaces are for one user only. There are different solutions to the problem, and all of them should be used to enable a comprehensive and fast introduction to the world of haptics. One is to elaborate introductory exercises, building up automaticity in handling the haptic tool. In this way, the teacher uses his or her master abilities and understanding for the construction of the exercises. Another possibility is that an experienced user holds the beginner's hand and helps her in doing the exploratory movements. This could also be done by using two haptic devices and voice communication while performing the same coupled movements in virtual reality.

7.2 Going from Problems to Guidelines

Having seen the problems that can arise in haptic interaction, it is possible to formulate a basic set of guidelines to avoid them. The relationship between the problems and the guidelines are similar to the relationship between a diagnosis and a prescription. You need to identify what the problem is before you can write out the prescription, and the better you understand the problem the better are the chances of getting effective treatment. Sometimes it is not possible to treat the problem directly but still possible to alleviate the symptoms. In other cases the best treatment can be to avoid the problem from the start.

Table 7.2 shows the problem summary converted into guideline form. In this table, I have merged the information from the three rows in Table 7.1.

Table 7.2. Guidelines related to the problem summary.

	Objects	Navigation and Overview
Guidelines and examples	***Guideline 1. Elaborate a virtual object design of its own*** Avoid objects with small and scattered surfaces. Objects with large connected surfaces are easier to find and explore. Use rounded corners rather than sharp ones. Virtual objects in virtual worlds can be given virtual properties. Utilize them. Optimize your haptic interface widgets as well. Think about affordance. Make sure that the models are haptically accurate and work without vision. Be aware that orientation of the object matters. Consider different representations to enhance different properties (negative relief emphasizes the line whereas positive relief emphasizes the contained surface).	***Guideline 2. Facilitate navigation and overview*** Provide well defined and easy-to-find reference points in the environment. Avoid changing the reference system. Make any added reference points easy to find and get back to. They should also provide an efficient pointer to whatever they are referring to. Utilize constraints and paths. Virtual search tools can also be used.

Context	Multimodality	Learning
Guideline 3. Provide contextual information Provide contextual information from different starting points: - Present the haptic model or environment in its natural context. - Provide information about the purpose of the program. - Provide information about possibilities and pitfalls in the environment. Use a short text message, like a caption under an image or model, provided as speech or Braille. That can make a significant difference. Idea: Consider using an agent or virtual guide that introduces the user to the object and also gives additional information if requested.	***Guideline 4. Utilize all available modalities*** Combine haptics with sound labels, a Braille display and/or synthetic speech for text output to help identify objects, etc. Try environmental sound to aid in getting an overview. Use audio (both sound labels and environmental sounds) to provide a context. Provide feedback to the user via any available sense.	***Guideline 5. Support the user in learning the interaction method and the specific environments and programs*** Be consistent; limit the number of rules to remember. Give clear and timely feedback on the user's actions. Facilitate imitation of other users and situations if possible. Develop elaborated exercises to make the handling of the interaction tools and methods automatic in the user. Idea: Consider using a virtual guide or remote users to help when a user faces a new environment.

7.3 Further Reasoning of the Guidelines

7.3.1 GUIDELINE 1: ELABORATE A VIRTUAL OBJECT DESIGN OF ITS OWN

- Avoid objects with small and scattered surfaces. Objects with large connected surfaces are easier to find and explore
- Use rounded corners rather than sharp ones.
- Virtual objects in virtual worlds can be given virtual properties. Utilize them.
- Optimize your haptic interface widgets as well. Think about affordance.
- Make sure that the models are haptically accurate and work without vision.
- Be aware that orientation of the object matters.
- Consider different representations to enhance different properties (negative relief emphasizes the line whereas positive relief emphasizes the contained surface).

Objects in a haptic virtual environment may just be copies of real objects but the real potential of virtual haptics arises when virtual objects are designed without the limitations of the real world, but taking into account the deficiencies of haptic displays. This guideline means that virtual object design is not only about designing real objects and putting them into a virtual world, but also about designing specifically for virtual interaction. Avoid shapes that are hard to explore; make objects easy to discriminate and manipulate and use the extra abilities to go beyond the normal laws of physics that come with virtual haptics.

Small versus large surfaces

As described in the Problems Section (7.1), small surfaces or thin objects can be close to impossible to explore with point interaction haptics. It is thus a good idea to avoid these kinds of objects in the virtual environment. If they are really needed, it is possible to make them touchable by moving away from the object-to-point interaction model. An example of this is used by Fritz and Barner in a mathematics viewer program [Fritz & Barner 1999]. Here, the graphs of 2D functions are represented as lines in 3D space. Instead of haptically rendering the lines as a hose winding in the room (which is what the graphical interface of the program looks like), Fritz renders the line as what is called a "virtual fixture". The virtual fixture attracts the user's finger to the surface of the hose or a line while letting the user move freely in the direction of the line. One way of looking at this technology is that it enlarges the object from being a thin hose to a large force field.

Virtual properties on virtual objects

The virtual fixture is also a distinct example of how virtual objects can be given virtual properties and benefit greatly from it. Another example is that objects in a virtual environment do not need to follow the normal laws of physics. There are several cases, especially when designing interface widgets, where a slightly unreal but well designed behavior of a virtual object makes it easier to use. See, for example, the Reachin slider described in haptic interface widgets in this chapter.

Sharp corners

In our first test with haptics for blind persons we used all the models available at the time and one of those was a simple one of a house (Figure 7.1). Several of the users in this test overestimated the angle of the roof of the house and in general I noted that the sharp angles of the model disturbed the users' exploration of the model. The problem is not that the angle is very acute, but since the model of the user in the environment is an infinitesimally small point, it is in practice impossible to move across the corner without loosing contact with the surface. This makes it hard to feel the details of the model near the corner and it seems as though some people interpret the angles as being more acute than they really are. For example one person described the model of the house as: "A tower with a very peaky roof."

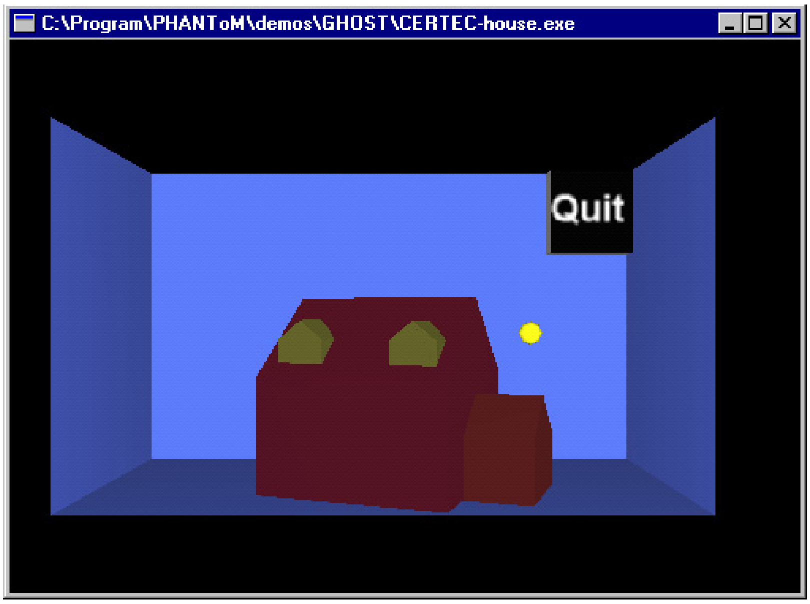

Figure 7.1. A model of a small house used in the 1997 tests.

Colwell and associates [1998a; 1998b] note the same problem in their experiments with the Impulse Engine 3000. This problem especially made beginner users feel "lost in space". Colwell suggest that navigational information should be provided to alleviate this kind of problem. Even though navigational aids can help when the user is "lost in space", I find it to be even better to avoid the situation from the beginning by avoiding the very sharp corners either by making the models rounded or by enlarging the interaction point to a sphere. The latter is quite easy if the software development kit provides the function but has the side effect that details of the objects disappear if the interaction sphere is made too large. Making the objects rounded can, on the other hand, produce models with a significantly larger number of polygons, which places a higher demand on the computer and rendering software. A combination of both technologies can be very effective.

The problem with the sharp angles is not at all the same if the angle is felt from the inside. In that case there is no problem in maintaining contact with the surface and the process of interpreting the shape can go on undisturbed, even when moving across the corner. Taken together, it is thus a good idea to avoid the really sharp corners and instead use models with slightly rounded corners.

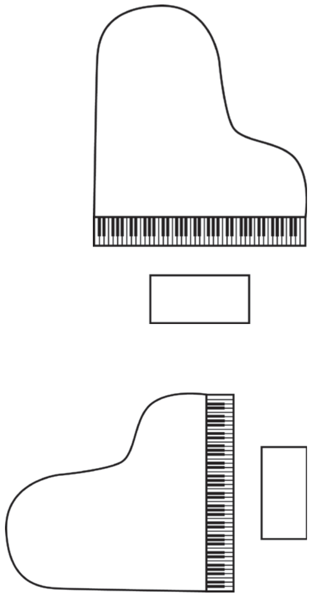

Figure 7.2. The user in this example had the preconception that the grand piano should be oriented as in the picture on the top. Instead, it was oriented sideways, which confused the user.

Orientation of the objects

Orientation of an object can also make a difference in its exploration. An orientation that does not correspond to the user's mental image of the object can make it difficult to understand.

An example from the Enorasi user tests (VRML Complex 3D objects): The user is informed that the model represents a grand piano and a stool and is asked to point at the different parts of the grand piano (keyboard, lid, etc.). This particular user had imagined the model being oriented with the keyboard facing the user (according to Figure 7.2), and since it was oriented the other way, he had great trouble finding the parts. When he understood, he said: "Oh, it's turned *that* way, now I understand." Then he also correctly pointed out the different parts.

In the case of the grand piano the user had expected it to be oriented as if he was to play it, which is probably quite logical.

Haptically accurate models

During the Enorasi 3D tests we noted the importance of what we call "haptically accurate models". Already before the tests the problem with holes (i.e., the user could "fall through" the object at certain points) was noted. Even for a seeing user, this kind of error often has great consequences for the haptical illusion and models with obvious holes were not included in the tests. Despite our efforts to select models of high quality, the ones we had access to were made for seeing persons and thus invisible parts were often carelessly modeled. The vase in the test had a strange ridge on the inside, the grand piano had no strings and neither the piano nor the stool were well modeled underneath. These inaccuracies were in most cases not serious enough to hinder the identification tasks, but it did disturb many of the test users. The worst problems occurred with a model of a sword (which was only tested by four persons). The cross section of the sword was elliptical (not sharp), and this resulted in none of the three users who could find and describe the sword being able to identify it as a sword. The fourth user could not even find the sword since it was so thin. The hole on the guitar from the same test was not really a hole; one could not explore the inside of the guitar and in addition it was possible to get stuck under the strings. Despite this, three out of the four users who tried this model identified it as a guitar. Thus some inaccuracies may be tolerated, but it is clear that key features of an object have to be correctly modeled (a sword should be sharp, for example).

One conclusion that can be drawn from this is that tests to see if a model is haptically accurate should be done without vision (the visual image may easily fool a seeing person into thinking that the model is better than it is – this was the case with the sword). Also, holes and other imperfections are easier to miss when guided by vision –it should thus be a general rule for seeing people developing haptics for the blind to always test applications themselves without visual feedback before testing the applications with the intended users.

Haptically accurate models can also be incredibly simple: In the traffic environment in the Enorasi test the cars were simply rendered as boxes. Even though this may seem crude, it can actually be said that the rendering of the moving cars was haptically accurate. Since the Phantom is a one point haptic device, the shape of a car hitting you is unimportant. A moving box works fine; it pushes you away in the same way as a meticulously modeled truck would have done. (And the users never had the chance to explore the cars to feel their actual shape.)

Haptic interface widgets

Haptic interface widget design is an area where it is easy and can be extremely rewarding to go beyond what is possible to make with real life widgets. Even if the design maintains a connection to the real world via a metaphor, it is possible to give the objects slightly unrealistic features that actually help the user. A simple example is the slider widgets in the Reachin API [see Reachin 2002] that work basically like normal sliders but instead of the normal button have a thin plate that attracts the user if she is close enough. This mechanism makes it both easier to find the slider and to keep in contact with the button while manipulating the slider.

In the follow-up test for this guideline [see Appendix 6], I tested performance in a memory game with a new button shape compared to buttons shaped like plain cubes (which is the most common today). The buttons had a rounded and scooped shape that was designed specifically to be effective in haptic interaction. It was thought that the rounded shape would make it easier to trace the shape of the object and that the small dent in the middle of the button would make it easier to feel where the center of the button was and harder to slide off the button unwillingly (Figure 7.3). The button was designed in 3D Studio Max and exported as a VRML file. The VRML file was then used as a shape in the GHOST program.

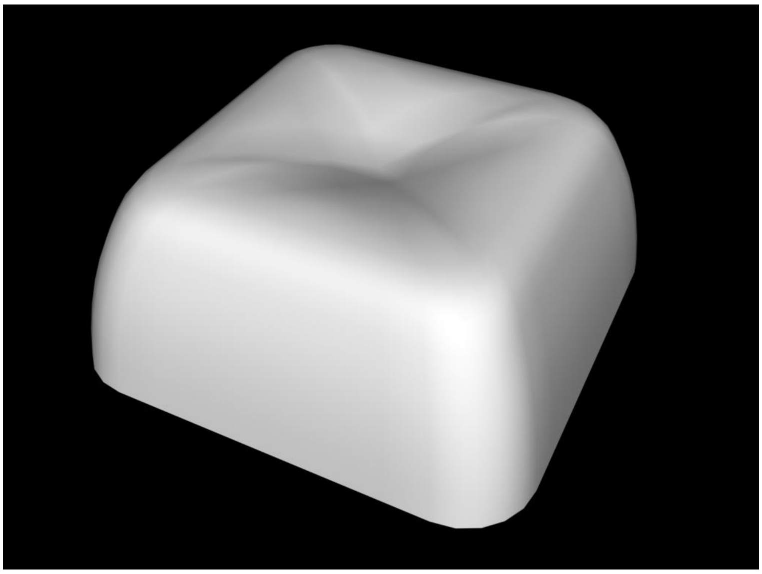

Figure 7.3. Perspective rendering of the button from 3D Studio Max.

The results of the tests show that the button shape did not make a significant difference in performance measured as number of button pushes or time to finish the game. Both the average times and number of button pushes were slightly higher with flat buttons than with the scooped button but the difference was not as large as in the other tests. Looking at the results for each user we can see that half of the users had better times with the flat buttons and half had better times with the scooped buttons. The same holds for the number of button pushes. It is thus hard to say definitively if the scooped buttons really made a difference on performance in this kind of task, even if there is an indication that it might be so.

The real difference in this test, though, is in the user rating of the environments. Six of the users preferred the scooped buttons, two thought that the scooped buttons were slightly better but that it did not matter in this kind of task and only two persons thought that the flat buttons were better.

Here are some user comments on the different button shapes:

- There was quite a big difference in the buttons; the scooped ones were easier to handle even though I actually did not notice it from the start. But the rounded sides were not all good; there were some disadvantages.
- The scooped buttons were better, but it’s not a huge difference.
- It was easier to handle the scooped buttons because you don’t slide away from them.
- The flat buttons were easy to slip off of; the scooped ones were better in that sense.
- The scooped buttons were good because it was easy to feel what it was.
- The flat buttons work well too, once you have learned to handle them.
- The flat buttons feel more distinct

The comments, “It was easy to feel what it was,” and “You don’t slide away from them,” suggest that the shape of the button both indicates what this object is for and guides the user when performing that action. Without going into a discussion about the term “affordance”, I can establish that these two qualities indeed indicate that the scooped-button design has a better haptic affordance. The negative comments, however, indicate that there is still more to do to achieve an optimal design.

Different representations enhance different properties

In some cases it is possible to chose different representations of an object and thereby enhance different properties of the object. After the Enorasi haptic image relief tests, I realized that the difference between positive and negative relief (lines rendered as ridges and grooves respectively) in the haptic image test is not only a question of personal preferences. The different line representations also work differently and enhance different aspects of the pictures. If the lines are rendered as grooves it is very easy to follow them with a haptic device since once you find the groove you are more or less stuck in it and thus the line property is enhanced. If the lines are rendered as ridges instead, they do not catch the user in the same way. It is still possible to follow the ridge, but it requires more active work from the users and the line works more as a border of a surface than as a line. In this case the ridges enhance the surface properties of the image instead of the lines. The difference is quite subtle and is probably not apparent for all users, but it is still there and could be used.

7.3.2 GUIDELINE 2: FACILITATE NAVIGATION AND OVERVIEW

- Provide well defined and easy-to-find reference points in the environment.
- Avoid changing the reference system.
- Make any added reference points easy to find and to get back to. They should also provide an efficient pointer to whatever they are referring to.
- Utilize constraints and paths, but do so with care.
- Virtual search tools can also be used.

Reference points

This guideline is one of the oldest: the first observations for it were made back in 1997 when we carried out our first tests with haptic/audio memory games. As with most of the guidelines, parts of this one are closely related to real life navigation for blind person. Reference points are important in any navigational task. In a virtual environment it is sometimes necessary to add extra reference points apart from the natural ones.

In the first memory game test, one analysis that I made was to compare one user who was prominently successful with others who were not. An important difference was the way in which the reference points were handled: the user who managed to navigate best had a specific way of getting back to the corners of the room if he was unsure about where he was. This way he had four, easy-to-find and well defined reference points to aid in navigating among the buttons in the game.

In the Enorasi VRML 3D objects tests we added bumps on the floor, which were meant to serve as reference points in the environment to make it easier to find the objects. These bumps were used in some cases, but were ignored to a large extent. In hindsight we can see that these were not good enough to work as references points that really helped in finding and getting back to the objects. Reference points must be easy to find and provide an efficient pointer to whatever they are referring to. If the reference point fails on either of these tasks it is often faster and easier to go directly to the object. This was certainly the case in the Enorasi programs. A better reference point and guiding mechanism for the programs in that study could have been something like a stand with a cross-shaped foot on the floor. The user could then easily sweep the floor to find a part of the stand, follow it to the center and then follow the center pole up to the object in question. To some extent this gives the same functionality as a virtual guide would, but this kind of path to the object is certainly less obtrusive than a virtual guide that takes your hand and leads it to the virtual object.

A consequence of the first point is that the reference system should not be changed unnecessarily. For example, instead of removing a disabled button it can be "grayed out" as an inactive menu item (perhaps by giving it a different texture and making it impossible to click). This way the button can still be used as a reference point even though it is nonfunctional. Keeping the reference points is not only necessary to facilitate navigation but also to make the environment easy to learn and understand, which is in essence the last guideline.

Constraints

Constraints can be used in many different ways in a virtual environment to make the navigation easier. One way that can be useful is to have paths (implemented for example as a small groove or ridge) to the objects in the environment. This way a user does not necessarily need to find the object directly, but can go via a path which can be made easier to find. There are cases were these paths would be more annoying than helpful, but in many environments they can be a great help.

Useful constraints in a virtual environment can also be the floor, ceiling and walls that aside from providing reference points also prevent the user from getting too far away from the interesting parts of the environment. The necessity of these types of constraints in the virtual environment is supported by Colwell and associates [1998b] who state: “Users may have difficulty orienting virtual objects in space; if this is important, other cues as to the orientation of the virtual world may be needed (e.g., by providing floors or walls to the space).” Challis and Edwards support this view further in their guidelines for tactile interaction [Challis & Edwards, 2000]. They conclude: “Good design will avoid an excess of ‘empty space’ as this is a significant source of confusion.” By empty space they mean areas on a display that do not communicate anything useful to the user.

Follow-up test on reference points and grids

In the follow-up test for this guideline [see Appendix 6], I compared the performance in a 12-button memory game with and without walls as reference points and constraints for the virtual environment. I also tested using a haptic grid to aid in navigation among the buttons. It turned out that the walls gave significantly better results than the game without walls, both in terms of number of button pushes and time to complete the game. The users had many comments on the virtual environment without walls; here are a few of them:

- Awkward without the walls I think…
- Hard if you lose your orientation, then you want to be able to get back to a corner.
- The buttons are good, but it’s a tough job to concentrate without the walls as a security.
- This was a lot harder…
- You lose your references here.
- Especially when the buttons were gone it was hard having nothing to relate to.
- Hopeless!
- This was harder then with the walls, but not a whole lot harder.

Reference points are indeed important in all kinds of navigation but in the case of blind users in a navigation-heavy virtual task it is apparent that the reference points and constraints provided by the walls and corners can make a real difference and in some cases even make the difference between success and failure.

The gridlines, on the other hand, gave poorer results than the reference game. The time difference was significantly worse with the grid whereas the difference in number of button pushes was not that great. All but two users thought that the gridlines were more of a disturbance than a help. Two users thought that the gridlines did help them but still they both had longer times and more button pushes than in the reference program. It seems as though the gridlines disturb the free scanning for many of the users but still help when it comes to a more mechanical use of the memory game. Many users complained that the gridlines disturbed them and that it took more time because they did not know immediately if they were touching a line or a button.

This is a selection of the user comments on the game with the gridlines.

- It was disturbing; you couldn't feel the difference between the different things.
- The lines disturb the scanning.
- I have to look for the buttons instead of remembering the sounds.
- You think that it is a button, but then you understand that it is a gridline.
- I thought that this would be good, but it was only disturbing.
- It jerks…
- Good with the lines as an orientation; you can feel if you go up or down a row.

Virtual search tools

Virtual search tools are another way of solving the problem of finding objects. A virtual search tool is intended to help the user when exploring an unknown environment and the idea is to make it possible to feel objects without touching them directly. In my licentiate thesis [Sjöström 1999] I proposed three different search tools:

- A search cross or search bar that makes it possible to feel when you line up with an object horizontally or vertically.
- A magnet that pulls the user towards the nearest object.
- A ball that makes it possible to feel objects at a distance but with less detail.

For the licentiate thesis I carried out a case study of the usability and usefulness of the search cross and search bar with two blind users. The tool was especially well accepted by one of the testers. He found the cross and search bar helpful when searching for objects, but the other user was more uncertain. He talked more about magnetic objects as a way to guide the user. Since all search tools apart from helping the user to find and explore virtual objects, also alter the sensation in different ways, it seems important to be able to easily switch between different search tools and no tool at all.

7.3.3 GUIDELINE 3: PROVIDE CONTEXTUAL INFORMATION

- Provide contextual information from different starting points:
    - Present the haptic model or environment in its natural context.
    - Provide information about the purpose of the program.
    - Provide information about possibilities and pitfalls in the environment.

- Use a short text message such as a caption to an image or model, provided as speech or Braille. This can make a significant difference.
- Idea:
  Consider using an agent or virtual guide that introduces the user to the object and also gives additional information if requested.

Very rare cases in real life force a person to recognize a random object without knowing its context. Providing context will help the user to associate with the haptic sensation and it will help the user understand the meaning of the environment or program.

The context guideline was added after the Enorasi user study. In the user tests, the test persons explored a number of 3D objects of different complexity, varying from simple geometrical objects to a model of a satellite with small details. Both context-specific tests, and tests where the user was not informed about the context in advance, were carried out. The Enorasi user tests demonstrate that some people can identify what the haptic model represents without having any previous knowledge of the context, but that contextual information puts the user in a much better position to understand both the details and the entirety of a model

In the Enorasi user study, subjects generally achieved better results in the tests with complex models of real life objects than in the tests with three simpler geometrical objects in a grid. There is no single reason for this but the context provided for the complex objects test seems to be one important part of the explanation. Apparently complexity does not necessarily imply difficulty – a well known but complex object may be more readily understood than a simpler but unfamiliar object. A complex object may actually contain more clues that can help the user in identification and exploration.

Another part of the Enorasi user study – the 2D image test – also showed clearly that context can make a big difference in the understanding of haptic simulations. In this test the user task was to explore and identify two different line drawings presented as haptic reliefs. The first test was a drawing of a stick man and the other of an elephant.

Without any contextual information, 15 of 24 users (62%) could identify the stick man and eight of 24 users (33%) could identify the elephant. The second part of this test was to identify parts of the drawing once the user knew what it was (if the user could not identify it himself we told him what was depicted). With this information available, 88 percent respectively 83 percent could successfully identify parts of the drawing such as legs, arms and head for the stick man and trunk, tail, head, etc. on the elephant.

Another example from the test is that a user believed that the sample drawing was more complex than it really was and therefore it took a while before he understood the drawing.

Context is important also in non-haptic interaction for blind people, which is pointed out, for example, by Ramloll and colleagues [2001] in a study where non-speech sounds were used for tabular information. Alty & Rigas [1998] also established that context plays an important role in assisting meaningful understanding of diagrams for blind people.

The indication that contextual information is very important is also interesting compared to Kamel and Landay's report, *Study of Blind Drawing Practice* [Kamel & Landay 2000]. They found that existing drawing tools for blind users gave inadequate contextual feedback on the state of the drawing and consequently they advocate systems that provide more and better feedback.

Captions

The contextual information provided for the images in the Enorasi tests were quite simple and could be compared to a caption. Normal haptic interfaces are not well suited for communicating text, but the kind of textual information needed to gain a basic understanding of the context can easily be given to the user via, for example, sampled or synthetic speech or Braille. In a haptic web-based image application the contextual information can, for example, be taken from the alternative text of the HTML page and/or the written caption for the image.

Virtual guides

Instead of captions and labels it seems as if virtual guides could be used to provide a context. Helping agents that introduce the user to the object, its context and shape are likely to enhance the performance in a similar way as the users were introduced to the virtual environments by a human in our experiments. Complex scenarios should be presented with an explicit context, using a suitable metaphor and/or making other clues helpful to the user. Free association (a haptic model without any clues presented) should be used sparingly, but can still be interesting for children's guessing games and the like.

There is still a great need for research in the area of how to provide context in haptic environments, but it has been clearly demonstrated that extra contextual information can make an enormous difference in the understanding of a haptic simulation.

7.3.4 GUIDELINE 4: UTILIZE ALL AVAILABLE MODALITIES

- Combine haptics with sound labels, a Braille display and/or synthetic speech for text output.
- Try environmental sound to aid in getting an overview.
- Use audio (both sound labels and environmental sound) to provide a context.
- Provide feedback to the user via any available sense.

The sense of touch has a number of prominent features that make it suitable for computer interaction: it is exact, it can be used both to give and to get information and it is unobtrusive (compared to sounds, for instance). However the sense of touch also has a drawback in that it has a relatively low bandwidth. The bandwidth of a sense refers to the capacity it has to receive and perceive information. Studies show that vision, as one might intuitively expect, is our highest bandwidth sense, followed by hearing and touch (Table 7.3) [Kokjer 1987]. The visual sense is two orders of magnitude better at carrying information than the auditory, which in turn is two orders of magnitude better than the tactual sense. Even though the number for vibrotactile interaction might not be accurate for haptic interaction, it is clear that there is a considerable difference between the bandwidth of the sense of touch and the other senses. This alone makes it a good idea to complement the haptic interaction with other modalities.

Table 7.3: Information bandwidth limitations for three senses according to Kokjer.

Sense Modality	**Limit (bits/sec)**
Skin (vibrotactile)	10^2
Ear	10^4
Eye	10^6

Given that most blind users are accustomed to using many different ways to compensate for their lack of sight, the exclusive use of haptics in research applications is not recommended for a person used to combining feeling, hearing and smelling.

Just the transition from normal touch to discrete point haptic interaction in a virtual environment can be a hurdle for the user. We have striven to make this transition as smooth as possible and to enable the use of other modalities in a similar way as is done in real life. Our intention has thus not been to study haptic interaction separate from all other kinds of interaction as is done in areas of experimental psychology, for example. Instead we strive to study how haptics can be used along with other means of interaction to make computer interfaces suitable for use by blind persons. The guidelines in this dissertation are strongly influenced by this point of view.

Several researchers point out the importance of other modalities in combination with haptic interaction: Srinivasan and Basdogan [1997] state that more efforts should be undertaken to bring different modalities together in virtual environments. They also conclude that the inadequacies of haptic displays can be overcome with appropriate use of other modalities. Colwell et al. [1998b] suggest that multimedia information may be required to give a sense of complex objects and what they mean, since users may not understand complex objects from purely haptic information. Jeong and Jacobson [2002] consider the question of how effective haptic and auditory displays are when combined, whether or not they interfere with one another, and how a user's previous experience with a modality affects the success of the integration and the efficacy of the multimodal display.

Sound labels

In the Enorasi user study we tested a set of floor plans that combined haptic and sound information. The graphical information in the map was provided as a high haptic relief. This made it possible for the users to feel the size, shape and layout of the rooms. The rooms and areas in the floor plans also had sound labels on them to identify each room (see Section 6.5.4). The label sound was invoked by pressing the floor in the room and the sound stopped immediately when the user lifted his or her finger.

Although we have not specifically tested maps with sound labels compared to those without, we can see that the sound information really adds to what is possible to supply with only haptics. For maps and floor plans such as these, sound is an effective channel of information for what is displayed on visual maps as text. An alternative to sound in this case could be to print the text on a Braille display. The advantage with this is that it is not as intrusive and is less irritating for those in the surroundings.

Environmental sounds

In the Enorasi maps we did not use environmental sound, but there is a potential use for that as well. One of the important functions of a map or drawing is to give an overview. For tactile and haptic maps this means a process that demands more work than what is needed by a seeing person to do the same with a visual map. Because the sense of touch only works at one or a few points at a time, it requires that the user actively scans the surface in order to establish a mental model and to use it to gain an overview. This can, however, be supported and facilitated by adding environmental sounds in addition to the sound labels. Environmental sounds provide information more indirectly than sound labels and can be designed in a number of different ways. Sound information can thus be used both to improve the understanding of the objects and to provide an overview of the environment.

Another way of using modalities besides haptics is to supply context to the environment. Is this sense it should be possible to use any or all of the following: Braille text, sound labels or captions and environmental sounds.

7.3.5 GUIDELINE 5: SUPPORT THE USER IN LEARNING THE INTERACTION METHOD AND THE SPECIFIC ENVIRONMENTS AND PROGRAMS

- Be consistent; limit the number of rules to remember.

- Give clear and timely feedback on the user's actions.
- Facilitate imitating of other users and situations if possible.
- Develop elaborated exercises to make the handling of the interaction tools and methods automatic in the user.
- Idea:
  Consider using a virtual guide or remote users to help when a user comes to a new environment.

To understand a haptic virtual environment is very much connected to learning how it works. The rules of learning are important in all interaction design but may be even more important when designing haptic interfaces since these rely even more on the user remembering what is there (basically because the exploration of the interface is slower than when using other senses).

Exercises, imitation and guiding

I have seen many new users move in the room as though it had only 2 dimensions. An experienced user can easily see when this is happening and guide the new user into moving in the full 3 dimensions. Another example is new users who are not aware of the peculiarities of point interaction haptics, which can lead to several kinds of misunderstandings.

One way to support the learning process in these cases would be to let the user have someone to imitate while getting started in the new environment. The problem here is that today's haptic interfaces do not make it easy to imitate someone since you are normally alone in the environment. Our tests with collaborative haptic environments (see Section 6.3 and Appendix 2) did not focus on learning in the haptic environment, but it would certainly be possible to use similar technology in a learning context as well.

Both Colwell et al. [1998b] and Challis & Edwards [2000] stress the importance of supporting the users in learning exploration strategies. Colwell states that, "Users may need to learn strategies on how to explore virtual objects with a particular device. This is probably not time-consuming, but useful strategies should be provided for users." Challis & Edwards established that, "Good design practice should, whenever possible, encourage a specific strategy for the exploration of a particular display" [Challis & Edwards 2000, p. 100].

An interesting question is how one should best guide the users towards an efficient exploration technique – a small number of persons appear to have an efficient way of scanning almost from the start, while others need considerably more training (and may be expected to benefit from guidance – possibly from an agent advising the user with respect to the scanning technique used). At Museo Marini, the museum in Italy where a majority of the Enorasi user tests were performed, a method has been developed to guide blind persons into an effective exploration technique that helps them experience the sculptures at the museum fully.

An interesting follow-up to this study would be to try to translate and apply this method in the virtual world. One goal for such a project could be to develop an agent that can help users to go from the initial state were the scanning is very conscious and cognitively demanding to the expert user state were object and environment scanning are automatic.

Feedback and consequence

To facilitate learning through conditioning it is important to provide clear and unambiguous feedback on the user's actions. It is also important that the interaction is based on a small set of easily understandable rules and that it is unwaveringly consistent when it come to cause and effect relationships in the environment. As stated above, feedback could be provided not only via haptics but also effectively via other senses. For example, a button that haptically clicks into place could give a clicking sound to further enhance the feedback.

7.3.6 EXCLUDED GUIDELINE - MANIPULANDUM DESIGN

The last point of the CHI and ISSPA guidelines (the predecessor to these guidelines, formulated in 2001) was about the manipulandum of the haptic interface. I have decided not to include that section as a guideline here, not because it is unimportant, but since I cannot give a clear recommendation.

The manipulandum is the tool that the user grasps in his hand. I have been advised that linguistically, the word "manipulandum" means "what should be manipulated" and that the tool that the user grabs should preferably be called a manipulator, for example. However, I have not seen anyone use the word "manipulator" in this sense, so for lack of a better choice I have decided to stick to the word "manipulandum", which was supplied to me by Chris Hasser at Immersion Corporation.

When using the Phantom, the manipulandum is a pen or a thimble. In the Wingman Force Feedback Mouse, it is the mouse body itself. The choice of manipulandum can indeed affect the haptic sensation a great deal since the force distribution to the user and the movements are different with different manipulandi.

Manipulandi that are in common use with different haptic interfaces today include:

- A thimble
- A pen
- A joystick handle
- A mouse

The form and surface of the manipulandum effects how the force is applied to the user, the kind of movements used, and the feeling of being in contact with the virtual object. For example, a thimble with sandpaper on the inside causes many people to use less force when grabbing a virtual object because they have the sensation that the objects are less slippery [von der Heyde 1998]. This is true even if the friction in the computer model is the same as when using a thimble without sandpaper.

Many of the blind users who have tested the Wingman Force Feedback Mouse complain about two things: it is too weak and the workspace is too small. They say that they have to be very careful since the virtual objects are so small. My suggestion is that the problem is in part a manipulandum that is not designed in the right way for a device with such a small workspace and limited force. A smaller manipulandum that encouraged a finger grip instead of a handgrip would most likely make the device easier to use.

This view is also supported by research and design experience. In an experiment studying the dexterity of the test users when manipulating an object in the hand, Zhai found that they were able to position the object more accurately when grasping it with their fingertips rather than the whole hand [Zhai & Milgram 1998]. Moreover, Cutkosky and Howe have presented a human grasp taxonomy comprising two general classifications: power and precision [Cutkosky & Howe 1990]. Precision grasps involve the fingertips, while power grasps involve the whole finger and the palm.

The Wingman Force Feedback Mouse forces the user into a power grasp for what is essentially a precision task since the mouse must be grasped with the whole hand. This is not experienced as a big problem for a sighted user since he can compensate with vision, but for a blind user it can degrade performance significantly.

This is also in line with our experience of using different manipulandi with the Phantom. In our tests with the Phantom we have seen that users sometimes work differently when they are using the pen instead of the thimble. It can be argued that with the thimble a user may believe that feeling is the same as in real life, which is not true. With the pen it is obvious to the user that what can be felt virtually is not completely the same as what he can feel with his hand. However, many users feel that they perform better with the thimble, which is probably because it encourages finger movements while the pen requires hand movements. This transition from finger to hand movements also amounts to a slight transition from precision to power. We have also heard the comment, especially from beginners, that the thimble feels more natural to use than the pen.

Thus, there are important points to make about manipulandum design. Yet we still have not been able to find any differences in raw performance when using the thimble compared to when using the pen. Similar results have been noted by for example Jansson and Billberger [1999].

In conclusion, we see that there are some important differences between manipulandi, especially when comparing the clear cases of precision grasp and power grasp. However, using the Phantom, we cannot at this point state that one manipulandum is better than the other.

7.4 Evolution of the Guidelines

The guidelines presented here have evolved over several years; the first step was taken in 1998 and since then we have developed five generations of guidelines. This is the history of the guidelines from 1998-2002.

7.4.1 STEP ONE: "WHAT THE PHANTOM TAUGHT US", AUTUMN 1998

At this time Kirsten Rassmus-Gröhn and I had been working with haptics for some years. Together we wrote an internal department report entitled "What the Phantom Taught Us". This was an attempt to sum up what was reasonable to communicate via point interaction haptics and how that was best done in different situations. We used the main headings:

- How does virtual touch work?
- Virtual touch in different ways
- What is the difference between good and not-so-good Phantom users?
- Rules of thumb for point interaction haptics

These rules of thumb were the first formulation of guidelines for haptic interaction design. They were mainly based on observations from our own development and testing but also reflections of what we had seen at the Phantom User Group Meetings, Immersion, SensAble, Stanford and other places we had visited.

7.4.2 STEP TWO: "THE IT POTENTIAL OF HAPTICS", AUTUMN 1999

In the autumn of 1999 I had reached the point of my licentiate thesis. It was entitled "The IT potentials of Haptics – Touch Access for People with Disabilities". I reworked considerably the rules of thumb for point interaction haptics. I added some new points and tried to restructure the system to make it more accessible and easier to use. At this time we had material from tests with a mathematics program, different memory games, a battleship game, search tools, radial menus and other programs for the FEELit Mouse and more.

7.4.3 STEP THREE: CHI AND ISSPA CONFERENCE PAPERS, SPRING 2001

The third generation of guidelines was the first time they were published as a separate article. At the CHI Conference in the spring of 2001, I presented a paper with the guidelines standing on their own. This paper had nine guidelines under the five headings:

- Navigation
- Finding objects
- Understanding objects
- Haptic widgets
- Physical interaction.

These guidelines were basically the same as the rules of thumb presented in the licentiate thesis but another restructuring made them clearer and more coherent. The ISSPA article "Designing Haptic Computer Interfaces For Blind People" including the full formulation of these guidelines and more background than the CHI article is available in Appendix 3.

7.4.4 STEP FOUR: ENORASI, SUMMER 2001

The significant effort of 2000 and 2001 was the European Union Enorasi Project. In the user study of that project, implemented during the summer of 2001, we both repeated some previous tests and carried out a large number of tests in new areas. One of the outcomes was a document entitled "Recommendations for Future Work". Here we summarized a set of new recommendations along with the previously published guidelines.

For Enorasi, we tested models of a complexity that we had not used before, and we also made tests with 2D information such as drawings, floor plans and maps. These new areas gave rise to a set of recommendations in an area that was not covered by the existing guidelines.

The most important new recommendations from Enorasi were:

- Give the user information about the context, either in the form of a caption or an agent that introduces the user to the object and also gives additional information if requested.
- Check that the models are real 3D models that include non-visual information that is needed to recognize the object.
- Simplify objects with many details. Try to keep the information-bearing details and limit the rest.
- Make it possible to zoom in and out of the object.

7.4.5 STEP FIVE: THIS DISSERTATION, SUMMER 2002

For this dissertation I have integrated the recommendations from Enorasi and the previous guidelines into five main guidelines. These few guidelines are naturally on a more abstract level than the previous ones, but a large set of examples under each guideline should make their usage straightforward. I have also conducted follow-up tests on the two oldest guidelines where explicit tests had not been conducted before.

7.5 Relation to Other HCI Guidelines

The guidelines presented here are intended for use when designing haptics interfaces. It is important to note that principles that guide the design of traditional interfaces, such as Shneiderman's "Eight Golden Rules" [1998], Bruce Tognazzini's list of basic principles for interface design [2001] or Nielsen's "Ten Usability Heuristics" [2002], still apply. The guidelines I propose can in principle be used *in addition* to other HCI guidelines, not *in place* of them. My intention is to focus the guidelines presented here on the layers of the interaction that are mostly influenced by haptic interaction specifics and to keep an open connection to usage of other guidelines as well.

There are other guidelines for accessible interface design that should be taken into account. The most well-known and important are the W3C Web Accessibility Initiative (WAI) guidelines for accessible web design [W3C 1999]. These guidelines are intended to promote universal design and they include guidelines for Web Content Accessibility, Authoring Tool Accessibility and User Agent Accessibility. They explain how to make web content accessible to people with disabilities. These guidelines do not discourage content developers from using images, video, etc., but rather explain how to make multimedia content more accessible to a wide audience.

An excellent information resource for professionals who work in the field of visual disabilities is the Tiresias web site [Tiresias 2002]. It has evolved from work carried out by Dr Janet Silver of Moorfield's Eye Hospital, London and Dr John Gill of the Royal National Institute of the Blind in the UK. Tiresias includes among other things a set of guidelines for the design of accessible information and communication technology systems. The guidelines pages include overviews of user groups, application areas, technologies and other aspects. Tiresias has a page on tactual displays, but it does not contain any guidelines at present.

8. Conclusions and Ideas for the Future

This work shows that there is a great potential in using haptic technology in applications for blind people. It has been shown that it is viable to translate both 2D and 3D graphical information (such as line drawings, VRML models, floor plans etc.) and to make it comprehensible for blind people via haptics. It has also been shown that it is possible for a blind person to orientate and navigate in a virtual haptic environment and that these tasks can be further supported by using complements such as sound information and Braille text. A blind person can use knowledge gained in the virtual world for real life orientation. Taken together, this means that it is definitely possible to make both a Windows system and applications with multimodal haptic interfaces.

The potential for haptics is also great in the education of blind children: Our haptic mathematics viewer has attracted a large interest among the blind people who have tried it even though many of them did not think that mathematics was particularly interesting from the start. The application simply makes mathematics more fun (or for some, at least less boring). Multimodal haptic games like Submarines can be used to make scientific concepts (like coordinate systems in that case) more interesting to blind children. With haptic technology it is possible to make completely new kinds of computer games for blind children, which can be used both for fun and learning. I am sure that the knowledge gained in this work along with a skilled low vision teacher would be an excellent basis for many interesting applications including haptic technology that could really add something new to the education of blind children.

8.1 Further Improvement of the Guidelines

Good design of haptic interfaces is not trivial. There are many problems that can be avoided by making clever design decisions. The guidelines presented in this dissertation provide a foundation for better haptic interface design that can also be enlarged in the future. The guideline headings are:

- Elaborate a virtual object design of its own
- Facilitate navigation and overview
- Provide contextual information
- Utilize all available modalities

- Support the user in learning the interaction method and the specific environments and programs

8.2 Further Ideas for Applications

In discussions with blind people, sighted people and low vision teachers, the following ideas for application arose:

- Adaptations for all kinds of programs that plot a graph
- An enhanced Internet browser
- Traffic training games
- Computer graphics access
- City maps and similar to improve autonomy
- Models of public areas like train stations and famous sites
- Works of art

8.3 A Multimodal Haptic Browser

A multimodal haptic Internet browser would alleviate the problems of certain web pages, especially those that make heavy use of graphics. (Even though Internet Explorer itself is quite well adapted to the needs of a blind person.) A multimodal haptic browser would communicate not only the text of the web document, but also the layout of the page and the parts of the graphics. Such a haptic Internet browser would also extend the possible uses of Internet technology for blind persons beyond what is possible with standard computer aids today.

Building on the outcome of this work, such a browser could be designed as follows:

The conceptual design would stress the importance of multimodality to enhance the possible interaction methods and uses of the browser. The program must be able to communicate more aspects of the web pages than just the text. Graphical elements of the page are shown haptically with the appropriate textual information available on demand. And it is also desirable to include document navigation methods based on haptics in addition to the standard keyboard-based navigation. These concepts can be supported, for example, by using:

- Texture and friction coding on the different kinds of text in the document. For example, course texture on headings and fine texture on body text. This makes it possible to skim the document for interesting text.
- Cursor routing with the Phantom pointer (the program starts reading at the beginning of the row the user is pointing to).

- Navigation and scrolling in the document with
  - A hand metaphor, i.e., grab the document and drag-n-drop it up or down
  - A scrolling wheel (like on a mouse)
  - Buttons
- Links with a special texture. Depending on the type of usage, links can also be given an attractive force to make them easier to find.
- An optional haptics-follows-cursor mode. This can be used for a guided tour of the links on the current page using the TAB-button, for example.
- Text supplied via speech or Braille.
- Tables represented as squares with different surfaces and/or a haptic outline.
- Images haptically represented in different ways (user selectable)
  - Make a haptic relief directly from the visual image (suitable for line drawings)
  - Edge detection (can help for some photos)
  - Images can be zoomed to cover the whole workspace
- Captions for the images provided via the text interface. Information is taken primarily from the ALT-text. If that is not available the document text close to the image is used.

A flexible and scalable software solution for the Windows platform would be to use Internet Explorer as a basis for the browsing capabilities and to create an add-on that uses MSAA - Microsoft Active Accessibility [Microsoft 2002] to get user interface information on which to build the haptic interface.

The add-on program needs to contain its own data structure for the haptic user interface since the haptic control loop requires fast and reliable data access. With the GHOST SDK, this data structure can be created by building a scene graph with specialized objects representing each type of user interface component. Since the interface objects in Windows are normally both containers for other objects as well as having their own representation (text, graphics, etc.), the corresponding haptic object must be able to provide the same functionality. The shape objects in GHOST do not allow any subtrees in the scene graph, so to match the Windows interface components we need to make a compound object based on the separator (manifold) class from GHOST and with one or more shape objects coupled to it. With this approach we use a new haptic subclass for each type of interface component that we want to show haptically.

A synchronization mechanism is needed to keep the haptic shadow model in sync with the graphical interface. To get reasonable performance, a binary search tree with pointers to both the MSAA objects and the haptic objects is needed to create a link between the two different representations. The program receives events from MSAA whenever there is a change in the graphical interface and can then via the links determine which haptic object should be updated or if an object should be added or removed.

Some remarks on how the guidelines can be utilized in the multimodal browser:

1. *To elaborate a virtual object design of its own* in this program would be to design each haptic interface class as well as possible from its own horizon. The object should represent a part of the graphical interface but it does not need to be a haptic copy of it. Rounded corners can be used on anything that stands out from the background. Allowing different representations of the graphics on the web page is also a way of improving the design on the object level.

2. *Navigation and overview are facilitated* both passively and actively in the design. The different surfaces corresponding to different kinds of text and the cursor routing, for example, provide a passive means of getting an overview of the document. The haptics-follows-cursor mode provides an active tool to show important parts of the document. Navigation can also be supported by adding walls to the haptic version of the interface. This provides both a boundary to the haptic workspace and reference points.

3. *Providing contextual information* in a web browser depends a lot on the web page itself, so we are still to some extent at the mercy of the web page designer. Captions from the ALT-text provide a context for diagrams and images. Context for the web page itself is to some extent given by the URL. What is important in an add-on like this is to communicate as much as possible of the context that is provided from the host program.

4. *Utilizing all available modalities*. In this case start by using Braille, speech and haptics. This provides a basic multimodality and takes the interaction far beyond what is possible with text or haptics alone. In addition, non-speech sounds can be used to provide feedback when using the browser, for example.

5. *Supporting the user in learning this specific program* can be done by keeping the interface as clean as possible and providing clear and timely feedback on the user's actions. This program would provide an interaction method that is quite different from what any one is used to at present, so an initial period of learning is inevitable. A step-by-step introduction to the different aspects of the program would certainly help the user to get the most out of a tool like this. A virtual guide could be one way of providing this introduction, but an ordinary class with a teacher and exercises is probably an easier way of getting up and running.

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Appendices

This dissertation is based on the articles in Appendix 1-6.

Appendix 1.
The sense of touch provides new computer interaction techniques for disabled people
Calle Sjöström, Kirre Rassmus-Gröhn
Technology and Disability, Volume 10, No 1, pp 45-52, IOS Press, 1999.

Appendix 2.
Supporting Presence in Collaborative Multimodal Environments by Haptic Force Feedback
Eva-Lotta Sallnäs, Kirre Rassmus-Gröhn, Calle Sjöström
ACM Transactions on Computer-Human Interaction (To CHI), Volume 7 Issue 4, pp 461-476, ACM, 2000.

Appendix 3.
Designing Haptic Computer Interfaces For Blind People
Calle Sjöström
Proceedings of the Sixth IEEE International Symposium on Signal Processing and its Applications, Kuala Lumpur, Malaysia, August 13 – 16, 2001.

Appendix 4.
Haptic Representations of 2D Graphics for Blind Persons
Calle Sjöström, Henrik Danielsson, Charlotte Magnusson, Kirsten Rassmus-Gröhn
Submitted to Haptics-E, the Electronic Journal of Haptics Research, 2002.

Appendix 5.
Navigation and Recognition in Complex 3D Haptic Virtual Environments
Charlotte Magnusson, Calle Sjöström, Kirsten Rassmus-Gröhn, Henrik Danielsson
Submitted to Haptics-E, the Electronic Journal of Haptics Research, 2002.

Appendix 6.
Follow-up Experiments on Haptic Interaction Design Guidelines
Calle Sjöström
Certec Report number 1:2002

Appendix 7.
List of Articles and Presentations at Scientific Conferences

Appendix 1

The sense of touch provides new computer interaction techniques for disabled people

Calle Sjöström, Kirsten Rassmus-Gröhn

The sense of touch provides new computer interaction techniques for disabled people

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Windows and the World Wide Web are two of the keys to the Information Technology explosion that we are all caught up in. Computer capabilities are increasing while they are getting easier to use. But how does a blind person handle a graphical environment like Windows?

This article deals with Certec's efforts to find a way to use haptics (i.e., controlling with movements and getting feedback via the sense of touch), to provide new computer interaction techniques for visually impaired people and people with physical disabilities. Haptic technology makes it possible to extend the range of touch from the length of an arm to a virtually unlimited distance.

Keywords: Haptic interface, Touch Windows, blind, sense of touch, visual disability

1. Introduction

Windows has undoubtedly been a revolution for computer users. Its spatial graphical paradigm with menus, buttons and icons unburdens the user from memorizing commands and reading long sections of text on the screen. But the drawback of all these good things is that Windows makes the computer harder to use for a blind person. The structure of the computer system is represented by pictures, and if you cannot see those pictures it is very hard to grasp this underlying structure, or even to access and use the computer at all. Nevertheless, many blind users prefer Windows to older computer systems even though they are unable to take advantage of all the benefits that Windows offers a sighted user.

However, there is one alternative access method with potential value: computer interfaces that use movements and the sense of touch as a complement to graphics. These interfaces are called haptic interfaces.

At Certec, Center for Rehabilitation Engineering Research at Lund University, we have been working with haptic interfaces for disabled users since early 1995. In one project, we are working on a connection between Windows and a haptic interface called "the PHANToM" [4]. With a connection like this, it would be possible to feel and control the interface components of Windows. We are also working on a connection between a standard rehabilitation robot and the PHANToM. Our aim is to enable the user to control the robot with small movements of one finger, and feel some of the things the robot is doing.

2. The PHANToM

The PHANToM (Fig. 1) is a haptic interface device from SensAble Technologies Inc. of Boston, MA. It is primarily intended for adding 3D-touch to 3D-graphics programs. At Certec, we realized early on that disabled users could benefit from the PHANToM.

With the PHANToM, the user puts one finger in a thimble connected to a metal arm. By moving his finger around, the user can feel virtual three-dimensional objects that are programmed into a computer. Moreover, he can control the computer as if the PHANToM were a mouse or a joystick. The PHANToM adds a new dimension to human-computer interaction, namely haptic interaction. Haptic interaction uses both the sense of touch on a small scale and movements on a slightly larger scale.

The virtual three-dimensional space in which the PHANToM operates is called a haptic scene. The hap-

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Fig. 1. The PHANToM (photo by SensAble Technologies Inc.).

tic scene is a collection of separate haptic objects with different behaviors and properties.

When activated, the PHANToM works together with the computer to interpret the users finger position in three-dimensional space and to apply an appropriate and variable resisting force. Three sensors track the position of the user's fingertip and this position is read by the computer. In the software, the position is compared to the boundaries of all objects in the haptic scene. If the user is not close to an object, the calculated force is zero, but if the fingertip is in contact with an object, the computer calculates a force that pushes the finger back to the surface of the object. The actual force that can be felt is provided by three DC-motors. This process (Fig. 2) is carried out 1000 times per second. The high frequency together with the high resolution of the encoders makes it possible to feel almost any shape very realistically with a device like the PHANToM [4].

The PHANToM has its main users in research and development. It is, among other things, used as a simulation platform for complex surgery tasks, VR research and to enhance 3D CAD systems.

3. Programs for learning and fun

Certec has developed a number of programs for the PHANToM. The programs have been demonstrated at exhibitions and conferences to both sighted and blind visitors. There have also been many dedicated test sessions at Certec with blind children and adults, as well as with a group of deaf-blind persons.

The programs used at these try-out sessions were scenes with simple static or dynamic geometrical objects, a haptic/audio memory game, a game called Submarines, and a simple clay-modeling program (written by SensAble).

”Submarines” is a haptic variant of the well-known battleship game. The ordinary pen-and-paper-based battleship game (Fig. 3) has been used to give school children a first idea of what coordinate systems can be used for. With ”submarines” it is possible for a blind child to have even more fun with coordinate systems.

The player feels 10 x 10 squares in a coordinate system. In the game, your finger in the PHANToM is a helicopter that is hunting submarines with depth charge bombs. If you put your finger on the ”surface of the water” you can feel smooth waves moving up and down. The surface feels different after you have dropped a bomb, and it also feels different if a submarine has been sunk. There are four different states for a square with associated haptic feedback:

- Not yet bombed - calm waves
- Bombed, but missed - no waves (flat)
- Bombed, hit part of a submarine - vibrations

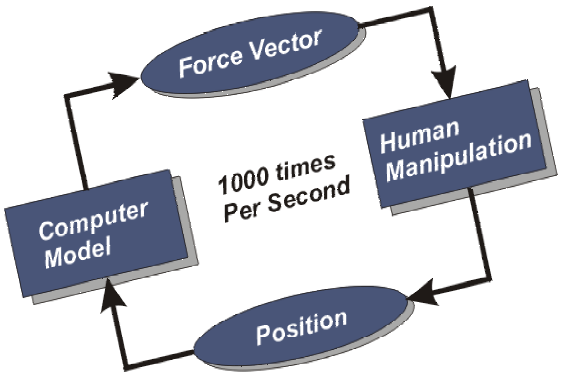

Fig. 2. The control loop.

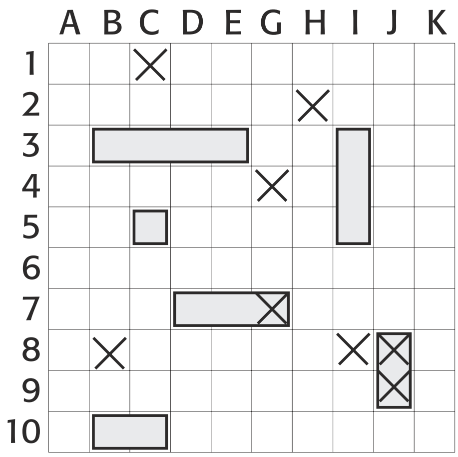

Fig. 3. A paaper-based battleship game.

- Bombed, hit entire submarine - small, rapid waves

This computer game uses the PHANToM, the screen, and the keyboard in the interaction with the user. It also uses sound effects as many current games do. It has been tested by at least 20 blind children and adults and by at least 50 sighted persons. They have all had fun with it.

”Submarines” has also been tried by a group consisted of six deaf-blind persons and their assistants and others that made the grand total of 15. Since the different conditions of the squares are provided as haptic feedback, our hypothesis was that it should work fine for deaf-blind users as well. As it turned out, it seems like the haptic feedback of the game was sufficient, in all but one case. In the game, the space key is used to drop the bomb in the water, and while the bomb falls, a hearing person hears the sound of the falling bomb in the speakers. Not until the bomb has reached the water, does the user get haptic feedback to indicate if it was a hit or not. Since there was no haptic feedback for the falling bomb, this confused the deaf-blind users.

The first PHANToM program at Certec, was a painting program for blind children, ”Paint with your fingers”. With the PHANToM, the user chooses a color from a palette. Each color on the palette has an associated texture that the user feels when painting with it. By changing program mode the user can feel the whole painting, and also print the painting on a color printer.

Early in our work we also developed a simple mathematics program. People who try to explain mathematics to blind persons often notice that to some extent it is a visual subject. A haptic interface helps blind persons to understand equations in terms of curves and surfaces. Our program makes it possible to feel a mathematical curve or surface with the PHANToM. A similar program, but with more functionality, has been developed at ASEL, University of Delaware [2].

4. Touch Windows

Computers are becoming everyday technology. Computers have opened up many opportunities for disabled people. For example, it is now fairly easy for a blind person to access written text. Any text in a computer can be read either with a one row Braille-display or a speech synthesizer. This is done in real time. In addition to being much more flexible, it also saves space compared to books with Braille-text on paper. At present, that is about as good as electronic access gets for computer users with visual impairments.

There is now a strong emphasis on documents with graphics, and increasingly so on the Internet. For blind Websurfers the pictures are not accessible at all. It is possible to define an alternative text in the HTML-document, explaining what the picture shows, but they are sometimes omitted for lack of awareness about the benefit for blind users.

As mentioned in the introduction, the fact that most computers now have graphical user interfaces (GUIs) is another big problem for non-sighted users. Windows and other GUIs are widespread and accepted, so almost all new programs are made for these environments. If Windows can be made accessible to non-sighted users, then Windows programs will almost automatically become accessible as well. That is why we have started the ”Touch Windows” project.

There are many reasons for having Windows on the computer even in the case of a blind user. The biggest single reason is that most programs today are made for Windows. For example one of our test users wanted to connect a synthesizer to his computer, but he was unable to do so without Windows since no DOS-program would work. Another reason for using Windows is that it is the system most commonly used in the workplace. If blind users can have the same type of computer system as sighted users, both will benefit greatly. For example, it is much easier to exchange documents, and they can provide technical assistance to each other.

Rather than making a haptic user interface tailored to the needs of blind users we intend to make the haptic Windows system, the ”Touch Windows” project, as similar as it can be to the graphic Windows. Even though Windows is designed with sighted users in mind we think that the benefits of a system that looks and feels the same are worth while.

In the haptic Windows system under development, we want to use haptic interaction mainly to provide an overview of the system. The idea is to make windowframes, buttons, menus and icons touchable via the haptic interface. That should provide the overall information in a similar way as the graphical images do in the standard Windows system. The text on the screen and other small details will probably be made accessible with more specialized techniques like speech synthesis and/or Braille-displays.

Dividing the functions in the interface also means that a haptic system like ”Touch Windows” would not render unnecessary any of today’s assistive technology for visually impaired computer users. Rather, the systems can complement and enhance each other. With a haptic interface it is possible to feel things in two or three dimensions. That makes it possible to write programs that convert graphics into something that can be felt. It is possible to translate the up, down, left and right of the Windows system on the screen into a touchable environment with the same construction and metaphors. It is a big advantage if blind and sighted users have the same inner picture of the system. Then they can talk about the system and help each other from common ground. Suddenly, it means a lot more to say things like ”the START-button is in the lower left corner”.

5. The Memory House

As a first step, to find out if it is even possible to understand and control such a complicated system as Windows with only haptic information, we created a program called The Memory House (Fig. 4). The Memory House [6] is a haptic/audio memory game. The

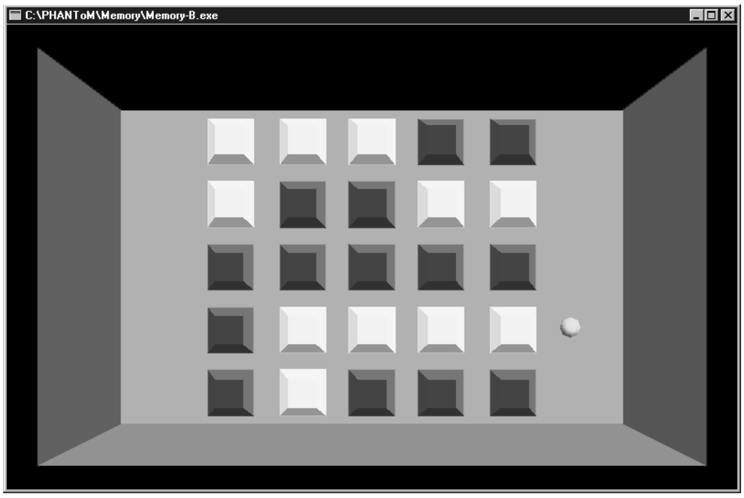

Fig. 4. The Memory House (original version).

game consists of 25 pushbuttons that produce a sound when pressed. There are 12 sound-pairs, and one ”Old Maid”. The buttons disappear when the player presses two buttons with the same sound in sequence.

In the Memory House the buttons are placed on five different floors. Between each row of buttons the user can feel a thin wall that helps him to stay within one set of buttons. It is possible to move from one floor to another anywhere, there's no ”staircase” or ”elevator”, the user only have to push a little bit harder on the floor or ceiling to slip through it. To make navigation among the floors easier there is a voice that reads the number of the floor each time the user moves from one floor to another. Many of the blind users liked this feature and used it for reference, but some of them found the voice annoying rather than helpful.

We have also made a few different versions of the Memory House. The original version (Fig. 4) had 15 buttons on the back wall and five on each side wall. Even though this approach makes good use of the three-dimensional space provided by the PHANToM we also wanted to have a version that is more similar to what can be seen on a monitor. Consequently we made a version of the memory house with all the buttons on the back wall (Fig. 5). The program has been tested, together with all the programs mentioned earlier, in a study comparing sighted and blind people. The sighted testers used a regular mouse and pictures or sounds, while the blind testers used the PHANToM and sounds.

Our tests show that it is possible for almost any blind user to navigate among the sounds and buttons in the game. Of the nine blind persons in our initial test only two were unable to finish the game (although they managed to find a few pairs). The other seven users managed to find all the pairs and many of them finished the game using about as many button pushes as the sighted testers. However, most of the blind testers needed more time than their seeing counterparts.

Perhaps the most interesting result was that our tests showed that it is actually possible for a blind person to use virtual touch to create an inner picture of rather complex environments. And, apparently, they are also able to connect sounds to objects in this inner picture.

Another interesting result from these tests is that some of the subjects were able to compare what they felt with the PHANToM to earlier experiences. For example, one tester likened a virtual model of a small house (Fig. 6) to ”The money-box I got from the bank when I was a child”. The money-box he mentioned has the form of a small house and he remembered it from the time when he could still see.

We conclude that it is meaningful to make graphical user interfaces accessible for blind people using haptic technology. Most of the blind users showed substantial confidence when using the haptic interface even with the rather limited experience they had.

These results have also been confirmed in less formal tests subsequent to the initial test described above.

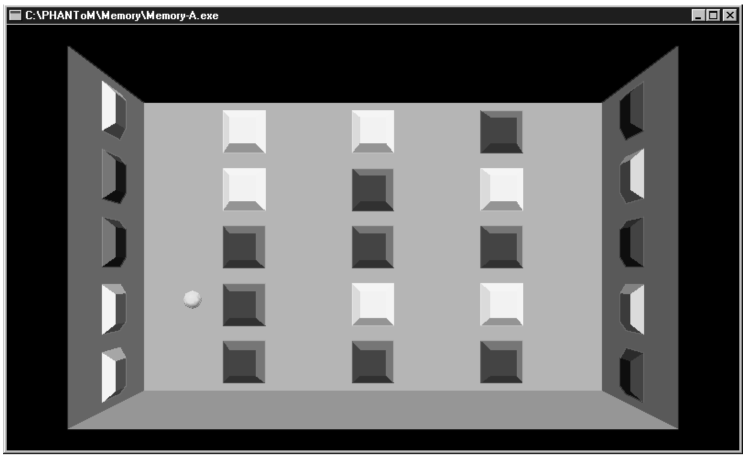

Fig. 5. The Memory House (version B).

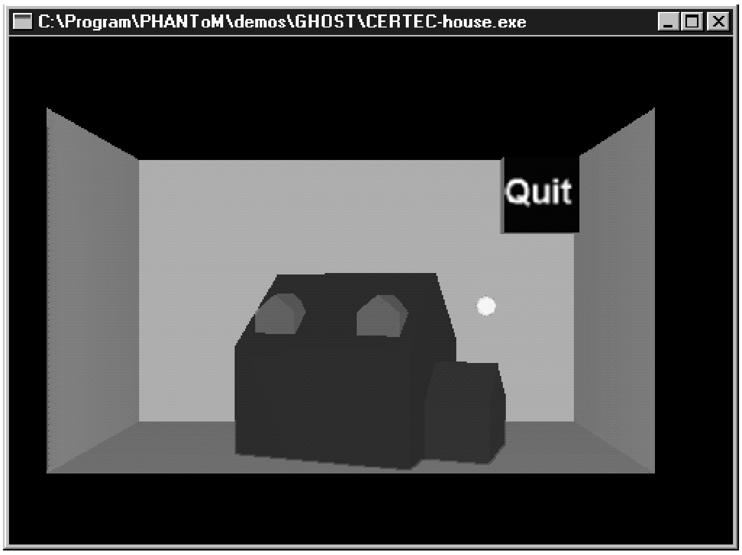

Fig. 6. A virtual model of a house.

6. 2D force feedback devices

The PHANToM is a high performance force feedback device with many benefits. The drawbacks for the end user are its complexity and high cost. Consequently, we have now started to transfer our experience from the PHANToM to new and much cheaper devices. A force feedback mouse like Immersion's FEELit [5], for example, may be a good platform for a haptic user interface with much of the functionality of the more

Fig. 7. The FEELit mouse (photo by Immersion Corp.).

Fig. 8. The Microsoft sidewinder Force Feedback Pro joystick (photo by Certec).

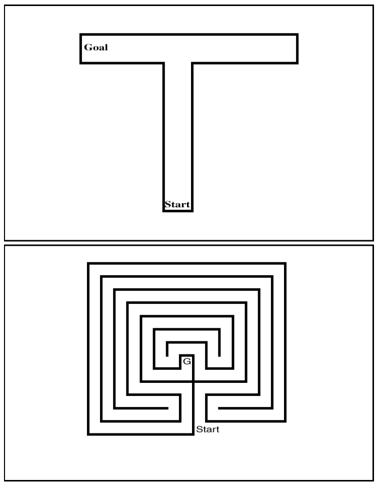

Fig. 9. Mazes (image by Anders Johansson).

expensive devices but at a significantly lower cost.

Force feedback devices using only two dimensions are sufficient for working in 2D environments like Windows. Unfortunately, the FEELit mouse (Fig. 7) is not yet available on the market, so we have done no tests with this hardware. However, Immersion staff have held a couple of pilot sessions with blind people using the FEELit mouse and speech synthesis, and we are engaged in an open discussion with them on the subject.

Other force feedback devices, such as game joysticks (Fig. 8), developed by companies like Microsoft, Logitech and Immersion, are beginning to enter the market on a large scale. These simpler devices can also be used by blind people, for both business and fun.

Certec is collaborating with two scientists who are working on the Microsoft Sidewinder Force Feedback Pro device [3] in order to test its potential usefulness to blind users. A labyrinth program has been written for this purpose.

In the ”Labyrinth” application, the user chooses a labyrinth, or maze (Fig. 9), with the push buttons on the base of the joystick. The joystick then pulls the user to the starting point of the maze. With the joystick, the user can explore the maze haptically, since its walls are simulated as force feedback in the joystick. When the user finds the goal of the maze the joystick oscillates.

There are a number of different mazes in the program, from simple examples to representations of complex historical labyrinths. The simplest maze is a ”T” labyrinth, and the most complex is that of the garden at Versailles. It turns out that by finding his way through the simpler mazes with the joystick, the user develops an inner picture (or representation) of the structure, while the more complex ones are almost impossible to successfully traverse. The more complex labyrinths consist of a large number of aisles, and the limited workspace of the joystick makes the aisles narrow and the walls too thin to recognize.

7. Haptic robot control

Another area to be explored is haptic robot control. For many years, Certec has been working with robots as assistants to people with physical disabilities. One of the problems has been how to control the robot. Among other things, we have tried to determine when free control is best and when it is more efficient to use programmed path control [1]. When it comes to free control, a haptic interface can be a great help. It provides a natural conversion between the movements of the hand and the movements of the robot, and it also gives feedback so that the user can feel what is happening. Many robot experts say that force feedback is essential to good robot control in these circumstances.

One benefit of using a universal high performance haptic interface for robot control is that it is possible to use personalized settings to control the magnitude of the users movements as well as how much force is exerted against the finger.

8. Around the corner

An interesting and very useful application for blind people is to create haptic maps and models of public spaces. If one can find one's way in a virtual environment before attempting to do so in the physical world, the chances of avoiding some potentially serious mistakes are much better. Haptic maps could be the key to better public environments for blind people by making it possible for them to have an influence in the design phase.

One step of the way to creating haptic maps would be a program that automatically converted line drawings into haptic information. It could be used not only for maps but also for much of the graphics on the World Wide Web. In fact, such a line drawing interpreter would constitute a big step towards a haptic WWW-browser.

Acknowledgements

The authors wish to thank the participants in the tests, Immersion Corporation, SensAble Technologies Inc, Anders Johansson and Joakim Linde. Special thanks to Anna-Karin Batcheller for excellent work on the text and to Bodil Jönsson for ideas and inspiration.

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Appendix 2

Supporting Presence in Collaborative Multimodal Environments by Haptic Force Feedback

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Supporting Presence in Collaborative Environments by Haptic Force Feedback

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An experimental study of interaction in a collaborative desktop virtual environment is described. The aim of the experiment was to investigate if added haptic force feedback in such an environment affects perceived virtual presence, perceived social presence, perceived task performance, and task performance. A between-group design was employed, where seven pairs of subjects used an interface with graphic representation of the environment, audio connection, and haptic force feedback. Seven other pairs of subjects used an interface without haptic force feedback, but with identical features otherwise. The PHANToM, a one-point haptic device, was used for the haptic force feedback, and a program especially developed for the purpose provided the virtual environment. The program enables for two individuals placed in different locations to simultaneously feel and manipulate dynamic objects in a shared desktop virtual environment. Results show that haptic force feedback significantly improves task performance, perceived task performance, and perceived virtual presence in the collaborative distributed environment. The results suggest that haptic force feedback increases perceived social presence, but the difference is not significant.

Categories and Subject Descriptors: H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Theory and methods*; *Input devices and strategies*; H.4.3 [**Information Systems Applications**]: Communications Applications—*Computer conferencing, teleconferencing, and videoconferencing*; H.5.3 [**Information Interfaces and Presentation**]: Group and Organization Interfaces—*Evaluation/methodology*; *Synchronous interaction*

General Terms: Human Factors, Measurement, Performance

Additional Key Words and Phrases: Presence, haptic force feedback, distributed collaboration

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1. INTRODUCTION

The modalities supported in distributed meetings, such as vision, hearing, and touch, influence the process of communication and collaboration between people. It has been argued that media that support different modalities vary in their capacity to carry data that is rich in information [Katz and Tushman 1978; Short et al. 1976; Daft and Lengel 1986; Rice 1993]. People who use technology are aware of this fact and therefore prefer to solve collaborative tasks that are equivocal and emotionally complex either in face-to-face meetings or in a sufficiently rich medium. Technological advances make it possible to meet in socially rich distributed environments through three-dimensional collaborative virtual environments, audio, and video. As a result, concerns about the degree of reality and presence in those distributed environments have been raised. But the variables that affect this perception of reality and presence are so many that a complete categorization would be hard to perform. A comparison of a sample of representative applications can only illustrate the impact on perceived appropriateness of each medium and the effects of supporting different modalities. Researchers have started to recognize the need to combine methods in order to understand more fully the concept of presence. Held and Durlach [1992] stress the importance of studies of the relations between the subjective and objective measures of presence.

The modalities most often supported by media are vision and hearing, whereas the touch modality has mostly been neglected. Therefore it is interesting to investigate what role the touch modality has in mediated interaction. Does it support social interaction, improve task performance, or increase perceived presence in distributed meetings? These are questions that are examined in this experimental study.

2. BACKGROUND

Researchers from different areas have defined the concept of presence in different ways and measured the extent to which people perceive a sense of togetherness in mediated interaction, or that they are present in a mediated environment. Two areas of research that have defined the concept of presence are the telecommunications area where social presence theory was formulated [Short et al. 1976] and the research area concerned with interaction in three-dimensional virtual reality [Hendrix and Barfield 1996; Slater and Wilbur 1997; Witmer and Singer 1998].

2.1 Social Presence Theory

Social presence refers to the feeling of being socially present with another person at a remote location. Social presence theory [Short et al. 1976] evolved through research on efficiency and satisfaction in the use of different telecommunication media. Social presence is conceived by Short et al. [1976] to be a subjective quality of a medium. Social presence varies between different media. It affects the nature of the interaction, and it interacts with the purpose of the interaction to influence the medium chosen by the individual who wishes to communicate. This implies that users are more or less aware of the degree of social presence of a medium and choose to use a medium that they perceive to be appropriate for a given task or purpose. Short et al. [1976] regard social presence as a single dimension which represents a cognitive synthesis of several factors such as capacity to transmit information about tone of voice, gestures, facial expression, direction of looking, posture, touch, and nonverbal cues as they are perceived by the individual to be present in the medium. These factors affect the level of presence that is defined to be the extent to which a medium is perceived as sociable, warm, sensitive, personal, or intimate when it is used to interact with other people.

2.2 Presence Defined in the Area of Virtual Reality

In the area of virtual reality, one aim is to generate an experience of being in a computer-generated environment that feels realistic. Presence is here defined as a state of consciousness, the psychological state of being there [Slater and Wilbur 1997; Hendrix and Barfield 1996]. Witmer and Singer [1998] define presence as the subjective experience of being in one place or environment, even when one is physically situated in another. Applied to teleoperations, presence is the sensation of being at the remote work site rather than at the operator's control station. Applied to a virtual environment, presence refers to experiencing the computer-generated environment rather than the actual physical locale.

Two psychological concepts are of interest when presence is defined as "being there," and those are involvement and immersion [Witmer and Singer 1998]. People experience a varying degree of involvement when focusing their attention on a set of stimuli or events, depending on the extent to which they perceive them to be significant or meaningful. As users focus more attention on the virtual reality stimuli, they become more involved in the virtual reality experience, which leads to an increased sense of presence.

According to Witmer and Singer [1998], immersion depends on the extent to which the continuous stream of stimuli and experiences that a virtual environment provides make people feel included in and able to interact with the environment. Factors which affect immersion include isolation from the physical environment, perception of self-inclusion in the virtual environment, natural modes of interaction and control, and perception of self-movement.

2.3 Physiology of Touch

The perception of touch is complicated in nature. The human touch system consists of various skin receptors, receptors connected to muscles and tendons, nerve fibres that transmit the touch signals to the touch center of the brain, as well as the control system for moving the body. Different receptors are sensitive to different types of stimuli. There are receptors sensitive to pressure, stretch of skin, location, vibration, temperature, and pain. Contrary to what one might think, there does not seem to be one receptor type for sensing pressure, another for sensing vibration, and so forth. Rather, the different receptors react to more than one stimulus type [Burdea 1996].

The skin on different parts of the body is differentially sensitive to touch. The ability to localize stimulation on the skin depends on the density of the receptors, which are especially dense in the hands and face. Moreover, a great deal of information provided by the kinesthetic system is used for force and motor control. The kinesthetic system enables force control and the control of body postures and motion. The kinesthetic system is closely linked with the proprioceptic system, which gives us the ability to sense the position of our body and limbs. Receptors (Ruffini and Pacinian corpuscles, and free nerve endings) connected to muscles and tendons provide the positional information.

2.4 Haptic Sensing and Touch Displays

Haptic sensing is defined as the use of motor behaviors in combination with touch to identify objects [Appelle 1991]. Many of the touch displays that have been developed in recent years use one-point haptic interaction with the virtual world. The effect is somewhat like tracing the outline of an object with your index finger in a thimble or holding a pen and recognizing it through this information alone. The only skin receptors affected by the display are those that are in contact with the pen or thimble. Haptic information is not primarily intended for the skin receptors of the human tactile system. However, it is impossible to separate the systems completely. The skin receptors provide pressure and vibration information present also in a haptic system. But it is the movement, the involvement of the kinesthetic and proprioceptic system, that provides the information necessary to the perception of the model as an object. Tracing the outline of a virtual object will eventually give the user some notion of the shape of the object.

Touch interfaces also include tactile interfaces, and usually a distinction is made between haptic and tactile interfaces. The tactile interface is an interface that provides information more specifically for the skin receptors, and thus does not necessarily require movement (motor behavior). An example of a tactile display is the braille display.

As yet, no single touch display can provide feedback that is perceived by the user as real. In specialized applications, where touch realism is important, tactile augmentation can be used. While in a virtual reality environment provided by a head-mounted display, subjects touch real instead of virtual objects [Hoffman et al. 1998]. The user then more or less believes that the object they are touching is a virtual one.

2.5 Supporting Touch in Interfaces

The results in one study on the effect of haptic force feedback indicate shortened task completion times when the task was to put a peg in a hole simulating assembly work [Gupta et al. 1997]. Also, Hasser et al. [1998] showed that the addition of force feedback to a computer mouse improved targeting performance and decreased targeting errors.

In another study the subject's performance was improved significantly when the task consisted of drawing in an interface [Hurmuzlu et al. 1998]. Sjöström and Rassmus-Gröhn [1999] have shown that haptic feedback supports navigation in and usage of computer interfaces for blind people. However, the studies did not investigate collaborative performance but single human-computer interaction.

In one study subjects were asked to play a collaborative game in virtual environments with one of the experimenters who was an "expert" player. The players could feel objects in the common environment. They were asked to move a ring on a wire in collaboration with each other such that contact between the wire and the ring was minimized or avoided. Results from this study indicate that haptic communication could enhance perceived "togetherness" and improve task performance in pairs working together [Basdogan et al. 1998; Durlach and Slater 1998]. Finally, one study shows, that if people have the opportunity to "feel" the interface they are collaborating in, they manipulate the interface faster and more precisely [Ishii et al. 1994].

3. RESEARCH QUESTIONS

The main aim of this study was to test the hypothesis that a three-dimensional collaborative desktop virtual environment supporting the touch modality will increase the perceived virtual presence, perceived social presence, and perceived task performance as well as improve task performance.

3.1 Hypotheses

(H1) Haptic force feedback improves task performance.

(H2) Haptic force feedback increases perceived performance.

(H3) Haptic force feedback increases perceived virtual presence.

(H4) Haptic force feedback increases perceived social presence.

4. METHOD

4.1 Experimental Design

In this experimental study a between-group design was used. The independent variable in the experiment was the collaborative desktop interface with two conditions, one three-dimensional visual/audio/haptic interface and one three-dimensional visual/audio interface. The variable feature was haptic force feedback. The dependent variables were three subjective measures: perceived virtual presence, perceived social presence, perceived task performance, as well as one objective measure: task performance. The subjective measures were obtained through questionnaires. The objective measure of task performance was obtained by measuring the time required to perform tasks. The subjects performed five collaborative tasks. The subjects were placed in different locations.

4.2 Independent Variable

The independent variable in this experiment was the distributed collaborative desktop virtual interface. In the test condition including haptic feedback the subjects received force feedback from dynamic objects, static walls, and the other person in the collaborative environment. The subjects could also hold on to each other.

In the condition without haptic feedback, the subjects did not receive any haptic force feedback. Instead, the haptic device functioned as a 3D-mouse. Furthermore, the subjects could not hold on to each other in the condition without haptic feedback.

4.3 Dependent Variables

4.3.1 *Task Performance*. The usability of a system can be measured by how long time it takes to perform a task and how well the task is performed [McLeod 1996]. These are objective measures of overt behavior. With regard to presence, the argument is that the higher the degree of presence the higher is the accomplishment of tasks by subjects. In this study task performance was measured by a single measure: the total time required for a two-person team to perform five tasks.

4.3.2 *Perceived Task Performance*. Perceived task performance was measured by a questionnaire using bipolar Likert-type seven-point scales. The questionnaire focused on the users' evaluation of their own task performance when using the system, how well they understood the system, and to what degree they felt that they learned how to use the system, as well as their skill level in using specific features in the system. The questionnaire considered the dimensions: performance in use of system, learnability, and use of specific functions. The questionnaire consisted of 14 questions. Some examples of questions measuring perceived task performance are shown in the top half of Figure 1.

4.3.3 *Perceived Social Presence*. The definition of social presence in this experimental study was "feeling that one is socially present with another person at a remote location." Social presence questionnaires were constructed around four dimensions which have been shown to differentiate social presence: unsociable-sociable, insensitive-sensitive, impersonal-personal, cold-warm [Short et al. 1976]. A bipolar seven-point Likert-type scale was used. The questionnaire consisted of eight questions. Some examples of questions measuring perceived social presence are shown in the bottom half of Figure 1.

4.3.4 *Perceived Virtual Presence*. In this experimental study presence—defined as "feeling as if being in a mediated environment"—will be referred

The following questions consider how you perceived that you could handle the system that you used in this experiment. Please mark with an X the alternative that corresponds with your impression.

How do you think that you managed to do the tasks in the system?

Not at all well |____|____|____|____|____|____|____| Very well

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

Very difficult |____|____|____|____|____|____|____| Very easy

Was it hard to manipulate objects collaboratively?

Very problematic |____|____|____|____|____|____|____| Not at all problematic

The following pairs of words describe how you could have perceived the virtual communications environment. Please write an X below the number that corresponds to your impression.

I perceived it to be:	1	2	3	4	5	6	7	
impersonal								personal
cold								warm
insensitive								sensitive
unsociable								sociable
negative								positive

Fig. 1. (Top) Examples of questions measuring perceived task performance. (Bottom) Examples of questions measuring perceived social presence.

to as virtual presence. Virtual presence was measured using a questionnaire with Likert-type seven-point scales. Witmer and Singer [1998] describe the specific questions in great detail. The factors measured in the questionnaire are: control factors, sensory factors, distraction factors, and realism factors. The questionnaire consisted of 32 questions.

4.4 Subjects

Twenty-eight subjects participated in the experiment. Of these subjects, 14 were men, and 14 were women. The subjects performed the experiment in randomly assigned pairs. There were 14 pairs: each consisting of one woman and one man (Figure 2). The subjects were students from Lund University in Sweden. The subjects were between 20–31 years old, and the mean age was 23 years.

None of the subjects had prior experience with the collaborative desktop virtual interface used in this study. The subjects did not know each other before the experiment, and they did not meet face-to-face prior to the experiment.

Fig. 2. Subjects are doing tasks using two versions of the PHANToM, on the left a "T" model and on the right an "A" model.

Fig. 3. PHANToM, a force feedback device (SensAble Technologies Inc.).

4.5 Apparatus

4.5.1 *The Haptic Display System*. The haptic display used in this investigation was a PHANToM (Figure 3) from SensAble Technologies Inc. of Boston, MA. It is primarily intended for adding 3D-touch to 3D-graphics programs, and the main users are in research and development. It is, among other things, used as a simulation platform for complex surgery tasks, VR research, and to enhance 3D CAD systems.

Three small DC motors provide the force feedback to the user, who holds a pen connected to the device (Figure 3). The movements of the users hand (or rather, the tip of the pen) are tracked by high-resolution encoders, and are then translated to coordinates in 3D space. If the position coincides with the position of a virtual object, the user feels a resisting force that

Fig. 4. Two views of the collaborative virtual environment with eight dynamic cubes placed in the room and representations of the users in the form of one green and one blue sphere. The right picture shows two subjects lifting a cube together.

pushes the tip of the pen back to the surface of the virtual object. Thus, by moving the pen, the user can trace the outline of virtual objects and feel them haptically. This haptic process loop is carried out about 1000 times per second. The high frequency and the high resolution of the encoders enable a user to feel almost any shape very realistically with a device like the PHANToM [Massie 1996]. Concurrently, a process runs to display a graphic representation of the virtual objects on the screen.

Two PHANToMs, placed in two different rooms linked to a single host computer, were used for the experiment. Both PHANToMs were identical in operation, but were of different models. One was attached to the table (the "A" model), and the other was attached hanging upside down (an older "T" model).

Two 21-inch computer screens were used to display the graphical information to the users, one for each user in the different locations. The screens, attached via a video splitter to the host computer, showed identical views of the virtual environment.

4.5.2 *The 8QB (Eight-Cube) Program*. The program used for the collaborative desktop virtual environment was built using the GHOST® Software Development Toolkit. The haptic environment consists of a room with constraining walls, ceiling, and floor, containing eight dynamic cubes that initially are placed on the floor (Figure 4).

The cubes are modeled to simulate simplified cubes with form, mass, damping, and surface friction, but lack, for example, the ability to rotate. The cubes are of four different colors (green, blue, yellow, and orange, two of each) to make them easily distinguishable, but are identical in dynamic behavior, form, and mass.

The cubes can be manipulated by either of the two users, or in collaboration. A single user may push the cubes around on the virtual floor, but since the users only have a one-point interaction with the cubes, there is no simple way to lift them. Lifting the cubes can be done in two different ways.

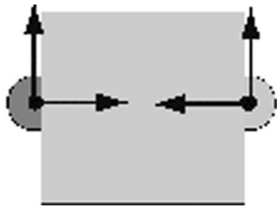

Fig. 5. Two users collaborate to lift a cube. The users press into the cube from opposite sides and lift it upward simultaneously.

Either the users collaborate in lifting the cubes (Figure 5), or a single user lifts a cube by pressing it against the wall and pushing it upward.

The users are represented by spheres with a diameter of 12 mm. In the graphical version they are distinguishable by color (one is blue, the other green). To separate the haptic feeling of a cube from that of another person in the environment, a slight vibration was added. Furthermore, the users can hold on to each other—a feature originally implemented to enable the users to virtually "shake hands." Holding is simulated by pressing a switch on the PHANToM pen. When only one user presses the switch to hold on to the other person, the force that holds them together is quite weak, and the user who is not pressing his switch only needs to apply a small force to pull free. If both users press their switches the force is much stronger, but it is still possible for the users to pull free of each other without releasing the switch. The 8QB program was used on a single host computer, with two PHANToM devices and two screens attached to it. Therefore, the two users always had exactly the same view of the environment. The program exists in two different versions, one with haptic feedback and one without haptic feedback. In the program without haptic force feedback, the user can feel neither the cubes, nor the walls, nor the other user in the environment, and the users cannot hold on to each other. In that case, the PHANToM functions solely as a 3D mouse.

4.5.3 *Audio Connection*. Headsets (GN Netcom) provided audio communication via a telephone connection. The headsets had two earpieces and one microphone each.

4.5.4 *Documentation*. One video camera was used to record the interaction from one of the locations, and a tape recorder recorded the sound at the other location. The angle of video recording was from behind the subject and slightly from the side so that the computer screen and the hand with which the person was controlling the PHANToM was visible.

4.6 Procedure

The assistant and the experimenter went to meet the two subjects at different meeting-places and accompanied each subject to the laboratory. Each subject was seated in front of the interface and given further instructions about the nature of the experiment. The two subjects received the same instructions. The subjects were then asked to count down 3,2,1, together before turning the first page to start the session. The subjects performed five collaborative tasks in both conditions. When the subjects had filled out the questionnaires they were encouraged to ask questions about the experiment of the experimenter and the assistant respectively when they were still alone. They then met the other person, the experimenter, and the assistant in a joint debriefing.

4.7 Tasks

Each collaborating pair of subjects was presented with five tasks. The tasks (A–E) were presented in the same order to each subject. Before the real test started the subjects had the opportunity to establish contact with each other through the telephone connection. They also practiced the functions, lifting a cube together and holding on to each other. The instructions for tasks A–D were the same for both the visual/audio-only condition and the visual/audio/haptic condition. Task E was formulated slightly differently in the two cases, since the possibility of holding on to each other is only available with haptics.

Tasks A–C consisted of lifting and moving the cubes together in order to build one cube without an illustration (task A), two lines (task B, Figure 6), and two piles (task C, Figure 7), out of the eight cubes. Task D required the subjects to explain one half of a whole pattern to the other subject, as each subject had only one half of an illustration each, and then build the whole pattern (Figures 8–9). The instructions for task E were slightly different in the two conditions. In both conditions the task was to navigate together around the pattern that the subjects had built in task D (Figure 10).

As mentioned before, the subjects could hold on to each other by pressing a switch on the stylus in the condition with haptics. This option was not available in the condition without haptic feedback. In that case the subjects held on to each other symbolically by keeping their cursors connected. There was a time limit set for each task. All pairs of subjects managed to complete all tasks within the maximum time allowed.

5. RESULTS

The analysis of the data using ANOVA showed three significant differences between the three-dimensional visual/audio/haptic condition and the three-dimensional visual/audio-only condition. The three significant results were task performance, perceived virtual presence, and perceived task performance. The dependent variable—perceived social presence—did not differentiate the conditions significantly when analyzed with ANOVA.

5.1 Task Performance

The first hypothesis was concerned with the extent to which haptic force feedback improved task performance. The results showed that task performance defined operationally as total task completion time differs significantly ($p < 0.05$) across the two conditions. The mean task completion time

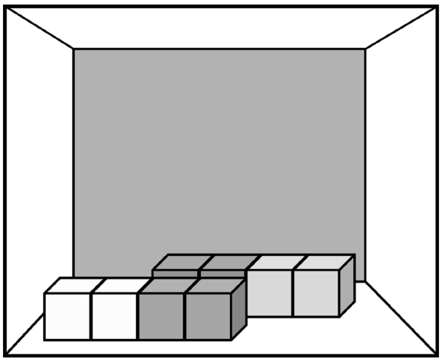

Fig. 6. Task B.

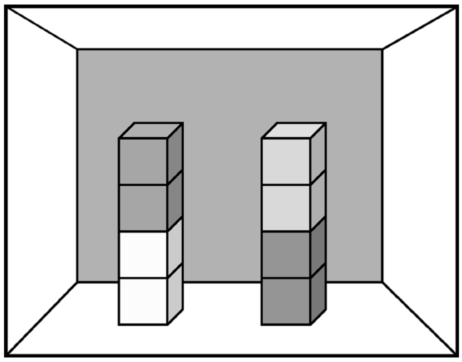

Fig. 7. Task C.

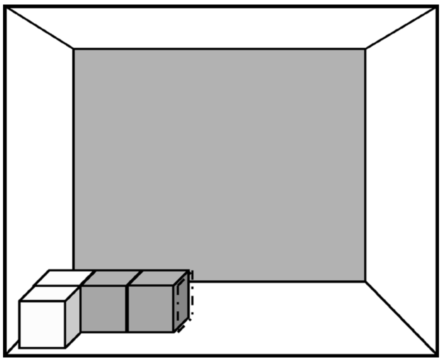

Fig. 8. Task D, person 1.

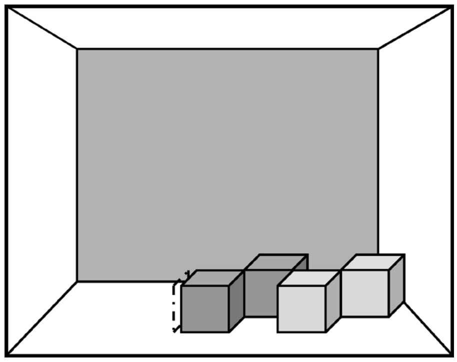

Fig. 9. Task D, person 2.

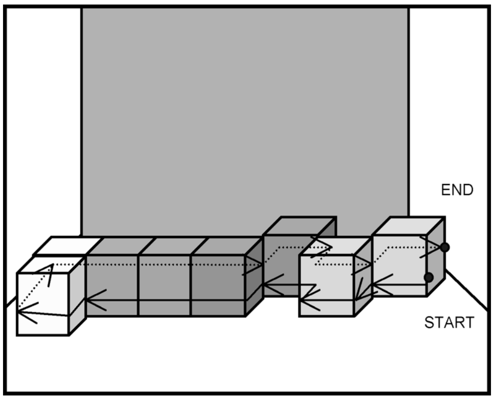

Fig. 10. Task E.

was shortest for the three-dimensional visual/audio/haptic condition (M = 1443 seconds, s = 435) and longest for the three-dimensional visual/audio-only condition (M = 2105 seconds, s = 550) (Table I). This means that subjects used about 24 minutes to perform five tasks in the haptic force

Table I. Experimental Results Regarding Total Time to Complete Tasks for the 14 Groups and Regarding Social Presence, Virtual Presence, and Perceived Performance for the 28 Subjects

				Haptic Feedback	No Haptic Feedback
Performance (sec.)	(n = 14)	F = 6.25	p = 0.028*	M = 1443	M = 2105
Virtual presence	(n = 28)	F = 25.5	p = 0.0001**	M = 174	M = 142
Perceived Performance	(n = 28)	F = 11.63	p = 0.0021**	M = 83	M = 71
Social presence	(n = 28)	F = 2.58	p = 0.1206	M = 42	M = 38

*= significant at 95% level
**= significant at 99% level

feedback condition, and subjects used about 35 minutes in the condition with no haptic force feedback.

5.2 Perceived Virtual Presence

One hypothesis posed was that haptic force feedback would increase perceived virtual presence. The total dimension—perceived virtual presence—measured by a questionnaire did differ significantly ($p < 0.01$) between the two conditions. The subjects mean rating of perceived virtual presence was significantly higher in the three-dimensional visual/audio/haptic condition ($M = 174$, $s = 17$) than in the three-dimensional visual/audio-only condition ($M = 142$, $s = 17$) (Table I). As there were 32 questions, the mean value for each question on the seven-point Likert-type scale was 5.4 in the three-dimensional visual/audio/haptic condition and 4.4 in the three-dimensional visual/audio-only condition.

5.3 Perceived Task Performance

Another hypothesis that was investigated in this study is whether haptic force feedback increases subjects' perceived task performance. This dimension was measured by a questionnaire and the items were analyzed together as a total. The ratings of perceived task performance differed significantly ($p < 0.01$) across the two conditions. Subjects thus perceived their task performance to be higher in the three-dimensional visual/audio/haptic condition ($M = 83$, $s = 9$) than in the three-dimensional visual/audio-only condition ($M = 71$, $s = 10$) (Table I). As there were 14 questions, the mean value for each question on the seven-point Likert-type scale is 5.9 in the three-dimensional visual/audio/haptic condition and 5.1 in the three-dimensional visual/audio-only condition.

5.4 Perceived Social Presence

The hypothesis that haptic force feedback would increase subjects' perceived social presence was not verified. The dimension social presence measured by a questionnaire did not differ significantly across the conditions when the items were analyzed together as a total dimension. The mean rating of the total dimension social presence was highest for the three-dimensional visual/audio/haptic condition (M = 42, s = 6) and lowest for the three-dimensional visual/audio-only condition (M = 38, s = 6) (Table I). This suggests that the subjects' perceived social presence was slightly higher in the haptic force feedback condition. As there were eight questions, the mean value for each question on the seven-point Likert-type scale is 5.3 in the three-dimensional visual/audio/haptic condition and 4.8 in the three-dimensional visual/audio-only condition.

6. DISCUSSION

This empirical study demonstrates that haptic force feedback gives added support to people performing collaborative tasks in a multimodal interface. When all other variables remained constant, haptic force feedback significantly improved task performance, increased perceived task performance, and increased perceived virtual presence.

Both the objective measure of time to perform tasks and the subjective measure of perceived task performance improved in the condition with haptic force feedback. It is reassuring that the subjective and the objective measures show the same result. Subjects' perception of better task performance suggests that it was easier to manipulate and understand the interface when the interaction was supported by haptic force feedback. It was also easier to perform specific tasks like lifting cubes. The results showing shortened task completion time are consistent with the results in the Gupta et al. [1997] study where performance improved when subjects received haptic force feedback.

Furthermore, the results demonstrate that the subjects' perceived virtual presence in the collaborative virtual environment increased when haptic force feedback was provided. This means that the subjects to a higher degree felt as if they were present in the virtual environment when they received haptic information.

However, results also show that haptic force feedback did not improve the perceived social presence significantly as a total dimension in this study. This means that the haptic force feedback did not add as much social information as hypothesized. But the mean values indicate that the haptic force feedback condition was perceived to increase social presence slightly. An aspect that may explain this result is that the effect of the audio connection may have overshadowed the impact of haptic force feedback in the interaction concerning social presence. It would therefore be interesting to conduct an experiment without an audio connection in order to investigate this hypothesis.

It is interesting to find that social presence, i.e., feeling that one is present with another person at a remote location, and virtual presence, i.e., feeling as if present in a remote environment, did not both increase when supported by haptic force feedback in this study. This implies that social presence and virtual presence might be regarded as different aspects of interaction in a collaborative environment.

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Appendix 3

Designing Haptic Computer Interfaces For Blind People

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DESIGNING HAPTIC COMPUTER INTERFACES FOR BLIND PEOPLE

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ABSTRACT

Certec has been working on touch interfaces – haptic interfaces – since 1995, exploring the possibilities they can offer people with different kinds of disabilities. With a haptic computer interface a blind person can learn mathematics by tracing touchable mathematical curves, playing haptic computer games, and gaining better access to graphical user interfaces like Windows.

This paper presents a brief overview of a set of tests that have been made and some of the results from these tests. This is followed by a set of design recommendations that we have been able to extract as an extended result of this research and development work. These guidelines are grouped under the headings Navigation, Finding objects, Understanding objects, Haptic widgets and Physical interaction.

1 INTRODUCTION

Computer access and the wide adoption of the Internet as an information channel have given blind persons access to information that used to be almost inaccessible. The fact that text in digital form can be easily accessed has actually given blind persons a new way of communicating with the rest of the world.

Most blind computer users have a screen reader combined with synthetic speech and/or a Braille display. This gives them access to text on the screen, but not to the graphics. Haptic interfaces use the sense of touch in user interaction. With a haptic interface it is thus possible to feel shapes that are based on digital information. There are now computer programs available that present some of the graphical information in a GUI via a haptic device.

Certec is the Division of Rehabilitation Engineering Research, Department of Design Sciences, Lund Institute of Technology at Lund University in Sweden. We have been working with haptic computer interfaces and haptic games for blind people since 1995.

2 THE EXPERIMENTS

This paper presents a set of principles for haptic user interface design. The user tests and experiments that lay the foundation for this article have not been designed specifically to achieve or test the principles. Instead, these tests have been conducted to test different user interface ideas, games etc. and to get an idea of how useful it can be to include haptics in a computer interface for blind people. The principles have emerged and been refined with "reflection-in-action" and "reflection-on-action" [4] during our tests and software development. We have found these recommendations useful, and we believe that they can work as general guidelines for all developers of haptic interfaces for blind people.

2.1 User tests of a haptic memory game - The Memory House

These tests were conducted to find out if it is possible to understand and control a system like Windows with only haptic and auditive information.

The game consists of 25 buttons that produce a sound when pressed. There are 12 sound pairs and one non-paired sound (the "Old Maid"). The buttons disappear when the player presses two buttons with the same sound in sequence.

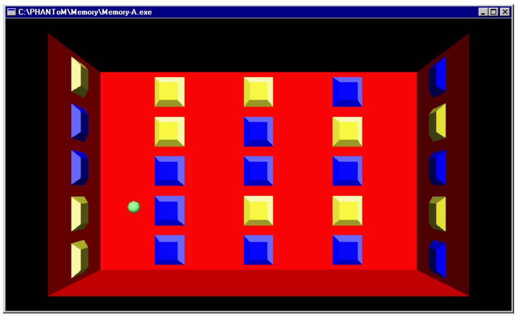

Figure 1. The Memory House

In the Memory House, the buttons are placed on five different floors. Between each row of buttons the user can feel a thin barrier that helps him to stay within one set of buttons. To make navigation among the floors easier, there is a voice that reads the number of the floor each time the user moves from one floor to another.

The program has been tested in a study comparing sighted and blind people (nine blind persons of different ages and 23 sighted children). The sighted testers used a regular mouse and pictures or sounds, while the blind testers used the PHANToM and sounds.

The main results from these tests indicate that it is possible for almost any blind user to navigate among the sounds and buttons in the game. Of the nine blind persons in our initial test only two were unable to finish the game (although they managed to find a few pairs). The other seven users managed to find all the pairs and many of them finished the game using about as many button pushes as the sighted testers. However, most of the blind testers needed more time than their seeing counterparts [6][7].

2.2 Pilot studies with Immersion's FEELit Mouse

In these tests, we conducted three different experiments using a prototype of the FEELit Mouse from Immersion Corporation. The experiments where:

1. Combining FEELit Desktop with synthetic speech for general Windows access
2. Testing "radial haptic menus"
3. Testing a set of virtual haptic search tools that can be used as aids in finding scattered virtual objects such as icons on the desktop.

The first is an example of direct translation from graphics to haptics. FEELit Desktop from Immersion is a program that directly translates many graphical interface objects to corresponding haptic objects. Our work has been to try to determine how well FEELit Desktop can compensate for things that are not made accessible by the speech synthesizer.

Radial menus are menus where the choices are indicated as rays pointing out from a center instead of being arranged in a column as in ordinary linear menus. A radial menu can be likened to a pie or a clock. In this case a radial menu with 12 choices was used and that made it very easy to use a clock analogy (e.g. "Copy is at three o'clock").

The virtual search tools are intended to help the user when exploring an unknown environment, for example, the Windows desktop on somebody else's computer. With these tools it is possible to feel objects without touching them directly. Three different search tools were proposed but only the first one was tested in this experiment.

- A "cross" that makes it possible to feel when you line up with an object horizontally or vertically.
- A "magnet" that pulls the user towards the nearest object.
- A "ball" that makes it possible to feel objects at a distance but with less detail.

We have carried out a case study of the usability and usefulness of these concepts involving two blind computer users [8]. Both users had minor problems with the small workspace of the FEELit Mouse. Their spontaneous reaction was: "This device requires tiny, tiny movements. Can't it be made a little bit bigger?"

The radial menus worked very well for both of the testers. They were successful in handling the menus and they were also able to make good use of the clock metaphor. Even though both testers thought that these menus worked well they where skeptical about introducing them in a Windows access system. They both wanted the access system to be as transparent as possible and they wanted it to give them the same picture as a sighted person gets when looking at the monitor.

The cross search tool was especially well accepted by one of the testers. He found the cross very helpful when searching. The other user was more uncertain about the cross. He talked more about magnetic objects as a way to guide the user. Since all search tools apart from helping the user to find and explore virtual objects, also alter the sensation in different ways, it seems important to be able to easily switch between different search tools and no tool at all.

2.3 Informal demos and tests of a haptic games and programs

Certec has developed a number of haptic games and programs that have not been tested formally. However the programs have been demonstrated at exhibitions and conferences to both sighted and blind visitors, and there also have been many trial sessions at Certec with blind children and adults, as well as with a group of deaf-blind persons.

The programs used at these sessions were scenes with simple static or dynamic geometrical objects, a game called "Submarines", and a simple clay-modeling program (provided by SensAble Technologies).

"Submarines" is a haptic variant of the well-known battle-ship game. The ordinary pen-and-paper-based battleship game has been used to give school children an initial idea of what coordinate systems can be used for. With "submarines" it is possible for a blind child to get the same kind of playful introduction to coordinate systems.

The player feels 10x10 squares in a coordinate system. In the game, your finger in the PHANToM is a helicopter that is hunting submarines with depth charge bombs. If you put your finger on the "surface of the water" you can feel smooth waves moving up and down. There are four different states for a square with associated haptic feedback:

- Not yet bombed - calm waves
- Bombed, but missed - no waves (flat)
- Bombed, hit part of a submarine - vibrations
- Bombed, hit entire submarine - bubbles

"Submarines" has also been tried by a group of deaf-blind persons. Since the different conditions of the squares are provided as haptic feedback, our hypothesis was that it should work well for deaf-blind users too. As it turned out, it seemed like the haptic feedback of the game was sufficient, in all but one case. In the game, the space key is used to drop the bomb in the water, and while the bomb falls, a hearing person hears the sound of the falling bomb in the speakers. However the deaf-blind users became confused since they did not get any haptic feedback before the bomb reached the water and there was no direct haptic feedback indicating whether it was a hit or not.

The first PHANToM program at Certec was a painting program for blind children, "Paint with Your Fingers". With the PHANToM, the user chooses a color from a palette. Each color on the palette has an associated texture that the user feels when painting with it. By changing program mode the user can feel the whole painting and also feel what other people have painted.

All of these programs have been tested by more than 20 blind children [5][7]. Perhaps the most interesting result from these sessions was that it is actually possible for a blind person to use virtual touch to create an inner picture of rather complex environments. And they are also able to connect sounds to objects in this inner picture.

Another finding is that some of the subjects were able to compare what they felt with the PHANToM to earlier experiences. For example, one tester likened a virtual model of a house to "The money box I got from the bank when I was a child". The money box he mentioned had the form of a small house and he remembered it from the time when he could still see.

2.4 A haptic mathemathics program

Early in our work we also developed a simple mathematics program. People who try to explain mathematics to blind persons often notice that to some extent it is a visual subject. Our program makes it possible to feel a mathematical curve or surface with the PHANToM. A program like this can help blind persons to understand equations in terms of curves and surfaces. A similar program, but with more functionality, has been developed at ASEL, University of Delaware [1].

It is interesting to compare the two programs because they demonstrate two different ways of showing 2D graphs in a 3D environment. The program from ASEL displays the graph as a thin line with a "virtual fixture", which gives the line an attractive force that helps the user find and follow the function. The program from Certec shows the function as a ridge or a groove in a flat surface. In this case the user can sweep the surface until she finds the ridge or groove and then follow it easily. Both ways are feasible.

3 APPARATUS

Most of our work has been carried out with the PHANToM, a high performance, 3D haptic interface from SensAble Technologies. We have also used other devices such as force feedback joysticks and the FEELit Mouse from Immersion Corp.

Figure 2. The PHANToM (photo by SensAble Technologies Inc.)

4 GUIDELINES FOR POINT INTERACTION HAPTICS - DESIGN REQUIREMENTS

In the course of the work with the above-mentioned experiments we have also gained general knowledge and experience of using haptics in computer interfaces for blind people. This knowledge was first summarized in my licentiate thesis "The IT Potentials of Haptics – Touch Access for People with Disabilities" [8]. The list presented here is a revised version of those principles.

4.1 Navigation

- Provide well defined and easy-to-find reference points in the environment. This is necessary to facilitate navigation. Natural reference points are for example the corners of a room. Good reference points are easy to find and come back to, and they should also be easy to identify [6].
- Do not change the reference system unnecessarily. A disabled haptic button should not be removed, but rather "grayed out" for example by giving it a different texture and making it impossible to click. This way the button can still be used as a reference point even though it is nonfunctional. [6].

4.2 Finding objects and getting an "overview"

- With pure one-point haptics it is easy to miss an object even if one is really close to it. One can often compensate for this when designing haptic software by using objects with large connected surfaces rather than scattered, thin and/or small objects [6][8].

- It can be just as difficult to determine that an object does not exist as it is to find an object. It is always easier to move along some kind of path (a ridge, a groove, a magnetic line, etc.) to the place where the object is located or where there is no object [6][8].

- In both of the cases just mentioned one can also choose to give the user a "virtual search tool" [8] instead of changing the virtual objects. A virtual search tool could be a bar, a ball, or a magnet, for example.

4.3 Understanding objects

- If it is not absolutely necessary for the haptics to feel like something real, it may be beneficial (and sometimes essential) to help the user follow the outline of the object. It is easy to make a thin touchable hose easier to find by giving it the appropriate attractive force. Without such a force it is almost impossible to feel the hose in 3D [1].

- Sharp edges and corners are much more difficult to feel and understand than rounded shapes when they are felt from the "outside". The user almost always loses contact with the object when moving past a sharp corner, thereby disturbing the cognitive process that translates the impressions received into an inner picture. Moreover, it is difficult to determine the size of the angle; many users believe that the angle is more acute than it really is [6].

4.4 Haptic widgets

- When going through a thin wall or past an edge, the finger often accelerates a great deal. Consequently, the next wall or edge should not be very close since there is a risk that the finger will go through that wall as well (sometimes without the user noticing). In this case it can sometimes help to replace the thin walls (between the areas) with a magnetic line that pulls the user to the center of the area instead. The problem becomes apparent when one wishes to represent menus and coordinate systems [3][8].

4.5 The physical interaction

- Be careful with the manipulandum design. The manipulandum is the tool that the user grasps in his hand. In the PHANToM the manipulandum is a stylus or a thimble. In other cases it might be a mouse body, a joystick handle or some specialized tool. The choice of manipulandum can affect the haptic sensation a great deal. This is because the form and surface of the manipulandum have an effect on how the resistive force is applied to the user, the kind of movements used, and the feeling of being in contact with the virtual object. For example, a thimble with sandpaper on the inside causes many people to use less force when grabbing a virtual object because they get the sensation that the objects are less slippery [2][8].

5 CONCLUSION

Haptic interfaces can be used in many different kinds of computer programs for blind people. We have found that our haptic programs in general work better when considering these guidelines, even though we do not claim to have complete knowledge of how digital objects should be accessed haptically in all cases.

Some of the tests presented here make effective use of sounds along with the haptic information; we have found that sound and haptics often complement each other very well.

We will continue our work with haptic interfaces and expect to refine and add to this list of guidelines continuously.

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Appendix 4

Haptic Representations of 2D Graphics for Blind Persons
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Haptic Representations of 2D Graphics for Blind Persons

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Abstract

Haptic interface technology has the potential of becoming an important component of access systems for people who are blind or visually disabled.

The purpose of this study was to learn more about how a haptic interface can be used to give blind persons access to 2D graphics and similar computer based graphics. User tests were carried out with 25 blind users from Sweden and Italy using the Phantom device from SensAble Technologies. The tests included mathematical curves, textures, haptic picture reliefs and haptic floor plans. This article reports on both technical solutions and results from the user tests.

The results were influenced both by the nature of the different tasks and by individual differences among the test persons. 78% of the users managed to solve the applied mathematical problem that was the task for the mathematics program. Four virtual textures where correctly matched with real life textures by 68% of the users. The results for the picture reliefs where highly dependent on contextual information: Approximately 50% of the users could identify the haptic picture reliefs without contextual cues, whereas more than 80% of the users could identify parts of the drawing once they knew what was depicted. More than 80% of the users could find a specific room in the floor plan.

This research has implications for new ways in which blind persons can gain access to graphical information, even on the Internet.

Introduction

Certec is the division of rehabilitation engineering at the department for design sciences, Lund Institute of Technology, Lund University in Sweden. The haptics group at Certec has been working with and studied the use of haptic interfaces since 1995, exploring the possibilities they can offer people with different kinds of disabilities. Haptic applications have the potential of becoming an important part of future information access systems for blind and visually disabled persons. Using a haptic device, it may also be possible to make virtual reality, pictures and graphs accessible for blind persons. To be able to develop useful applications for this group, however, it is important to gather more information about the ability of blind users to interact with different haptic virtual environments. Thus, during the summer of 2001, we carried out a user test study including 25 blind users using the Phantom haptic device from SensAble Technologies [41]. In this paper we concentrate on the parts of the test that consider different kinds of 2D graphics and 2D information. Other parts of the study are covered in the article "Navigation and Recognition in 3D Haptic Virtual Environments for Blind Users" by Sjöström et.al [39].

Four different applications that present 2D information in haptic form for use by persons who are blind or have severely limited vision were tested. In some cases, sound was also added to the programs. All applications should be viewed as demonstration applications. This means that they may not include full capabilities to serve as commercial software, but they illustrate different aspects of haptic technology for computer users who are blind or visually disabled.

The first application that we tested is a viewer for mathematic functional graphs. A special version of this program that displays the result of an ecological simulation with herbivores and carnivores on an isolated island was designed for this test. This special version is based on a general mathematics viewer that accepts textual input to state the function to be rendered. The output is a line rendered as a groove or a ridge that could be traced with one finger on the back wall of a virtual room. In this program the user can manipulate the fertility of the animals and analyze how this affect the whole ecological system on the island.

The second application is a demonstration of how real life textures can be represented in virtual haptic environments.

The third application is a program that tests how black and white line drawings can be rendered as haptic reliefs more or less automatically. Different scanned images that were converted to a haptic height map that could be traced via the Phantom were used.

The fourth application is based on the same technology as the haptic image viewer but uses floor plans instead of general pictures and is also enhanced with sound.

To our knowledge, this study is one of the most extensive tests of haptics for people who are blind that has been published so far. Most of the earlier published tests (referred to in this paper) have used use a maximum of twelve blindfolded sighted users and none incorporate more than ten blind users.

We only had test users who were blind because we wanted to study the effect of haptic technology without support from visual information and we wanted to test our ideas with potential users of the system. There is strong evidence that vision and haptics have representational similarities [4][7]. To have only blind users is a way of getting around problems in interpreting the results that might arise when haptic and visual impressions are mixed.

Background

Access to visual information for people who are blind

To blind and nearly blind persons computer access is severely restricted due their loss of access to graphics information. Access to visual information is essential in work and social interaction for sighted persons. A blind person often accesses visual information through a process involving a sighted person who is able to convert the visual image into a tactile or verbal form. This obviously creates a bottleneck for any blind person who wants access to visual information and it also generally limits his or her autonomy.

Access to graphical information is one of the key problems when it comes to computer access for people who are blind. All Windows systems are entirely based on the user being able to gain an overview of the system through visual input. The Windows interface is actually more difficult to use than the old text-based system. Still, Windows can be attractive for blind people due to the many computer programs available in that environment and the value of being able to use the same platform as others.

Haptic and tactile interaction

Most of the work that has been done with graphics for blind persons uses tactile touch whereas we in this study use haptic touch. We will motivate that shortly, but first a short definition:

Haptic sensing is defined as the use of motor behaviors in combination with touch to identify objects [1]. Many of the touch displays that have been developed in recent years use one-point haptic interaction with the virtual world. The effect is somewhat like tracing the outline of an object with your index finger in a thimble or holding a pen and recognizing it through this information alone. The only skin receptors affected by the display are those that are in contact with the pen or thimble. Haptic information is not primarily intended for the skin receptors of the human tactile system. However, it is impossible to separate the systems completely. The skin receptors provide pressure and vibration information present also in a haptic system. But it is the movement, the involvement of the kinesthetic and proprioceptic system, that provides the information necessary to the perception of the model as an object. Tracing the outline of a virtual object will (after some time) give the user a notion of the shape of the object.

Usually a distinction is made between haptic and tactile interfaces. The tactile interface is an interface that provides information more specifically for the skin receptors, and thus does not necessarily require movement. An example of a tactile display is the braille display.

Static versus dynamic touch information

Tactile images normally provide a raised representation of the colored areas in the corresponding picture. It is possible to use microcapsule paper (a.k.a. swell paper) to convert a black and white image to a tactile version. This technique gives access to line drawings, maps etc. in a permanent fashion. The main drawback is that it takes some time to produce these pictures, but in many applications this is not a big problem. These devices can be compared to the printers in computer systems for sighted people. Static reliefs can also be produced by embossing thick paper as is normally done with Braille text. By using vacuum formed plastic, it is possible to produce tactile pictures that are more robust than embossed paper.

What is much harder however, is to access graphical information that is variable such as web graphics or graphical user interfaces. To access such information one needs an updateable touch display that can take the place of the monitor in a normal computer system. Several researchers have carried out investigations with updateable tactile pin arrays [21][31]. The main problem with this technology is to get a sufficiently high resolution. The tactile pin arrays of today are still nowhere near the resolution that is available with embossed paper or vacuum formed plastic.

In this study we investigate different ways to access graphical information dynamically via the sense of touch and a haptic computer interface. The haptic interfaces that are available today have very high resolution and they are becoming more and more robust. Haptic interfaces also have the possibility to render dynamic touch sensations and variable environments. Haptic technology is thus a very interesting alternative for computer graphic access for people who are blind.

One of the problems that must be dealt with when working with haptic interfaces is that the technology limits the interaction to a discrete number of points at a time. The Phantom, which is used in these tests, has one point of interaction. Although this might appear to be a serious limitation, the problem should not be overestimated. It has been shown by several independent research teams that haptic interfaces can be very effective in, for example, games, graph applications and for information access for blind persons [3][8][12][13][36][38][49].

Related work

This work is related to much of the work that has been done on tactile imaging, access technology for blind persons and haptics in general.

Mathematics and graph display systems

In the field of computer based simulations for the blind haptic representations of mathematical curves have attracted special interest. One of Certec's first haptic programs was a mathematics viewer for the Phantom [34][35]. In this program the 2D functional graph was presented as a groove or a ridge on a flat surface. It turned out that this representation was quite effective and the program was appreciated even though it was not very flexible (for example the functions could not be entered directly, but had to be chosen from a list). The program could also handle 3D functional surfaces.

At about the same time, Fritz et.al. designed a haptic data visualization system to display different forms of lines and surfaces to a blind person. This work was presented later in [8]. Instead of grooves/ridges, Fritz uses a "virtual fixture" to let the user trace a line in 3D with the Phantom. This program and our original program are the first mathematics programs for the Phantom that we are aware of.

Later on, Van Scoy, Kawai, Darrah and Rash has made a mathematics program with a function parser that is very similar to our mathematics program [42] but includes the possibility to input the function via a text interface. The functional graphs are rendered haptically as a groove in the back wall much as we did in our original program. However, the technical solution is quite another: in this program the surface and the groove is built with a polygon mesh that is generated from the input information.

Ramloll, Yu, Brewster et.al. have also presented an ambitious work on a line graph display system with integrated auditory feedback as well as haptic feedback [26][49]. This program can make use of either the Phantom or Logitech Wingman Force Feedback Mouse. The haptic rendering is somewhat different for the different haptic interfaces: With the Phantom the line is rendered as a V-formed shape on a flat surface. With the Logitech mouse, which only has two dimensions of force feedback, the graph is instead rendered as a magnetic line (very similar to the virtual fixtures used by Fritz above).

Finally, Minagawa, Ohnishi and Sugie have used an updateable tactile display together with sound to display different kinds of diagram for blind users [21].

All of these studies have shown that it is very feasible to use haptics (sometimes together with sound) to get access to mathematic information. For this study we chose to stick to the groove rendering method, which have been found very effective, but we changed our old implementation to a polygon mesh implementation that is more fitted for today's haptic application programming interfaces. Moreover, we wanted to take the mathematics application closer to a real learning situation. Therefore we chose to put the functional graph into a context, namely an ecological system of an isolated island with herbivores and carnivores. This is of course only an example of what this technology could be used for but still an important step forward towards usage in a real learning situation.

Textures

Most of the research that has been performed on haptic textures so far concentrates on the perception of roughness. Basic research on haptic perception of textures both for blind and sighted persons, has been carried out by, e.g., Lederman et. al. [18], Jansson et. al. [13], Colwell, Petrie and Kornbrot [3] and Wall and Harwin [43]. McGee et.al. investigated multimodal perception of virtual roughness [20]. A great deal of effort has been put into research on applied textures for blind and visually disabled persons, see [19] and [6].

Different technical aspects of haptic texture simulation have been investigated by Minsky [22], Siira and Pai [33], Greene and Salisbury [9], Fritz and Barner [8] among others.

Compared to much of the above mentioned research, we are not interested in isolating the haptic aspects of textures but rather to include textures in multimodal virtual environments for blind and visually disabled persons. That means that we are interested not only in the roughness of the texture but also in other aspects of the texture. Therefore, we base the textures in this test on real textures and we do not mask out the sound information that is produced by the haptic interface when exploring the virtual textures. Most of the authors above use a stochastic model for simulation of the textures. Although this model is very effective in simulating sandpaper it is not possible to use it for most real life textures. As we will describe later, we have thus chosen another method.

Tactile and haptic imaging

In the two-part article "Automatic visual to tactile translation" [44][45] Way and Barner describe the development of a visual-to-tactile translator called the TACTile Image Creation System (TACTICS). This system uses digital image processing technology to automatically simplify photographical images to make it possible to render them efficiently on swell paper. A newer image segmentation method that could be used within TACTICS has also been proposed by Hernandez and Barner [11]. The Tactics system addresses many of the problems with manual tactile imaging but since it generates a static image relief it cannot be used for GUI access etc. Our program works very well with black and white line drawings, which is basically the output of the TACTICS system. That makes us believe that technology similar to this can be used in conjunction with the technology presented in this paper to make a very efficient haptic imaging system.

Eriksson et.al. have presented several reports and practical work on how tactile images should be designed to be understandable by blind readers [5][40]. Eriksson reports on the design of the tactile images itself as well as how they can be described in words or by guiding the blind user.

Pai and Reissel have designed a system for haptic interaction with 2-dimensional image curves [24]. This system uses wavelet transforms to display the image curves at different resolutions using a Pantograph haptic interface. Wavelets have also been used for image simplification by Siddique and Barner with tactile imaging in mind [31]. Although the Pantograph is a haptic interface (like the Phantom) it has only 2 degrees of freedom. We believe that the 3 degrees of freedom makes the Phantom much more fitted for image access (since lines can be rendered as grooves as described above) and it might also lower the need for image simplification.

Roth, Richoz, Petrucci and Puhn have made some significant work on an audio haptic tool for non-visual image representation. The tool is based on combined image segmentation and object sonification [30]. The system has a description tool and an exploration tool. The description tool is used by a moderator to adapt the image for non-visual representation and the exploration tool is used by the blind person to explore it. The blind user interacts with the system either via a graphics tablet or via a force feedback mouse. Although we believe that audio can be a very good complement to haptics we have chosen to concentrate on haptics for the present study. We also wanted to have a system that could ultimately be handled by a blind person alone and that excludes a descriptor/explorer scheme.

Kurze has developed a guiding and exploration system [16] with a device that uses vibrating elements to output directional information to a blind user. The stimulators in the device are arranged roughly like a circle and the idea is to give the user directional hints that he can choose to follow or not. Kurze has also developed a rendering method to create 2D images out of 3D models [17]. The idea of an interface that can point to objects that are close to the user is quite interesting and can certainly help when exploring an unknown environment (a similar idea is our "virtual search tools" [37]).

Shinohara, Shimizu and Mochizuki have developed a tactile display that can present tangible relief graphics for visually impaired persons [31]. The tactile surface consists of a 64x64 arrangement of pins with 3 mm interspacing. The pins are aligned in a hexagonal, rather than a square formation to minimize the distance between the pins. Although we believe that a tactile display can provide a slightly more natural interaction than haptic displays, we still think that the resolution if the tactile displays are far to low.

The probably closest relation to this work is an "image to haptic data converter" that was recently presented by Yu et.al. [48]. This program converts scanned line drawings into a format that is interpretable by a haptic device. The system provides a method for blind or visually impaired people to access printed graphs. Currently, the graphs can be rendered on either the Phantom or Logitech's Wingman force feedback mouse. This method has a simpler production process than the conventional raised paper method and the motivation and idea is pretty much the same as the one we have in our program for image access. However Yu is using a technique that includes automatic image tracing which is not used in our program. Both methods have their strong and weak points, and we cannot say that one method is always better than the other. In the long run it could be good to let the user choose rendering and/or simplification method depending on the kind of picture he or she wants to feel.

To conclude this section we believe that much of the work done on tactile imaging can be valid also in the world of haptic interaction together with programs similar to our imaging program. We have chosen to use a 3D haptic device because of its high resolution and its ability to easily render updateable graphics. The rendering method that we have chosen is straightforward and can be put to work in a system that can be handled by a blind person alone.

Aims of the present study

The purpose of this part of the study was to see if and how a haptic interface can be used to give blind persons access to line drawings and similar computer based graphics. We investigate four specific areas in this study.

1. How can haptically represented mathematical graphs add to blind persons' understanding of the underlying phenomenon?

It is known that mathematical line graphs can give sighted persons an understanding of certain scientific phenomena. It has also been shown that blind people are able to comprehend haptically represented line graphs [50]. Therefore we decided to design and test a haptic graphing program that display a mathematic phenomenon in a natural science context.

2. How can real life textures be simulated in haptic virtual environments for blind persons?

It is well known that textures normally are perceived mainly in a tactile manner but that textures can also be perceived via a probe and/or simulated with a haptic interface. Surface properties can provide important information about objects and it is reasonable to believe that simulations of real textures can be an important part of virtual environments for blind people. If simulated real textures can be matched to real textures, it is reasonable to assume that they can also be useful in virtual environments for blind people. Thus our test programs for virtual textures are based on samples of different real textures.

3. How can drawings be rendered haptically and understood by blind persons?

Tactile pictures have been used for a long time as an alternative to graphics for blind persons. Again it is known that blind people are able to comprehend haptically represented line graphs and that makes us want to test how haptically represented pictures can be understood by blind persons.

4. How can maps and floor plans be represented haptically and used by blind persons?

We know that tactile maps can be understood by blind persons and that better access to maps is asked for by many blind persons. The questions here is how haptic maps should be designed for access by a blind person and if the maps can be understood. We also want to know if the knowledge gained via the haptic map can be used for real life orientation.

Material and methods

Subjects

25 blind test users, 14 from Italy and 11 from Sweden, carried out the test. Nine of them were female. 13 were blind from birth. Their age varied from 12 to 85 years with a mean of 39 and standard deviation of 19. They had varying professional backgrounds, but there were more students and telephone operators than in an average population. For time reasons, not all test users participated in all of the tests. All of the test users had limited or no experience in using the Phantom. All the users were blind. For a detailed presentation of the individual subjects, see table 1.

Test persons, Italy

Year of birth	*Sex*	*Blind from birth*	*Profession*
1964	F	Yes	Telephone operator
1946	M	Yes	Consultant
1977	M	Yes	Student
1951	F	No	Telephone operator
1974	M	Yes	Student
1928	M	No	Professor
1938	F	Yes	Teacher
1976	F	Yes	Student
1953	F	No	Telephone operator

1954	M	No	Telephone operator
1982	M	Yes	Student
1916	F	No	Librarian

Test persons, Sweden

Year of birth	*Sex*	*Blind from birth*	*Profession*
1949	M	No	Student
1956	M	No	Educational consultant
1949	F	No	Telephone operator
1958	M	Yes	-
1989	F	Yes	Student
1967	M	No	Computer technician
1989	M	Yes	Student
1986	F	No	Student
1979	M	Yes	Student
1979	M	Yes	Student
1973	M	No	Student

Apparatus

The hardware that we used for haptic interaction was the Phantom from SensAble Technologies [41]. The mathematics software was built upon the GHOST SDK from SensAble Technologies and the other programs were built using the Reachin API from Reachin Technologies [28]. We used two Phantoms in parallel for the tests, one was equipped with a thimble and the other was equipped with a pen as manipulator. Twelve of the users used the Phantom with a thimble, 8 with a pen and 5 users switched between the tests so that they used both the thimble and the pen.

Test procedure

The test procedure started with the test leader explaining how the test was going to be carried out and what was going to happen. Then there was a pre-test and initial tests for approximately one hour. The purpose of the pre-test was to make the users familiar with the equipment and the haptic sensation. The next session was the real test that lasted approximately two hours.

The test set-up is described in Figure 1. This set-up makes it possible to record the test user's face and hand movements as well as the computer monitor and comments from users and test leaders with a standard video camera. The test leader recorded the results in a protocol during the tests. The users were asked to rate the challenge of the different tasks. The users responded to a questionnaire on the test experience afterwards.

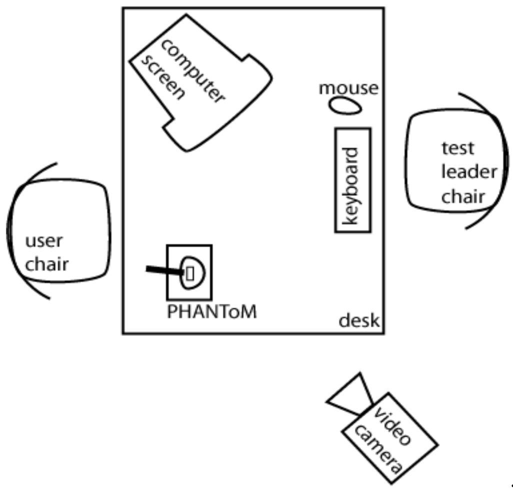


Figure 1, The test set-up used.

Aside from this set-up we used physical models in the texture test. In the mathematics tests, the keyboard was handed over to the test user in order to be able to request the display of coordinates (with a simulated text-to-speech system).

Haptically represented mathematical graphs

This virtual environment was a dynamic one with a curve displaying information from a simulation of an ecological system with imaginary carnivores ("mega-crocodiles") and herbivores ("super pigs") on an isolated island. A slider in the environment could be moved to adjust the fertility of the herbivores, or in mathematical terms change a parameter of the differential equation that represents the number of animals on the island. In order to recalculate the curve, a button had to be pressed after the slider had been moved to a new position.

The tasks in these tests varied from simply feeling the curve and describing it to finding the smallest value of herbivore fertility that produced a system where the animal strains do not die out.

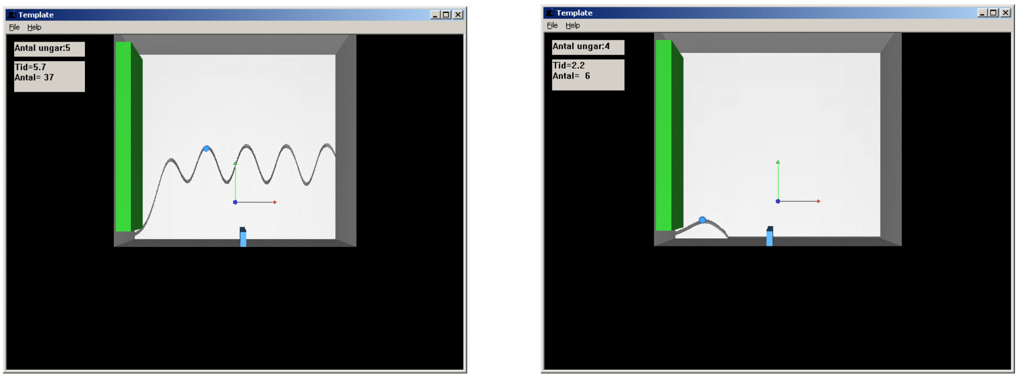
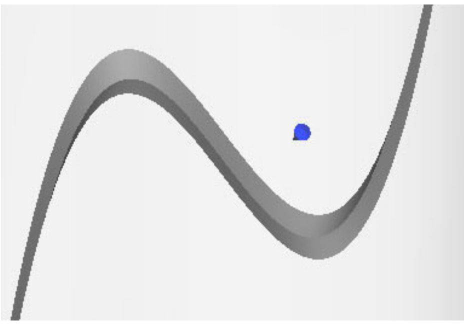


Figure 2. The mathematical environment with herbivore fertility set to 5 respectively 4 births per time unit.

The graph in the system is rendered as a groove in the back wall of the virtual environment (see figure 2). The user was instructed to sweep the back plane until he or she fell into the groove, then the user could choose to trace the curve or to move to another place on the curve without following it. The left wall and the floor also represent the coordinate axes (only positive time values and positive number of animals). The user can place the cursor at any place on the curve and press the space bar on the keyboard to get exact information about a value. The X and Y values are then displayed in text that can be accessed e.g. via synthetic speech or Braille. The synthetic speech in this test was simulated by letting a human read the values on the screen as they changed.

The groove is constructed by putting polygons together to form a wall with an engraved path. We used the system with a groove in the back wall in our initial mathematics program [34][35], but at that time it was easier to calculate the forces directly than to go via a polygon representation. With today's object oriented haptic APIs it is easier to construct the groove as a polygon mesh like we have done in this test. The program calculates a new polygon mesh when the program is started and each time the input parameter has been changed. When this happens the function is evaluated along the X-axis and the calculated Y-values determine the position of the vertices of the polygon mesh. Each sample requires 8 triangles in the polygon mesh as seen in the figure 3b.



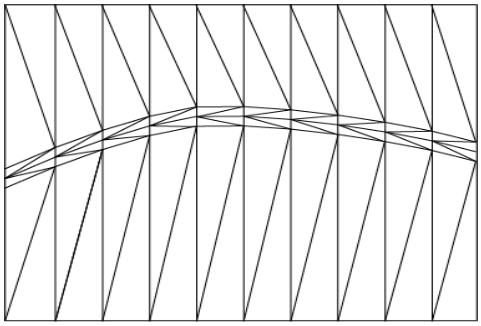


Figure 3a. Close up of a groove in the mathematics environment

Figure 3b. Schematic picture of the polygon mesh used to render the groove

Haptic simulation of real textures

The virtual environment in these tests consisted of a room with simulated textures on squares on the back wall of the virtual environment. In the first test, one square with corduroy fabric was used. The user was also given a thin piece of wood mounted with the real corduroy texture. The task was to explore the virtual texture and then orient the real texture sample in the same way as the one in the virtual environment.

In the second test, the virtual environment consisted of four different textures. The user was given five different real textures, mounted on wood, and the task was to choose four of them that corresponded to the textures in the virtual world and then to spatially arrange them in the same way as in the virtual world. The simulated textures included grinded wood, fine sandpaper, coarse sandpaper and the same corduroy as in the first test. The fifth real sample was a semi-coarse linen type cloth. It was available only as a real texture sample to choose from and not simulated in the virtual environment.

The texture simulations where made by optically scanning the real textures, processing the image and render it as a haptic height map. We used the “BumpmapSurface” from the Reachin API to render the image haptically. The BumpmapSurface take an image in PNG-format as an input to render a height mapped surface on any object in the virtual environment. The sensation of the texture can be altered by manipulating the image that is used as an input and by changing parameters for friction, stiffness, damping and map height. The production steps required for the texture simulations are similar to the steps used to produce the line drawing relief. However, in this case we had to use different image processing steps for the different textures demonstrates which means that it is not really easy to use this method for automatic haptic texture creation. The map height, stiffness and damping of the simulated surfaces were different for the different textures in order to make the simulations feel more like the originals. The simulations very to a large degree hand-tuned to give the right sensation. After the initial steps of scanning and blurring we had to try the sensation and then tweak the different parameters until we felt that the simulation was good enough.

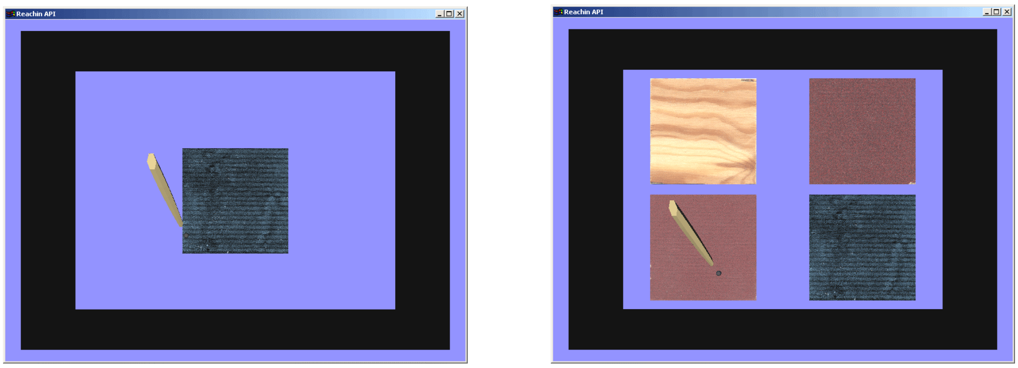


Figure 4. The virtual environments for the texture tests. The first picture shows the environment with only one corduroy sample. The second picture shows the environment with a wooden plate, two kinds of sandpaper and corduroy fabric. (The pen on the pictures shows the position of the user interaction point.)

Line drawings

In this experiment the Virtual Environment consisted of a room with a relief line drawing of a stick man or an elephant. The relief for the stick man was positive (lines as ridges), while the relief for the elephant was negative (lines as valleys). The picture was placed on a square representing a piece of paper that was a few mm thick and placed in front of the back wall. The first task was to explore the line drawing, describe it to the test leader and also guess what it represented. The users that did not manage the first task were told what was depicted. The second task was to identify a part of the drawing, such as a foot.

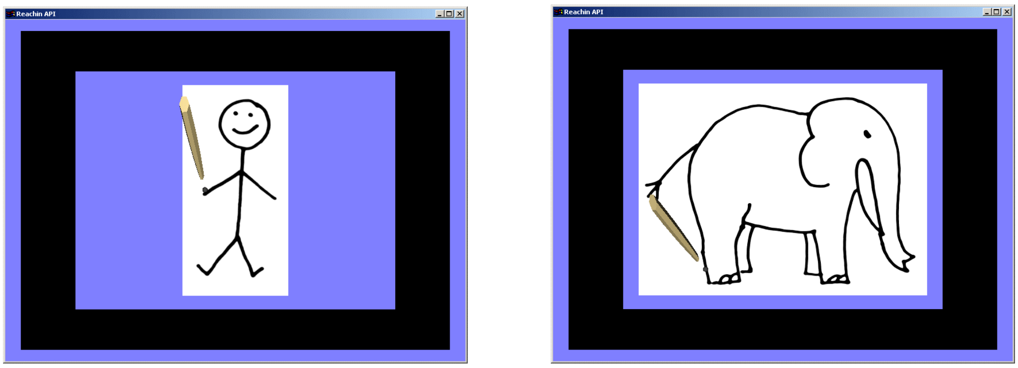


Figure 5. The two line drawing environments used in the test.

The haptic relief was rendered from scanned black and white images. The process of transforming the images to haptic reliefs was performed manually for these tests, but since the steps are rather straightforward in this case it is possible to carry them out automatically for any line drawing.

The process steps are:

1. Scan the image to a grayscale file
2. Apply gaussian blur
3. Render the image haptically as a height map where dark areas correspond to high or low areas depending on if lines are represented as lines or valleys.

Again, we used the "BumpmapSurface" from Reachin API to render the image haptically and for this test we used a map height of 4 mm. The blurring of the image is necessary to make the relief less sharp. Even though it is possible to render the image without blurring it is not recommended since this makes the interaction with the relief very uncomfortable.

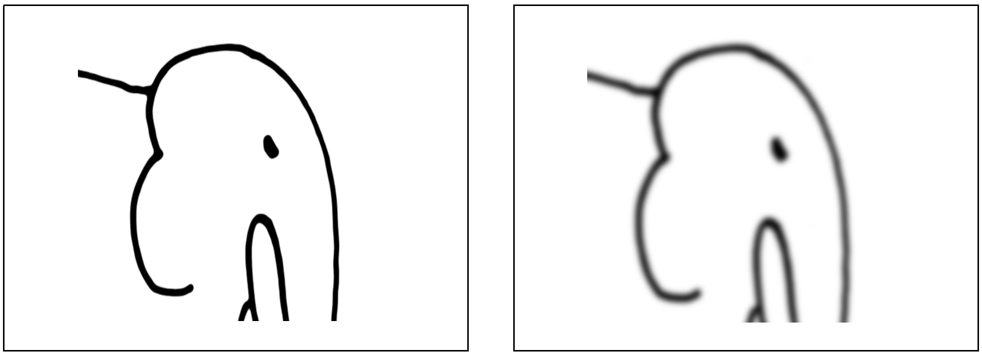


Figure 6. Part of one original image and the corresponding blurred version used for the haptic interaction.

Haptic maps and floor plans

The virtual environment in this test consisted of a positive relief map. Walls were accordingly shown as ridges. To avoid moving through the doors without noticing it, the door openings had a threshold that was simulated as a very low ridge. The walls and thresholds were designed to make it possible to move around the rooms to feel the size and form of the room without accidentally falling through the door. At the same time it was important to make it easy to distinguish walls from door openings even when tracing the wall and to make it easy to move between two rooms when that was desired. To make all this possible, the thresholds were made thinner than the walls and only a few millimetres high. The walls were 25 mm high, which is more than what is normal in tactile reliefs but we believe that it works very well in haptic reliefs. To move between the rooms, the user could either stay close to the floor and move in and out through the doors, or "jump" over the walls and move directly from room to room. Both strategies were used by the test users.

The rooms and areas in the floor plans had sound labels on them to explain the function (e.g. kitchen) of each room. The label sound was invoked by pressing the floor in the room and the sound stopped immediately when the user lifted his or her finger. The sound was repeated with about a second of delay as long as the floor was pressed down.

The test included two floor plans: one of a 6-room imaginary apartment and one of a real 18-room corridor (plus additional spaces) at our department in Sweden (see Figure 7). In the apartment test the user was asked to explore the apartment to get an overview of it. The task was to count the rooms and locate a specified room in the virtual environment without using the sound labels. In the corridor test the user was asked to locate a treasure on the map represented as the room with a different texture on the floor. They were then asked to physically locate the room with the treasure in the real corridor. The second part of the floor plan test was only carried out in Sweden since we did not have the time to make a map of the test site in Italy.

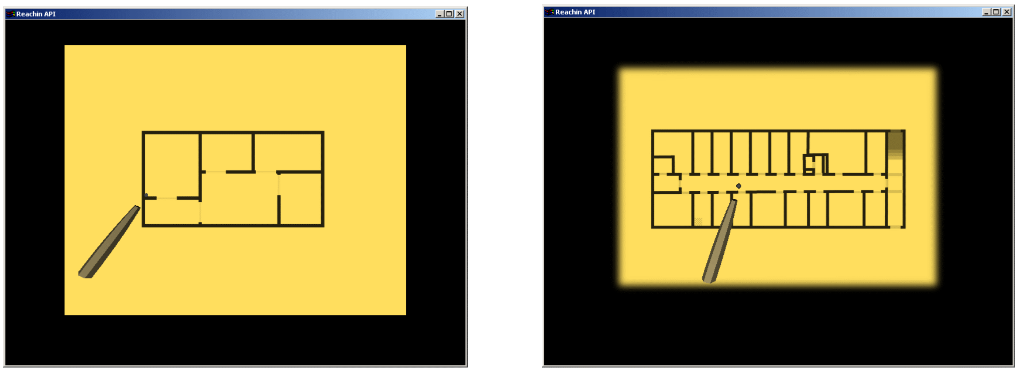


Figure 7. The two different floor plan environments used in the test.

Results

We did not find any significant correlations between the performance in general and the user characteristics: age, sex, blindness from birth, job and type of manipulandum. On the individual tasks there were some weak correlations. The identification of line drawings was correlated with age, 0.41 for the stick man and 0.31 for the elephant. The users' desire for a program for feeling line graphs was correlated with age, -0.57, and with blindness from birth, 0.50.

There are reasons to believe that training could improve the results, as it did in a study on identification of objects [14] and a study on production and interpretation of perspective drawings [10].

Haptically represented mathematical graphs

All the 24 users who tried this program could feel the curve and all but one of them (96%) could find specific parts of the curve. The challenge of these tasks was rated as 1.3 (on a scale from 1 to 5, 5 being the most challenging). Eighteen users tried to solve the ecological problem and 14 (78%) of them managed to do so. Seven of these 18 users (39%) needed some help with handling the slider and button in the program. The overall challenge of this test was rated as 2.2 on the average.

Haptic simulation of real textures

Twenty-four of 25 users (96%) could orient the texture correctly. The average time to complete the task was 28 seconds. Seventeen of 25 users (68%) managed to choose the 4 correct textures and put them in the right position. Only 5 of 25 users (20%) identified less then 3 of 4 textures correctly. The position of the textures did not cause any errors. The average time to complete the task was 140 seconds. The overall challenge of the texture test was judged as 2.6 on the average.

Line drawings

Fifteen of 24 users (62%) could identify the stick man. Three of the users who failed thought it was a flower or a tree. Twenty-one users (88%) could identify parts of the object such as arms, legs or head once they knew it was a stick man. The average challenge of this test was judged as 2.7.

Eight of 24 users (33%) could identify the elephant. Twenty users (83%) could identify parts of the animal (such as the trunk and the tail) once they knew it was an elephant. The challenge of this test was judged as 4.0 on the average.

Nine of 14 users (64%) preferred ridges, while 3 users (21%) preferred grooves. The rest said that it did not matter or that it depended on the type of picture.

Haptic maps and floor plans

Nineteen of 23 users (83%) could count the right number of rooms in the apartment (6 rooms). No one answered more than one room too many or too few. Nineteen of 23 could find the specified room (only one user failed both tasks). The challenge for these tasks on the average was judged as 1.4.

Six of 7 (86%) users could find the treasure on the corridor map within the test time. Of these 6, 5 could then find the treasure in real life. The user who failed mistook a bricked up door for a real one and thus ended up in the wrong place. The challenge was on the average judged as 2.2.

Discussion and conclusions

According to the different topics of our study, the following discussion of our results and their implications for future research will focus on the five areas: (1) the use of haptically represented mathematical graphs; (2) haptical simulations of texture; (3) haptical realizations of drawings; (4) haptical representations of maps and floor plans; (5) transfer of haptically gained knowledge to real life situations.

1. How can haptically represented mathematical graphs add to blind persons' understanding of the underlying phenomenon?

Haptically represented applied mathematics apparently function quite well. 78% of the users did manage to solve the problem, and to do so they had to understand the underlying phenomena. We purposely chose a complex scientific phenomenon to see if our representations could really stand a difficult test. This strengthens us in the belief that haptically represented mathematics is feasible, and we also conclude that haptically represented mathematical graphs can provide blind persons with an understanding of the underlying scientific phenomena.

The sliders and buttons in the current program are rather rudimentary. The users offered many comments on improvements, such as sound feedback on the buttons and sliders. An improvement here will most likely improve the results as well.

Many researchers have done work on mathematics and line graphs, (see the section entitled "Related work"). It is relevant to explain why we are doing this, since some researchers have found little interest in mathematics among teachers of blind persons [25]. We gathered user requirements from 36 persons who were blind or visually impaired to guide our research. They rated the ability to feel mathematical curves as 2.3 on a scale of 1 to 5 with 5 as the highest. In comparison, all of the other 5 possibilities were given a rating of 3.6 or higher. One argument for us doing this, despite the low rating, was that it is difficult for the user to know before trying if he or she actually wants this facility. Another argument from a democratic point of view is that it is not justifiable to exclude blind persons from parts of society.

After having tried the program, 14 of 20 users (71%) said that they wanted to have a program like this. They said they wanted to use this kind of program for understanding sociological phenomenon, checking their bank accounts, checking the stock market feeling sound waves etc. Today, 50% of the users have the opportunity to feel curves, typically through the use of some kind of swell paper or plastic relief.

2. How can real life textures be simulated in haptic virtual environments for blind persons?

Based on previous research, there is no doubt that it is possible to simulate textures with haptics, see for example [18][19][20][13][9][33][22][43] (and certainly many more). In this study, we wanted to examine the usefulness of textures in virtual environments for blind people. Consequently, we were interested in representing different types of real textures haptically to be able to use these on objects and in pictures in haptic, virtual environments. As far as we can determine, real textures (apart from sandpaper) were not used as the basis of the simulation in the above-mentioned studies. It is reasonable to assume that textures of haptically represented objects make them feel somewhat more real, which can be used to distinguish different types of objects from one another. It is also quite plausible that there are restrictions as to which textures can be used, since haptic simulation on its own cannot communicate all aspects of a texture.

The results of the texture test show that blind persons can understand haptically simulated textures and that they can relate them to different kinds of real textures. But the test also illustrates that there are certain significant limitations to take into consideration. It is evidently difficult to feel the difference between certain simulated textures. Fine sandpaper and rougher fabric are quite similar when they are simulated. The “sharpness” of sandpaper is pronouncedly tactile and therefore difficult to recreate haptically. This problem is clearly confirmed by the results: the single biggest mistake made was that the test users were not sure of the difference between fabric and fine sandpaper.

We noticed that some users tried to scrape the real textures with their fingernails in order to compare the textures with the corresponding haptic representations. This is an interesting strategy since it limits the interaction with the real textures so that the information gained is about the same as what one can simulate with a haptic interface.

A few users had difficulties in subtest 2 because they only felt the simulated textures in one direction. This is not a problem with many textures but with a ribbed one, such as corduroy, it is a serious difficulty because this texture feels entirely different from another direction. This means that one can confuse corduroy with both finer and coarser textures depending on the direction in which one feels them. This type of mistake is probably more common among beginners than accustomed users who have learned to actively scan objects in different directions.

So, we can draw the conclusion that haptically represented textures can be very useful in virtual environments for blind people, but that there are certain limitations to be aware of.

3. How can drawings be rendered haptically and understood by blind persons?

Our results show that it is rather difficult to identify a haptic image without any contextual information. However, it seems that having a general idea of what is represented makes image understanding much easier.

Alan Holst [12] describes two alternative philosophies about access to Windows-systems. According to the first, you do not have to know what the screen looks like to be able to work in

Windows. In this view, the user has to memorize a large set of options to achieve a given effect. Using speech alone as the access method often works this way, and Holst finds that this does not give enough feedback for him to be an effective improviser. It only works as long as nothing unusual happens.

The other way of looking at Windows access is the view that you need a good cognitive or mental map of the screen to be an effective Windows user. Haptic interfaces enable the user to build a cognitive map [36] and they make the screen more concrete. Holst finds that a haptic interface enables him to improvise and be more creative.

If you have a mental map, our results show that it is possible to understand drawings. There are also possible ways of giving contextual information, e.g. using the ALT-text to enhance even more the probability for a correct understanding of the drawing.

Some of the users commented that we should have used ridges for the elephant and grooves for the stick man. This is probably true because the elephant consisted of an area surrounded by lines, whereas the stick man did not have included areas, except for the head, which was not a big area. Ridges encourage you to explore the included area but the grooves encourage you to follow the lines. This most likely influenced our results in a negative manner.

The indication that contextual information is very important is also interesting compared to Kamel and Landay's report on a Study of Blind Drawing Practice [15]. They found that existing drawing tools for blind users give inadequate contextual feedback on the state of the drawing and consequently they advocate systems that provide more and better feedback. It appears as though there are a lot to be done in this area.

We conclude that haptically represented drawings can be understood by blind persons, at least if they have some contextual information.

4. How can maps and floor plans be represented haptically and be used by blind persons?

It was quite evident that the maps worked well for a majority of the test users. That more that 80% of them managed to count the rooms and find their way back to a specific room without the help of sound indicates that the haptic maps can provide them with a mental image, in this case of the apartment represented. Over 80% of the test users also managed to find the treasure on the considerably larger map, which means that it is also possible, to gain an overview of even more complicated haptic drawings. We maintain that haptically represented drawings can be understood by people who are blind.

We observed that both the method of going through the doors and of "jumping over the walls" was used to move between the different rooms. Some people alternated between the two.

We have not specifically tested maps with sound labels compared to those without, but it is reasonable to imagine that sound in some form would help the user because it provides additional information to support visual recollection. In all events, sound is an effective channel of information for what is displayed on visual maps as text. An alternative to sound in this case could be to print the text on a Braille display. The advantage with this is that it is not as intrusive and is less irritating for those in the surroundings. In principle, it makes no difference for this application in the format it was tested.

One of the important functions of a map or drawing is to give an overview. For tactile and haptic maps, this means a process that demands a bit more work than what is needed by a seeing person to do the same with a visual map. Because the sense of touch only works at one or a few points at a time, it requires that the user actively scans the surface in order to establish a mental model and to use it to get an overview. This can, however, be supported and facilitated by adding environmental sounds in addition to the sound labels used in this test. Environmental sounds provide information in a more indirect manner than sound labels and can be designed in a number of different ways.

Another important aspect of the haptic map system is to supply maps in different scales and with different amounts of detail, as is the case with maps for sighted people. It is still an open question as to how one can best implement larger maps and drawings in which zooming and scrolling are required when the entire map does not fit in the hardware's work area. To technically achieve this does not require a significant expansion of our system; the problem lies in making the interaction so that the user can maintain orientation and overview in the system even while zooming and scrolling.

If you compare haptic and tactile maps, you first observe that both technologies can coexist and to a large extent that solves a variety of problems. There are many similarities but also a number of significant differences.

Haptic maps can be minimized more than tactile ones because printed text does not require any space on the map (since the text can be rendered on a Braille display or via synthetic speech). It is also likely that the actual image can be made smaller than the corresponding tactile image and still be easy to understand, but we have not tested this.

Tactile maps make almost exclusive use of positive relief because it is much easier to feel in the size that is normally used. A negative relief has to be closer in size to that of a finger in order to be clearly perceptible and then a combination of tactile and haptic sensations are used. With virtual haptics, on the other hand, there is no problem in feeling negative reliefs and they can in principle be quite small. The fundamental difference is due to how the user is modeled in the virtual world. The most common is that the user is modeled as a point or a little sphere (millimeter size) and then it is not the size of the finger but the size of the interaction point that determines how narrow negative reliefs one can feel.

Many advise against making tactile reliefs high, the reason being that they can be difficult to interpret since they do not constitute a distinct shape separating them from the background [5]. Haptically, though, it does not appear to be problematic to use reliefs in centimeter dimensions. The interaction shape makes it possible for high as well as low reliefs to be clearly felt against the background, so the choice can be based on other considerations, such as what is required to gain a sufficient amount of information.

Using tactile touch you can feel several points of a relief at the same time as is done in reading Braille, but this is not possible when using haptic touch. With a haptic interface, you cannot feel the entire pattern at the same time so it is very difficult to interpret this type of information. On the other hand, it would be possible to build in a Braille cell in the handle of a haptic interface and in that way combine the tactile and the haptic interfaces. (This could also be used to place Braille labels on virtual haptic models.)

Finally, it is important to see the possibilities that arise when using computer-based information. It is, for example, easier to combine the sense of touch with other modalities in a haptic computer interface than with tactile pictures. (Even if there are solutions for tactile images with computer-based sound, e.g. the NOMAD [23].) It is also possible to create public databases, to e-mail files to friends and colleagues, as well as to use, at least to a certain extent, the same underlying information for both seeing and blind users.

5. Can the knowledge gained from a haptic map be used in real life?

Even if the test that put the information from the virtual drawings to use in a real environment was only performed by 6 people, we see a strong indication that the information is actually transferable to a real situation. The only test subject who failed to find the room with the treasure in the real apartment, in spite of the fact that she had found it on the map, had interpreted that map correctly but misinterpreted the real environment thus ended up in the wrong room.

We also received many positive comments about the maps and how useful they would be in different situations.

We can see several important uses of this technology in the future, for example: haptic web browsers, interactive multimodal simulations of applied mathematical problems, automatic visual-to-haptic image conversion, haptic representations of public map databases and graphical user interface access for people who are blind. We would also like to encourage future research around these areas in combination with for example color to texture mapping, zooming and moving in maps, combinations of 2D and 3D models, virtual agents as guides in the map environments, real guides via network haptics and integration with virtual search tools.

To conclude, the good results of this study seem to corroborate our firm belief that further research in this area can produce a good number of methods to alleviate blind persons' graphical information deficit.

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Appendix 5

Navigation and Recognition in Complex 3D Haptic Virtual Environments

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Navigation and Recognition in 3D Haptic Virtual Environments for Blind Users

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Abstract

The following paper reports results from a study of 25 blind users from Italy and Sweden carried out during the summer of 2001. The tasks reported test recognition of geometrical objects, recognition of real life objects, mathematical surfaces, navigation in a traffic environment and a memory game. The paper reports the results from the user tests and technical aspects of the test programs.

The outcomes of the tests show that blind users are able to handle quite complex objects and environments and that realistic virtual environments in some cases appear easier to handle than more abstract test environments. This highlights the importance of context, and thus the usefulness of other input channels besides the purely haptic one. Another important factor observed is haptic scanning strategy. Tentative results for age, gender and blindness from birth are presented, and the importance of accurate haptic models is pointed out.

Introduction

The haptics group at Certec has been working with and studying the use of haptic interfaces since 1995, exploring the possibilities they can offer people with different kinds of disabilities. Haptic applications hold great promise for blind persons. It may be possible to make virtual reality, pictures and graphs accessible for blind persons by use of a haptic device. In order to develop useful applications for this group, however, it is important to gather more information about the ability of blind users to interact with different haptic devices and virtual environments. Thus, during the summer of 2001, we carried out a user test study including 25 blind users with the PHANToM haptic device from SensAble Technologies [19].

In this paper we concentrate on the portions of the study that consider recognition and navigation in 3D virtual environments for people who are blind. Other parts of the study are covered in the paper “Haptic Representations of 2D Graphics for Blind Persons” by the same authors [18].

Five different haptic virtual environments were investigated in this study. In the first test we worked with geometrical objects of very low complexity. The tasks included recognizing objects and matching them to real objects of the same shape. Both single object recognition as well as recognition of a group of several objects were included.

In the second test we used 3D VRML computer models of real objects that were significantly more complex than the geometrical objects in the first test. In this case the users were asked to identify and describe different objects.

The third test used a general mathematics viewer that accepted textual input to state the function to be rendered. If the input was a function with only one input variable, the output was a line rendered as a groove that could be traced with one finger on the back wall of the virtual room. If the function had two input variables, the output was instead a haptic representation of the functional surface defined as $z=f(x,y)$.

The fourth test was a simulated traffic environment. In this program the users worked in a simulated environment with houses, streets, sidewalks and cars.

The fifth and last test described in this paper was a haptic memory game with pairs of sounds on buttons in a virtual room.

All applications should be viewed as demonstration applications. This means that they do not include full capabilities to serve as commercial software, but they illustrate different aspects of haptic technology for people who are blind or visually disabled. All the programs that we used for this study are available as digital appendices to this paper.

Background

Virtual environments for people who are blind

To date, virtual reality technology has almost exclusively been aimed at sighted users. 3D computer games are impossible to play for a person who cannot see and the output of 3D CAD programs are for those who can see the visualizations. A large proportion of the 3D information already available today could be of even greater use with virtual reality that is also accessible for blind persons. And with 3D computer information available for blind persons, the increase of flexibility a computer may introduce becomes accessible for this group as well. Just as for sighted users who use drawing or CAD programs, it will be possible for a blind user to try something and then undo it if the result is not satisfactory. Furthermore, it is possible to make different versions of an environment without changing the original, to share information across digital networks, to explore/interact with potentially dangerous environments, etc.

Haptic devices are intended to make it possible to touch virtual environments and thus potentially hold great promise in this respect. As yet, however, haptic devices suffer from some limitations. A commonly used haptic device, the PHANToM, enables the user to interact with the virtual world only through a single point. There are other devices that allow interaction at several points such as the CyberGrasp or the CyberForce [5], but the cost of these is somewhat prohibitive. And even with these devices we are still fairly far from the kind of interaction that takes place when a user interacts with real world objects using both hands. Despite this, haptic devices have proven to be useful for basic shape and texture recognition for blind users [2][7][8]. The usefulness of haptics when it comes to diagrams and mathematical curves has been the subject of study [3][21][23][24] as well as maps [18][20] and complex schematic environments [10][15][16]. Furthermore, it has been shown that practice may significantly improve the ability of the users to interact with this kind of one point haptic virtual environment [6].

To make effective virtual reality for blind persons, the user must also be able to handle models of real life objects of higher complexity.

Due to the difference between touch in the real world and virtual haptics, it thus becomes important to investigate how users interact with haptic devices and more complex environments in a wide variety of cases.

Purpose

The purpose of this part of the study was to obtain a better understanding of how blind persons can understand and interact with more complex and realistic virtual environments using a one point haptic interaction device such as the PHANToM. With this in mind, the tests were designed to investigate the questions: Can a blind person understand haptic models of real objects? Can a blind user understand a more complex/realistic haptic virtual environment? Can a blind person navigate in this kind of environment? How disturbing is the VRML approximation perceived to be?

Material and methods

Test users

Twenty-five blind test users, 14 from Italy and 11 from Sweden, carried out the test. Their ages varied from 12 to 85 years with a mean of 39 and standard deviation of 19. Nine of the users were female and 13 were blind from birth. They had varying professional backgrounds, but there were more students and telephone operators than in an average population. For time reasons, not all test users participated in all of the tests. All had limited or no experience in using the PHANToM. See Table 1.

Test persons, Italy

Age	*Sex*	*Blind from birth*	*Profession*
85	F	No	Librarian
73	M	No	Professor
63	F	Yes	Teacher
58	M	No	Rehabilitation consultant
55	M	Yes	Consultant
50	F	No	Telephone operator
48	F	No	Telephone operator
47	M	No	Telephone operator
37	F	Yes	Telephone operator
27	M	Yes	Student
27	M	Yes	Telephone operator
25	F	Yes	Student
24	M	Yes	Student
19	M	Yes	Student

Test persons, Sweden

Age	*Sex*	*Blind from birth*	*Profession*
52	M	No	Student
52	F	No	Telephone operator
45	M	No	Educational consultant
43	M	Yes	-
34	M	No	Computer technician
28	M	No	Student
22	M	Yes	Student

22	M	Yes	Student
15	F	No	Student
12	M	Yes	Student
12	F	Yes	Student

Table 1. The test users in Italy and Sweden

Only one of these persons (85 years of age, blind at the age of 64) had severe difficulties with the haptic environment. This person appeared to find both the concept of virtual reality and a haptic environment in general difficult to understand. The person also seemed to use both hands to a greater extent than the other test persons when exploring the real world. It was interesting to note that the haptic illusion seemed to disappear as soon as this person tried to feel the object with the other hand (the hand not occupied by the haptic device). Despite this, the person could complete a few tests, and might have done better with more training [6]. It must be pointed out that this person appeared already to have problems with the concept of a virtual environment – several other users could not resist the temptation to feel for the virtual object, but in these cases the haptic illusion did not break down.

Apparatus

The hardware used for haptic interaction was the PHANToM from SensAble Technologies [19]. The software for the geometrical objects tests, the mathematic surfaces and the memory games were built on the GHOST SDK from SensAble Technologies. The programs for real life objects and the traffic environment were built using the Reachin API from Reachin Technologies [13]. We used two PHANToMs in parallel for the tests; one was equipped with a thimble and the other with a pen as manipulandum. Twelve of the users used the PHANToM with a thimble, 8 with a pen and 5 switched between the tests so that they used both.

Test procedure

The test procedure started with the test leader explaining how the test was going to be carried out and what was going to happen. Prior to conducting real tests, all test persons underwent a pre-test phase, where they were able to get acquainted with the PHANToM device and the concept of virtual haptics. The idea behind the pre-tests was to minimize first-time user problems. The pre-test and initial tests lasted for approximately one hour. After this the users were allowed to take a break. The next session with real tests lasted approximately two hours.

The test set-up is described in Figure 1. This set-up makes it possible to record the test user's face and hand movements as well as the computer monitor and comments from users and test leaders with a standard video camera. The test leader recorded the results and comments in a protocol during the tests. The users were asked to rate the challenge of the different tasks. The users also responded to a questionnaire on the test experience afterwards.

In addition to this set-up we used physical models in the geometrical objects test.

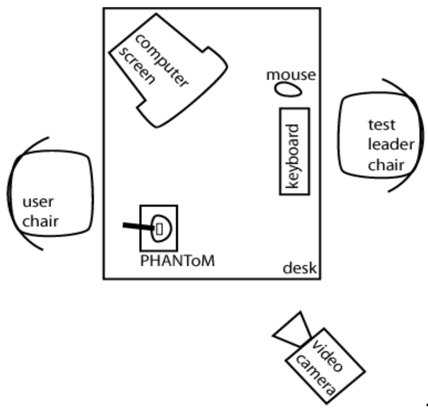

Figure 1. The test set-up.

For most applications, a series of tests was conducted with different levels of difficulty. Ideally, all users were to succeed with the first test in the series, while the later tests were more challenging.

The tests that were carried out were of a mixed nature, but the focus in general has been on making qualitative observations even though quantitative data was also gathered during the tests.

Test descriptions

Geometrical objects test

In this two-part test, the first environment that was tested consisted of a room with a single geometrical object (left part of Fig. 2). On the desk, there were two boxes. In one, there were a number of physical representations of different geometrical objects, similar to children's building blocks. The other box was empty. The user was instructed to explore the virtual model, and then to pick out the object that matched from the physical models (right part of Fig. 2). The real objects had the following shapes: rectangular parallelepiped (4 with different proportions were included), cylinder, roof, half cylinder and sphere. The virtual object was either a double cube, a cylinder or a roof.

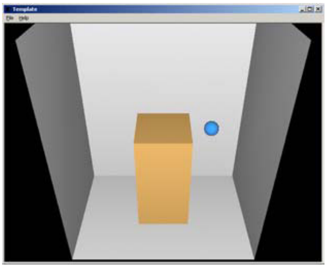

Figure 2. Virtual world and real world objects for single object test. The blue sphere shows the user interaction point.

The second test environment consisted of a room with three geometrical objects of different shapes. The objects were placed in a grid made of small ridges on the floor (left part of Fig. 3). On the desk, there were two boxes. In one, there were a number of physical representations of different geometrical objects. The other box contained a wooden grid but no geometrical objects.

The user was again instructed to explore the virtual environment and make a copy of it with the wooden models (right part of Fig. 3). The user was not told the number of geometrical objects in the virtual world.

Figure 3. The 3x3 grid environment. First, a screen dump of the virtual environment, then the physical models to make the copy with.

The programs for these tests are built with the Ghost SDK from SensAble Technologies. The programming is very straightforward since all the shapes that we used exist as predefined shapes in the software library. Note that the grid in the virtual model is made from long cylinders. The fact that the bars are rounded makes it easier for the user to move from one square to the next while still keeping contact with the floor.

All objects in this and all the other tests were given a surface with some friction on it. (It has been demonstrated that the right amount of friction makes surfaces easier to follow [1].) In these two tests, the objects had identical surface properties; the colors are thus only for the visual image of the environment.

Real life objects

In this part of the study, the user was to feel different objects from real life and discuss their physical properties with the test leader. The first test was a recognition test where the user was asked to identify the object, a vase (see Fig. 4). The surface properties were quite different on the outside and inside of the vase: the inside was slippery as if the surface was glazed; the outside was rough like unglazed pottery.

The answer to the recognition test was also considered correct if the user named a shape that was similar to a vase (e.g. urn or fish bowl).

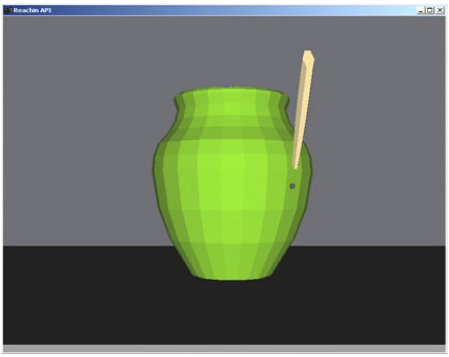

Figure 4. VRML model screen dump: a vase. The pen and the small sphere at its tip show the user interaction point.

In the two following tests the users were told what the models represented (a grand piano with a stool and a satellite, see Fig. 5). The users were instructed to describe the object and to locate different parts of it.

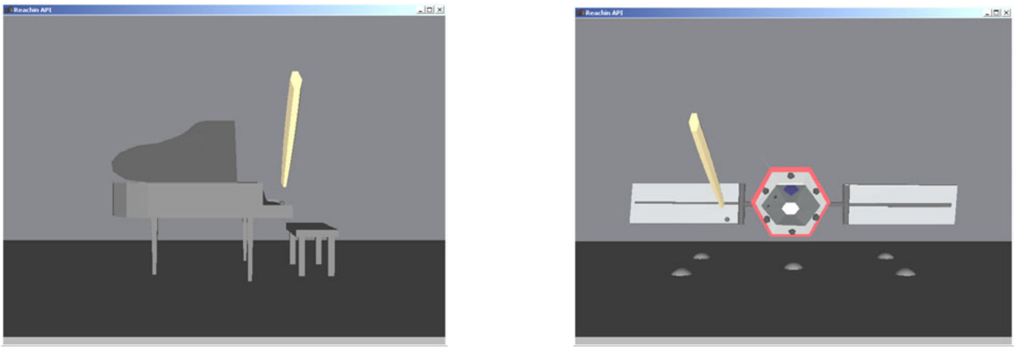

Figure 5. VRML model screen dumps: a grand piano with stool and a satellite.

Additionally, four users were asked to describe and identify models of a guitar and a sword in the form of a recognition test (Fig. 6).

Figure 6. VRML model screen dumps: a guitar and a sword.

All the programs for this test were made with the Reachin API from Reachin Technologies. An easy way to make environments for the Reachin API is to use VRML files. The API includes a loader program that can read VRML files and display them visually as well as haptically. The environments here were based on VRML files that were initially created only for visual use. By adding code that defined the haptic properties of the objects it was thus possible to make these VRML models touchable. All objects except the vase had uniform surface properties, i.e. a general surface including some friction was used.

Note that the models that have objects hanging in free space also have 3-5 bumps on the floor. They were added as reference points to make it easier to find the objects. It turned out that the bumps were hardly used. This will be taken up in the discussion section.

Mathematical surfaces

For this test we used our recently redesigned curve display program (see Fig. 7). This program makes it possible to submit an equation corresponding to a mathematical surface and get a haptic rendering of it. The program can render functions of both one and two variables. If the function has only one input variable, the output is a line rendered as a groove that can be traced with one finger on the back wall of the virtual room. If the function has two input variables the output is instead a haptic representation of the functional surface defined as z=*f*(x,y).

The groove or surface is constructed by putting polygons together to form a wall with an engraved path in the 2D case or a surface in the 3D case. We used the same system in our initial mathematics program [14][16], but at that time it was easier to calculate the forces directly than to go via a polygon representation. With today's object oriented haptic APIs it is easier to construct the groove as a polygon mesh as we have done in this program. The program calculates a new polygon mesh when it is started and each time the input parameters have been changed. When this happens the function is evaluated along the X-axis (and Y-axis if there are two input variables) and the calculated values determine the position of the vertices of the resulting polygon mesh.

The function to render is submitted to the program via a simple text interface. Currently it is possible to use +, -, /, *, sin, cos, sqrt, exp and log, which means that higher-order polynomials, for example, x^2, must be entered in the form x*x. Complex expressions can be formed using parentheses, e.g. x*(2+exp(x*y)).

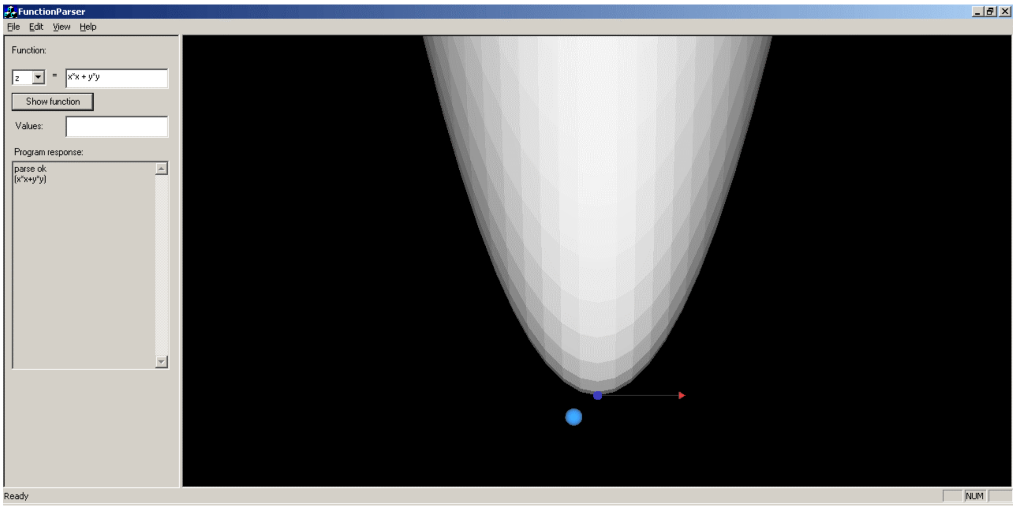

*Figure 7. Screen dump of curve display program: z=x*x+y*y surface.*

For this program we used the Ghost SDK from SensAble Technologies. We modified the standard polymesh class slightly to make it possible to push through the surface. This allows the users to feel the surface from both directions, which can be quite good for some surfaces. (The surface on the picture above can thus be felt as a tip from the "outside" or something like a bowl from the "inside".)

Traffic environment

The virtual environment for this test consisted of 6 houses (2 rows, 3 columns) with roads in between. The roads, sidewalks and houses had different surface properties (roads and sidewalks were rough while houses were smoother). The first task was to explore and describe the environment. Then, the user was asked to find a way from the leftmost house in the front (house A) to the rightmost house in the back (house B) (see Fig. 8). The user was asked to find the shortest route between the two houses while staying as much as possible on the sidewalk (flying was not allowed). The houses A and B each emitted a sound (non-speech) when pressed to confirm for the user that it was the right house.

In the second part of the test, 3 dynamic objects (cars) were added to the environment. The cars moved back and forth on the roads. The cars emitted sound if they hit the user (a thud followed by screeching tires). This sound effect turned out to be effective, and appeared to greatly enhance the illusion.

The task was again to travel from house A to house B, but this time there was a risk of being hit by a car. Depending on the user's interest, sometimes more than one attempt was made to reach the destination, and sometimes the test leader would act as a traffic light and tell the user when it was safe to cross in the re-attempts.

Four users also tested a simple "move the world" function in this environment. These four could move the contents of the world using the up (move back), down (move forward), left and right keys on the keyboard.

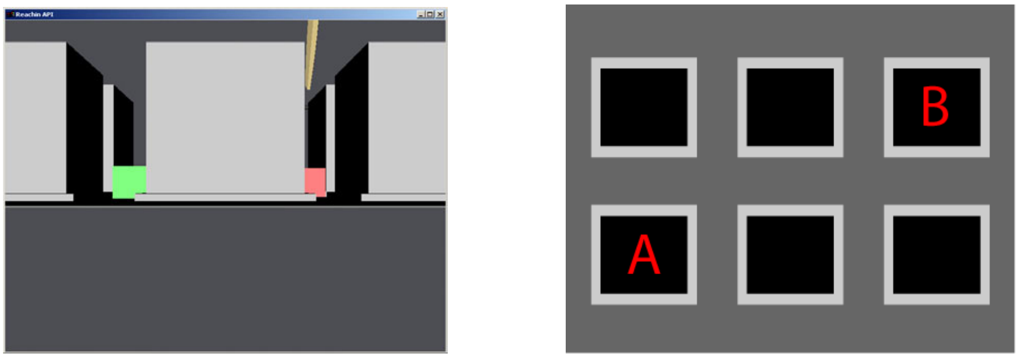

Figure 8. On the left: screen dump of the traffic environment. The cars are the small colored cubes between the houses. The three cars move back and forth on the roads.

On the right: bird's eye view of the same environment

Sound Memory game

For this test, the environment was a game program. The room in the game contained six or twelve cubic buttons attached to the back wall. Every button produced a sound when pressed. Since this game is modeled after the "Memory" card game, every sound appeared twice and the buttons with the same sound needed to be pressed in succession – directly after one another. This made a pair. It did not matter how long it took between pressing the buttons with the same sound, as long as no other button was pressed in between. When a pair was found the buttons disappeared (see Fig. 9). The sounds that were used were 1-2 second samples of different animals: a dog, a horse, a sheep, a cow, a cat and a bird.

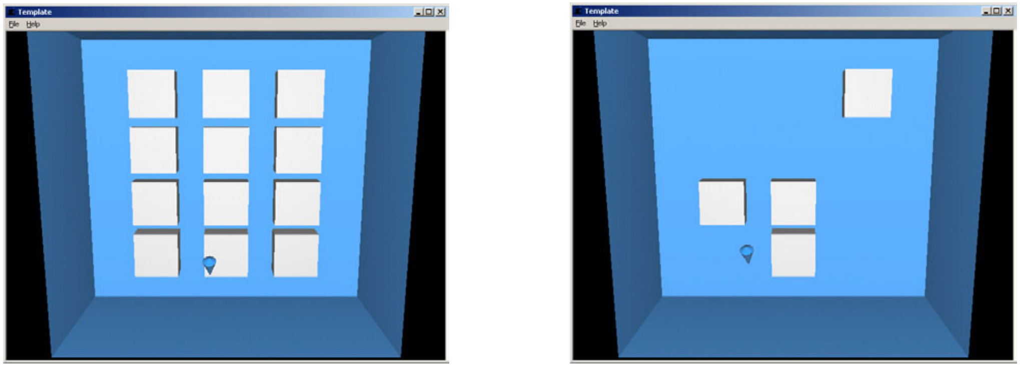

Figure 9. The initial sound memory environment (left) and how the environment looked after some pairs have been found (right).

The Ghost SDK was used for this program together with Microsoft's DirectX SDK to play the sounds.

Results

Geometrical objects

Twenty users out of 25 (80%) managed to identify the single geometrical object correctly. All the test users who did not manage to pick the correct real object were given the double cube object (square base area but double height) in the virtual environment. They all identified the general shape correctly, but made errors when judging the proportions of the object. The errors are as follows:

- Two persons picked out the short block, which was as long as the double cube but with a rectangular base area.
- Two persons picked the long block, which was longer than the double cube and with the same rectangular base area as the short block.
- One person picked the cube.

All the test users who were given the cylinder or the roof identified it correctly. The time to complete the task was 57 seconds on the average and the challenge of this task was on the average judged to be 1.7 on a scale from 1 to 5 (5 being the most challenging).

The grid test was significantly more difficult: although 20 users out of 23 (87%) picked the right number of objects, and 18 out of 23 (78%) placed them in the right squares only 9 out of 23 (39%) managed to present the correct solution. On the average the test took 5 minutes and 34 seconds to complete (the fastest time was 1 minute 39 seconds, and the test was stopped after 10 minutes – this maximum time is recorded in two cases). Of the 5 users that made a mistake on the single geometrical object, only one succeeded on the grid task. If we look at the 14 errors they come out as follows:

- 5 had the right number of objects in the right places but did not pick the right 3rd shape, although the objects selected were judged correctly in 2 of the 3 dimensions.
- 3 users misjudged the proportions of one object but otherwise solved the task correctly.
- 2 users had all the right objects but had placed one of the objects in the wrong square.
- 1 user failed due to stress – after the test results were recorded he was told that he had made a mistake and then he immediately completed the test successfully.
- 3 users finally made errors both by getting the shapes wrong and positioning them incorrectly (or leaving objects out).

The challenge of this task was judged to be 3.3 on the average.

Looking at different groups of test persons we see that 8 of the 14 errors (57%) were made by persons younger than 30 years. Eleven users under 30 took this test, and 72% of those failed (42% of the older users failed). Nine of the 14 errors (64%) were made by persons who were blind from birth. Thirteen users blind from birth took this test, and thus 69% of these failed on the overall level (50% for those not blind from birth). Seven of the 8 women (88% of the women who did this task) made errors and 7 of the 15 men (47% of the men).

The use of thimble or pen did not appear to have had any influence on the overall success rate (50% of those who failed used the thimble and 50% used the pen).

Real life objects

The vase

Nineteen out of 24 users could identify the vase (79%). Those who failed said, for example, “bathtub” or just “something very big with slanting walls”. Of the 22 results on surface properties 20 could feel and describe the difference, one could not and one was uncertain. The challenge was judged to be 2.2 on the average.

Of those who failed on the identification task, one was younger than 30 and 4 were older. Two were blind from birth and 3 were not. Three were women and 2 were men.

The grand piano and stool

Twenty of 24 could identify and describe both the grand piano and the stool objects (83%). Two persons were confused by the fact that they imagined the piano oriented with the keyboard towards them. The challenge was judged as 3.3 on the average.

Of those who failed to identify the different parts of the object one was younger than 30 and 3 were older. Two were blind from birth and 2 were not. Two women and 2 men failed this identification.

The satellite

Twenty-two of 23 could find the parts of the satellite (96%). The challenge was judged as 3.5 on the average. The one user who failed was under 30, blind from birth and male.

The guitar and the sword

Three persons out of four could identify the VRML model of a guitar. During the fourth test, technical problems occurred and the test was not completed. The four persons were also asked to identify a sword. This object was thin and fairly small, but three out of four could still find and explore it. The fourth person found it, but lost it all the time and got the impression that it was disappearing. None of the four identified it as a sword.

General

The test persons were asked if they found the fact that the models were made up of flat triangles disturbing. On the average the degree of "disturbance" was rated as 1.6 on a scale from 1 to 5 (1 denoting "not disturbing at all" and 5 denoting "very disturbing").

Mathematical surfaces

Seven users performed this test and all of them could feel and describe the surfaces. Only one of the seven who took this test was a woman (the test was only carried out with users who had a particular interest and knowledge in mathematics). The challenge was judged as 1.5 on the average. Just as in the VRML case the fact that the objects were made out of flat triangles were not considered very disturbing (1.2 on the average on a scale from 1 to 5).

The users were asked how they could obtain this information today. Three said that they could not, one said he could get it from models and one said that he could use 2D representations.

Traffic environment

Twenty-one users of 21 could identify houses, sidewalks and roads. Seventeen of 21 (81%) completed the house-to-house exercise successfully.

All four persons that tested the "move the world" function could handle it after some initial confusion. The challenge of the exercise was judged as 1.5 on the average while the fun was judged as 4.5 (1 boring – 5 great fun).

The two persons actually failing the exercise (for two persons the result was difficult to interpret) were both over 30, blind from birth, one was a man and one a woman. The two results difficult to interpret came from users younger than 30, blind from birth and male.

Memory game

On the 6 button memory, 25 out of 25 succeeded. The average time to complete the game was 1minute 35 seconds. Twenty-four out of 24 successfully completed the 12 button memory. The average time until the game was completed was 1 minute 46 seconds (the sounds were shorter in the 12 button memory). The challenge was judged as 1.8 on the average.

Discussion

Geometrical objects

The general result of this test, that 80% of the users were able to recognize geometrical objects this way, is in line with the results reported by Jansson [7]. It is clear that blind persons are able to identify simple shapes using the PHANToM despite the fact that a one-point interaction is very different from their natural mode of exploring objects. It might be that the identification of virtual objects takes longer than the identification of real objects, but the users are still able to perform the identification.

It is apparent that the only shapes that really caused problems in our test were the parallelepipeds. All the test users who had problems with this task made some kind of mistake when judging the proportions of a rectangular parallelepiped object. That proportions are difficult to judge is probably due in part to the fact that different kinds of movements are made in different directions. It is possible to move the fingertip back and forth with movements of only parts of the finger whereas movements sideways and up/down require a movement of the whole finger and/or the wrist. We have also seen similar results in informal tests of a virtual clay program: even though the clay has exactly the same stiffness in all directions, many users say that it feels different when moving the fingertip sideways than when moving it back and forth.

The difficulty of the grid test (with 3 geometrical objects in a 3x3 grid) was actually somewhat surprising. Even if the difficulty to judge proportions accurately is disregarded (raising the success rate to 12 out of 23) this result was unexpectedly low.

A closer analysis of the kind of errors performed indicates that the majority were due to inefficient and/or incomplete haptic scanning. The users did not explore the object fully in all three dimensions, but limited their exploration to two dimensions, usually by following the floor. As the haptic scanning strategy is something that can be learned, the results may be expected to improve with training [6].

It is an interesting question how one best should guide the users towards an efficient exploration technique – some users appear to have an efficient way of scanning almost from the start, while others need more training (and may be expected to benefit from guidance – possibly from an agent advising the user with respect to the scanning technique used). At Museo Marini, the museum in Italy where some of the tests were performed, a method has been developed to guide blind persons into an effective exploration technique that helps them experience the sculptures at the museum fully. An interesting follow-up to this study would be to try to translate and apply this method in the virtual world.

Eighteen persons out of 23 (78%) had put the right number of objects at the right places which indicates that inefficient and/or incomplete haptic scanning has less effect on tasks that include locating positions only. However, another version of the haptic scanning problem caused problems even with the location of the objects: the users who did not succeed with this task were often seen to follow the *outline* of the grid square instead of scanning the floor within the square. This means that they could miss the entire object placed in the interior of the square.

There appears to be a higher error frequency among the users under 30 on this test, and furthermore a substantial difference in performance between men and women was noted. Whether this reflects real differences or whether this is due to the limited statistics available is still an open question. The age factor is actually connected both to blindness from birth (more younger users were blind from birth) and age of onset of blindness. It is not possible to separate these factors in the present test. When it comes to the results concerning gender it is possible that this difference may be connected with the ability to do mental rotations (an overview of cognitive sex differences can be found in [4]) as the haptic objects and the real objects sometimes were rotated with respect to each other. More tests are needed to verify this point.

We have also noted three other factors that seemed to influence the test results:

- training - this was the first test in the series
- motivation – several of the users did not appear as motivated during these tests as they did in their later work
- stress – the users knew we were timing the exercise and thus some tried to complete as quickly as possible even though we told them not to bother about the time. This may have led some users to hit on the first object that felt roughly right without carefully checking whether there were other objects which more closely resembled the virtual object.

The test also confirms the observation made in [8] that the use of a thimble or a pen for the interaction does not influence the results in this kind of tasks. This stands in contrast to the fact that we have gotten some very firm statements about the different manipulandi during informal test sessions. Many blind persons state that the thimble gives a more natural interaction and that it feels better to use that then the pen. This is heard especially often from beginners. It has also been shown that better friction inside the thimble can make persons use less force to grip and lift a virtual object even if all parameters in the virtual world are unchanged [22]. There are thus cases when the manipulandum is important for the result of the interaction, but when, where and to which degree is still an open question.

Real life objects

This test showed that the users could identify and understand also fairly complex objects. In view of the poor results on the grid test this result again was somewhat surprising even though the tests are not strictly comparable. Apparently complexity does not necessarily imply difficulty – a well known but complex object may be more readily understood than a simpler but unfamiliar object. A complex object may actually contain more hints that can help the user in the identification and exploration (this way complexity can be helpful in a way not indicated by the results presented in [10]). The previous experiences and understandings of the user thus come into the picture. This may be both a help and a hindrance. It was apparently helpful for the users who managed to find the thin support rod that holds up the lid of the grand piano. It was probably also helpful for the one user who had a grand piano himself and who could comment on the size of the stool in front of it (the stool was too large in comparison with the piano). And it was probably helpful in general for all users when it concerned both the vase and the grand piano. In contrast, the user who had imagined the piano with the keyboard facing him was initially hindered by his preconception, and it took much longer for him to understand the object.

Another observation made during the test was the importance of haptically accurate models. Before the tests, the problem with holes (i.e. the user could "fall through" the object at certain points) was already noted. For a seeing user this kind of error often has great consequences for the haptical illusion and models with obvious holes were not included in the tests (this problem is discussed in [2]). Despite our efforts to select good models, the ones we had access to were made for seeing persons and thus invisible parts were often carelessly modeled. The vase had a funny ridge on the inside, the grand piano had no strings and neither the piano nor the stool were well modeled underneath. These inaccuracies were in most cases not serious enough to hinder the identification tasks, but it did disturb many of the test users. The one exception was the sword used in the four-user test, which was elliptical (not sharp). This had the effect that none of the three users who could find and describe the object could identify it as a sword. Instead they would describe it as being long, thin and elliptical. The hole on the guitar from the same test was not really a hole; one could not explore the inside of the guitar, and furthermore it was possible to get unpleasantly stuck under the strings. Despite this, three out of the four users who tried this model identified it as a guitar. Thus some inaccuracies may be tolerated, but it is clear that key features of an object have to be correctly modeled (a sword should be sharp for example).

One conclusion that can be drawn from this is that the tests to see if a model is haptically accurate should be performed without visual feedback (the visual feedback may easily fool a seeing person into thinking that the model is better than it is – this was for example the case with the sword). Also holes and other imperfections are easier to miss when guided by vision – thus it should be a general rule for seeing people developing haptics for the blind to always test applications without visual feedback before testing the applications with the intended users.

Furthermore, this test highlights the fact that haptic key features of an object are not necessarily the same as visual key features. Sharpness is an obvious haptic key feature of a sword, while a common visual key feature probably is the cross-like shape with a long pointed "rod" at one end (the features that are considered as key features may differ between different users).

Reference points

In this test the users did not have access to additional sound information, helping agents, guided tours, etc. The only help accessible was bumps on the floor, which served as reference points in the environment to make it easier to find the objects [17]. These bumps were used to some extent by the four person tests (particularly the sword), but were otherwise ignored to a large extent. In hindsight we can see that the bumps were not good enough to work as references points that really help in finding and getting back to the objects. Good reference points must be easy to find and provide a good pointer to whatever it is referring to. If the reference point fails on either of these points it is often faster and easier to go directly to the object. This was certainly the case in most of these programs. Examples of working reference points are the corners of the room in the memory game. In that case we have often seen users go back to the corner when they were not certain where they or an object in the environment were positioned. A better reference point and guiding mechanism for the programs in this study would have been something like a stand with a cross-shaped foot on the floor. The user could then easily sweep the floor to find a part of the stand, follow it to the center and then follow the center-pole up to the object in question. To some extent this gives the same functionality as a virtual guide would do, but this kind of path to the object is certainly less obtrusive than a virtual guide that takes your hand. Another possibility might be to be drawn to the object as a result of requesting help.

VRML approximations

That the VRML approximations (that even the rounded shapes are made by meshes of flat triangles) are not very disturbing is good since it makes it easier to integrate the worlds of 3D graphics and 3D haptics. This result conflicts somewhat with a result from an earlier study of ours where we found that the sharp angles of virtual haptic object were often overestimated [15]. We thought that this might mean that the facets of the VRML models would be quite disturbing, but that was apparently not the case in this test. Still, the user comment that we should make more exact models (see below) could in part be criticism of the VRML approximations.

User comments

The user comments on these environments varied from "Takes training - maybe good after that…" to "Cool" and "Surprisingly good…" About 50% of the users had very positive comments about the application as a whole whereas the other 50% where more restrained in their comments.

The users were also asked for suggestions for improvements and the following comments (among others) were received:

- Add sounds
- Give help to find objects
- Model things not only from seeing person's view
- Make more exact models
- Let me feel with the whole hand
- Train on simple objects first

That the blind users still could handle complex objects such as the grand piano and the satellite (the screen dump of the satellite looks somewhat simple in Fig. 5, but it contains a lot of detail) so well is very encouraging. With haptically accurate VRML models and additional help we feel that it is reasonable to expect users to be able to handle significantly more complex environments.

Mathematical surfaces

All of the seven persons who tested the general haptic curve/surface display program could feel and describe the surfaces. Just as for the VRML case they were not particularly disturbed by the fact that the surfaces were made up of small flat triangles. This strengthens the case for polymesh models in this kind of application, as long as the models are haptically accurate as discussed above.

At the same time, this test illustrates the problem of testing this type of more advanced mathematics programs. The testing of a general curve/surface display program requires some level of mathematical knowledge, and the number of test users thus becomes quite restricted. To overcome this obstacle, one could create specific tasks that allow testing of program properties without requiring a high level of formal mathematical knowledge. We did this in another part of this study [18]. In that test the users had to solve tasks relating to a model ecosystem, and although the mathematics involved were fairly advanced it was possible to also solve the problems with limited mathematical knowledge (the tasks were to verbally describe a 2D curve, to point out maxima and minima and to solve a simple optimizing problem). This problem setting made it possible to also perform the tests with our two youngest test users who were 12 years old. To find good tasks for more general 3D surface properties remains an open challenge.

Traffic environment

The street environment did not present any particular problem to our test persons. This environment was generally enjoyable. Even though the navigational task did contain some difficulty (81% success) it received a low challenge rate. This kind of environment could readily be extended to training, games and map applications.

It is interesting to note that the rendering of the moving cars actually could be said to be haptically accurate, even though they were modeled as plain cubes. Since the PHANToM is a one point haptic device, the shape of a car hitting you is unimportant. A moving box works fine; it pushes you away in the same way as a very carefully modeled truck would have done.

It is also important to note that this environment with several moving objects would be fairly confusing if it were presented without the information that it represents a traffic environment.

To further enhance this kind of environment, realistic 3D sound should be added to make it possible to hear the direction the cars are coming from. We also received several other suggestions and comments from the test users:

- Very illustrative for children. With 3D sound. Training orientation
- Good and interesting for children. Learn and have fun
- Difficult to stay on the sidewalk. Sidewalk that was too thin.
- Add traffic lights!
- Add info-sound about house numbers, street names, etc.
- Add 3D-sound and several users at the same time
- Smaller houses could work

- Very interested in this kind of application as a visualization tool for street environment.
- Cool! More interested in the program as a game than for training.
- Nice as a game! Blind people have too few computer games!
- Adjustable car velocity.
- City maps…
- Gateways should be possible to feel. Push on the houses for information. Sound illustrations in 3D.
- 3D sound to localize cars. Pedestrian crossings with haptics and sound. Make a real model, with slopes also!

To allow users to explore larger worlds, some kind of zooming or moving operations are necessary (preferably several). Four persons tested a simple move function and the results were encouraging. After some initial confusion (the move function was quite crude, and it was possible to end up inside the houses) the users appeared to find a working strategy: they would put the finger close to a surface and then moved the surface away. That this crude moving function could be made useful makes it reasonable to assume that more elaborate moving functions will make it possible in the future for blind persons to get haptic access to worlds considerably larger than the small PHANToM working space.

Memory game

The memory tests were not as complex as those already reported by Sjöström [14][16]. Still they show that the users could handle and interact with quite complex environments where objects sometimes disappear. It should be noted that even the 85-year-old test person who became blind at the age of 64, and who had problems with the haptical illusion, succeeded in the 6 button memory.

If we compare the results of this study with our earlier results we find that we have a higher success rate for the 6 and 12 button games in this test than for the 24+1 button game that we used in the earlier test. There is also a very big difference in the time needed to complete the test. The time required for the memory games in this test was on the average less than 2 minutes, whereas the time required to finish the more complex games was 8:30 minutes (see also table 2).

	Success rate	Average time (min)
6 button memory	25/25 (100%)	1:35
12 button memory	24/24 (100%)	1:46
25 button memory, blind users	6/9 (67%)	8:30
25 buttons, sighted users who were allowed to see the environment	21/21 (100%)	3:50

Table 2. Results from this test compared to results from an earlier test with both blind and sighted users.

A few users said that the open spaces (when buttons have disappeared) are hard to handle. One user suggests a marker to show where buttons have been to make it easier. Another user suggests a grid as a means of making the navigation easier. The fact that buttons disappear in this program definitely makes it harder to play for a blind person since reference points disappear as the game progress. In this case we consider it a part of the game, but for production environments it is important to address this problem.

We conducted our first tests on the memory game to find out if it was possible to understand and control such a complicated system as Windows with only haptic information. Perhaps the most interesting conclusion from that test was that it was actually possible for a blind person to use one point virtual touch to create an inner picture of a rather complex environments. That conclusion is further strengthened by the results of the present test.

These tests do not test shape recognition as much as navigation, and thus the results are in agreement with the result in the grid test where the navigational part of the task was seen to be easier to handle for our blind users.

Conclusions

The outcome of these tests show that blind users by the use of haptics are able to handle and understand quite complex objects and environments (see Fig. 10), and that realistic virtual environments in some cases appear easier to handle than more abstract test environments.

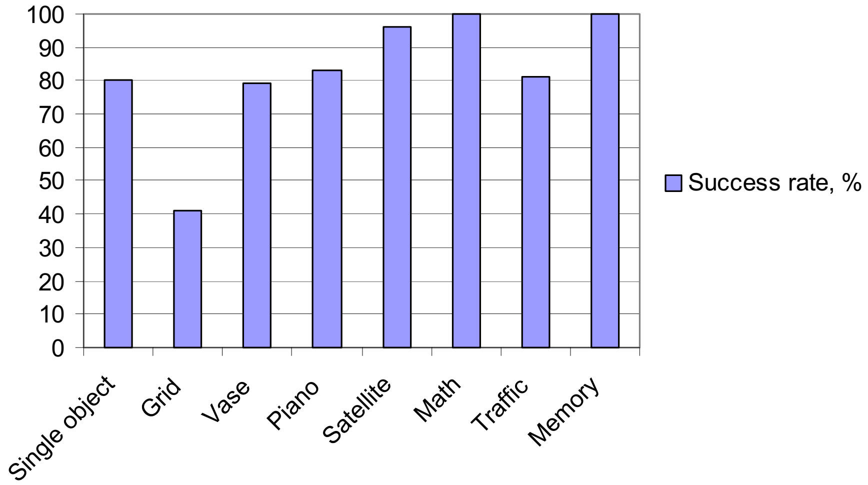

Figure 10. Success rates for the different tests.

Thus, context is seen to influence results significantly also in haptic surroundings. The result of a line drawing test performed within the same test series furthermore supports this conclusion [18]. In this test the success rate increased from 33% to 83% once the user knew that the unknown line drawing represented an elephant. The importance of context is a fact that again highlights the importance of additional input such as sound in a complex haptic VE [12][23]. Another factor observed to be important is haptic scanning strategy (cf. exploration path in [9]), and the need to consider ways of helping the user in this respect is pointed out. An indication that proportions in different directions can be difficult to judge accurately is also obtained, as well as an indication that age and gender may influence test results in this kind of tests.

Surprisingly enough the influence of blindness from birth appears less significant. It is possible that the age indication actually is connected to blindness from birth, or the age of the onset of blindness. The exact influence of these factors, or the combination of them, cannot be separated within the present test.

The evidence from the tests when it concerns shape recognition versus orientation/navigation is somewhat conflicting. The test results support the conclusion that navigational tasks in quite complex virtual haptic surroundings can also be handled by blind users. The evidence when it comes to shape identification is somewhat conflicting; the geometrical objects appear hard while the real life models appear easier (as long as expected key features of the object are present). This may to some extent just reflect the test setup and further tests to resolve this issue should be performed.

It has been shown that for the objects included in this test, the blind users are not greatly disturbed by the VRML approximation. What does disturb the illusion however is if the model is not haptically accurate. Holes, un-modeled or poorly modeled parts make it more difficult to understand objects and if the imperfections are bad enough, it may actually make it impossible for a user to obtain an understanding of an object.

Finally, we want to point out that although the test time consuming, as many as 92% (23 of 25) of the test persons wanted to take part in future tests. Furthermore 96% (24 of 25) of the test persons commented specifically on the added value of this technology. Thus the enthusiasm for this type of applications among the intended users is considerable!

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Appendix 6

Follow-up Experiments on Haptic Interaction Design Guidelines

Calle Sjöström

Certec Report number 1:2002

Follow-up Experiments on Haptic Interaction Design Guidelines

1 Background

As a member of the Haptics Group at Certec I have performed research and development on haptic interfaces for blind people since 1995. We formulated our first guidelines for haptic interaction design in 1998 and since then they have been revised on a regular basis.

The guidelines have its roots in observations that we have made when developing and testing haptic applications for blind people. After the initial observation is made we try to find out if there is something that can be generalized from the special case to gain knowledge that can be used in future. We normally iterate several times between "reflection-in-action", "reflection-on-action" and further observations. The concept of reflection-in-action is from Schön (1983). Many of these observations prove to be special cases, but in certain cases we end up with a piece of information that is general, relevant and useful enough to be called a guideline.

Previous versions of the guidelines have been published in (Sjöström 1999, Sjöström 2001a and Sjöström 2001b). The current version of the guidelines is part of my doctoral disseration.

For the current generation of guidelines I decided to make a follow-up study on parts of the two oldest guidelines where explicit tests had not been conducted before.

2 Aims and questions of the study

The aim of this study is to gain more information on three areas of haptic interaction design:

1. Virtual object and interface widget design
2. Reference points in the virtual environments
3. Usage of constraints and gridlines in the virtual environment

On point one, I want to explore what difference the design of the virtual objects and widgets can make to the overall experience of a virtual environment. Sharp corners of virtual objects have been proven to give some interaction problems in our earlier tests (Sjöström 1999) so for this test I designed a new button shape with rounded corners and a dent in the middle of the button to prevent slipping off it.

We have also seen that some people very distinctly use the corners of the virtual room as reference points to aid when navigating. To test the importance of this kind of reference points I here compare the results of a virtual room with the sidewalls (and thus the corners) and a room without any sidewalls at all.

Grids can be used to aid in precise navigation and to add extra reference points in the environment. When used in drawing programs and similar for sighted people, gridlines can normally be turned on and off by the user and it seems reasonable to believe that a similar solution could be helpful in a haptic environment.

3 Material and Methods

3.1 SUBJECTS

Ten sighted but blindfolded users carried out the test. All were related to the Department of Design Sciences at Lund Institute of Technology. All of the test users had tried the Phantom one or a few times before, but none of the test users had more than moderate experience of haptic interfaces. Three of the test users were female and seven were male. All the test users were right handed and thus held the Phantom-pen in their right hand.

3.2 APPARATUS

I used a Phantom Premium 1.0 from Sensable Technologies for the touch interaction (see Sensable 2002a). The Phantom was equipped with a rebuilt pen with a rubber grip instead of the standard stylus.

3.3 TEST PROGRAMS

Four different programs were made to compare the different interaction designs. The programs were memory games with haptics and sound, similar to memory games that we have tested before (see e.g. Sjöström, Rassmus-Gröhn 1999).

The tasks involved in playing the game is exploring the environment, getting an inner picture of it, pushing the buttons, remembering the position of the different sounds, getting back to the remembered position etc.

All the programs functioned exactly the same except for one parameter that was changed from the reference game. The general task in the memory games is to find pairs of buttons with the same sound. When the user pushes two buttons with the same sound in sequence the buttons disappear and the game is finished when all buttons are gone. The games in this test had twelve buttons and thus six pairs with different sounds. The six sounds were the same in all games, but the position of each sound were randomized each time a new game was started.

All the programs for this test were written in Visual C++ using the GHOST SDK from Sensable Technologies (Sensable 2002b). All the games have the buttons on the back wall of the virtual room. The size of the virtual room is 130 mm * 140 mm * 50 mm (width*height*depth). The buttons are approximately 25 mm wide. All the buttons in the environments use the same amount of friction: 0.4 static and 0.3 dynamic (friction coefficients as defined in the GHOST SDK).

The test programs used in this test can be downloaded from our web site:
http://www.certec.lth.se/haptics/software/GL/

Test program 1

This program has been used as the reference. It has a virtual room with four walls, a ceiling and a floor (see Figure 1). The buttons in the game has a rounded and scooped shape that was designed specifically to be effective in haptic interaction. The rounded shape is supposed to make it easier to trace the shape of the object and the small dent in the middle of the button makes it easier feel where the center of the button is and harder to slide off the button unwillingly (see Figure 2 and 3). The button was designed in 3D-Studio Max and exported as a VRML-file. The VRML-file was then be used as a shape in the GHOST program.

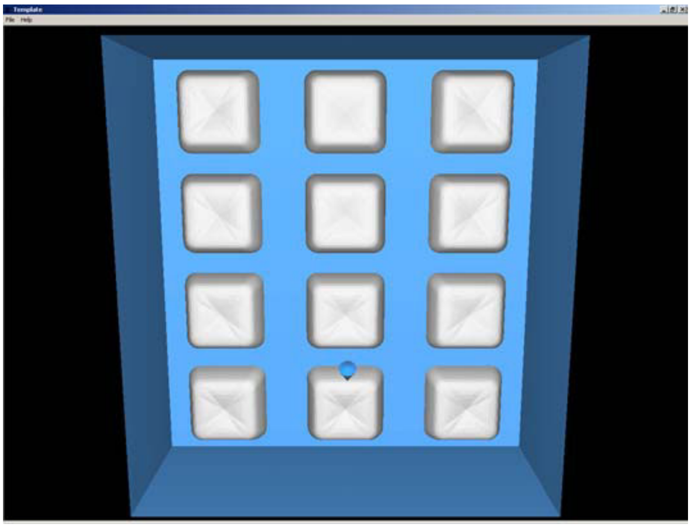

Figure 1 Screen dump from Memory test program number 1.

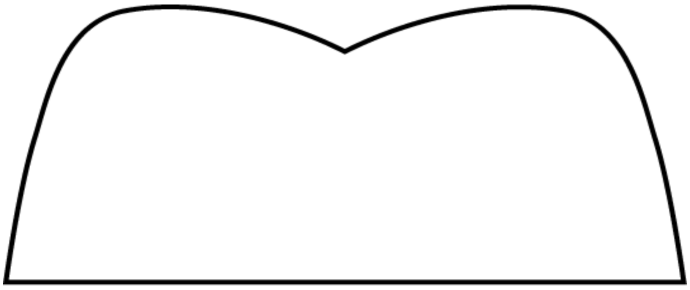

Figure 2 Cross-section of the button shape used in test A, C and D.

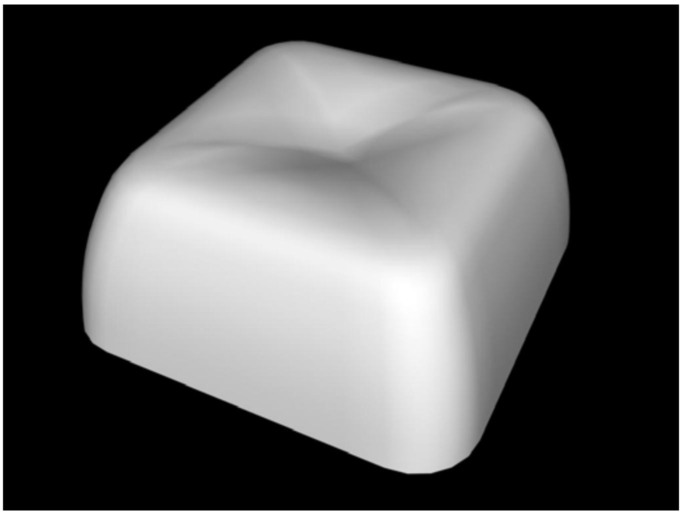

Figure 3 Perspective rendering of the button from 3D-Studio Max.

Test program 2

Test program number 2 used standard flat boxes as the button shape instead of the scooped button used in the other tests (see Figure 4). The result of this design compared to the first design give information about the effect of optimizing the haptic widgets in tasks like this. Since the memory game task to a large extent is a navigational one the effect of widget optimizations cannot be expected to be very large.

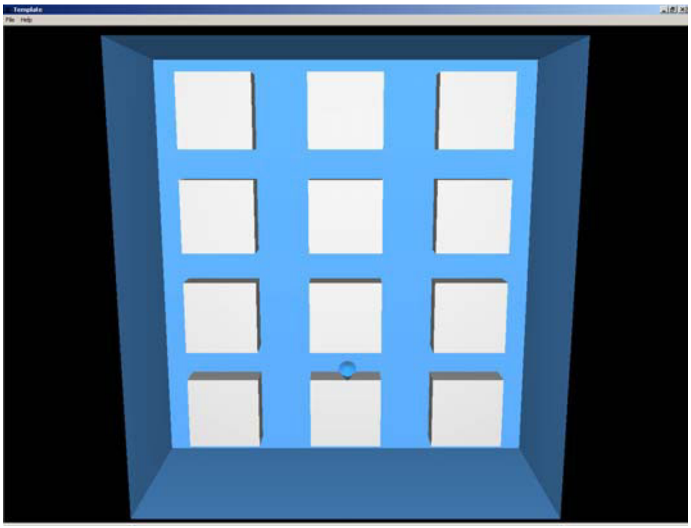

Figure 4 Screen dump from Memory test program number 2. The buttons are flat instead of scooped as in test 1.

Test program 3

This program tests how important reference points like the corners are in a virtual environment. The test program uses the same buttons as program 1, but in this virtual environment there are no sidewalls (see Figure 5). The only wall is the back wall of the room where the buttons are placed. This wall covers the whole working area of the Phantom, so in practice the virtual room is limited by the flat wall on the back and the spherical workspace of the Phantom device on all other sides.

The walls and the corners of the virtual room can normally be used as reference points in the virtual environment and they also work as limitations of the workspace so that the user never get too far away from the buttons. Reference points are particularly useful if the user looses orientation for some reason. In this program it is still possible to use the buttons themselves as reference points, but not the corners or walls.

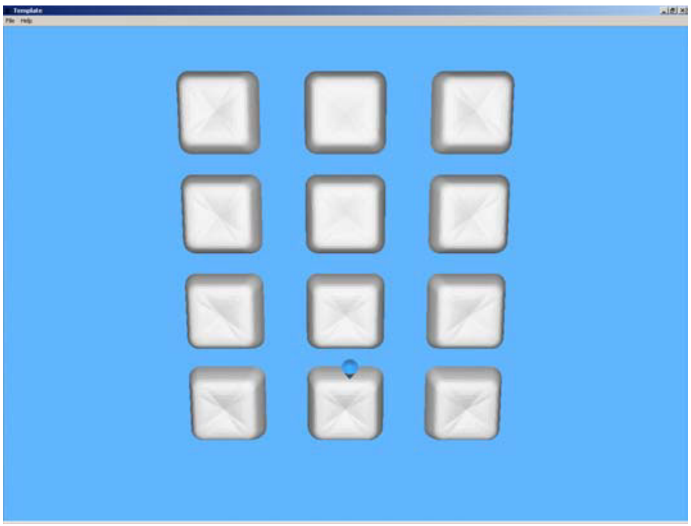

Figure 5 Screen dump from Memory test program number 3. The virtual environment has a backwall but no sidewalls.

Test program 4

This program tests the usage of gridlines in the virtual environment (see Figure 6). Gridlines can help finding the buttons but they could also be disturbing to the user. In this program the gridlines were cylinders with a radius of 1,1 mm. The shape and size of the lines were choosen to make the gridlines as little disturbing as possible but still clearly feelable. The gridlines line up with the buttons horizontally and vertically.

The gridlines could also make it easier for the users to feel were there has been a button since the crossing gridlines are still there even though the button is gone.

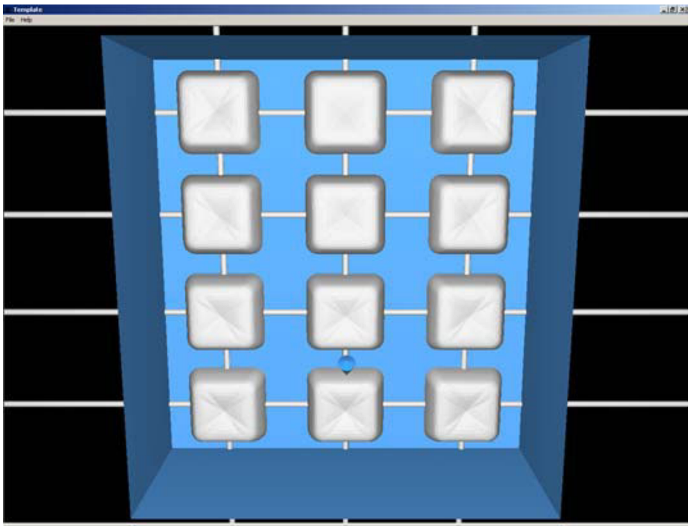

Figure 6 Screen dump from Memory test program number 4. The gridlines on the back wall line up with the buttons to make them easier to find.

3.4 TEST SETUP AND PROCEDURE

The test procedure started with the test leader explaining how the test was going to be carried out and what was going to happen. Prior to the real tests, all test persons underwent a pre-test phase. This pre-test is included to let the test users get acquainted with the Phantom and to get by some if the initial problems of virtual haptic interaction. Since the users in this test all had some experience of the Phantom the pre-test was limited to about 15 minutes per user. During the pre-test the users first got the possibility to feel and identify 8 different virtual models of geometrical objects. After this the user tried a special pre-test version of the Memory game. This pre-test memory had mixed buttons to avoid any influence on the button preference in the test. Each user completed the pre-test Memory game two times.

In the test phase the user played the four different Memory games one after each other. The sequence of the games was randomized to compensate for possible effects from learning etc that could change the user's performance over time. The users were instructed to play as fast and securely as possible without rushing.

The programs automatically logged time from start to success, number of button pushes needed, user position and reaction force during the whole game. The test leader took notes about comments from the users during both pre-test and test. After the test the users were asked to rate the different designs compared to the reference and to comment on their experience in general. This combination as quantitavive and qualitative measures gives a good and complete picture of the specifics of each interaction design.

During the whole test, the users sat at a desk with the Phantom and speakers but nothing more on it (see Figure 7). The whole test including introduction, pre-test, test, and discussion afterwards took about 45 minutes per user.

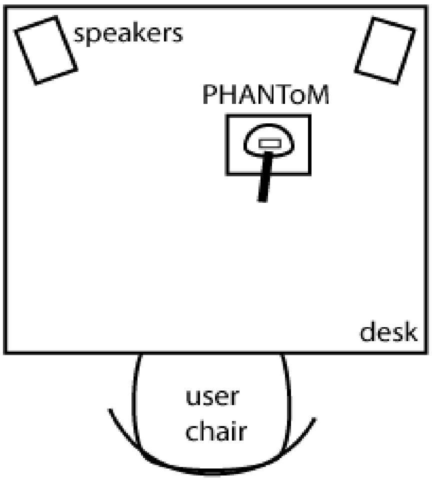

Figure 7 Test setup

4 Results

The time to success, number of button pushes needed and rating for each test and user is shown in Table 1.

Table 1 Summary of the test results

	Test 1 Reference, scooped buttons			Test 2 Flat buttons			Test 3 No sidewalls			Test 4 Grid		
User	Time	N	Rating	Time	N	Rating	Time	N	Rating	Time	N	Rating
A	02:19	22	0	03:09	33	-1	03:59	49	-1	04:50	27	-1
B	03:38	42	0	02:20	29	1	---	--	-1	04:52	47	-1
C	02:11	20	0	01:49	19	-1	03:06	26	-1	03:55	19	-1
D	01:05	18	0	00:48	17	1	01:03	16	-1	01:56	18	-1
E	01:10	16	0	02:49	21	-1	02:46	29	-1	02:14	19	-1
F	02:35	32	0	04:29	43	0	03:53	44	-1	03:22	34	1
G	01:31	22	0	01:21	19	-1	01:34	17	-1	05:11	37	-1
H	01:46	21	0	01:37	20	-1	01:41	16	-1	03:28	17	-1
I	01:53	28	0	03:14	27	-1	04:02	40	-1	02:43	24	-1
J	00:56	21	0	01:34	23	0	01:44	26	-1	01:37	23	1
Av.	**01:54**	**24**	**0**	**02:19**	**25**	**-0,4**	**02:59**	**31**	**-1**	**03:25**	**27**	**-0,6**

Test 3 for User B was terminated after 3 minutes and 15 secondes and more than 50 button pushes since the user was frustrated and did not progress. One pair was taken at that time. The average results for this test is calculated using an estimated result of 6:00 minutes and 50 button pushes for this specific test and user.

5 Discussion

The reference design was better then the other designs on all the parameters time, number of button pushes and user rating. The difference was largest with the gridlines and the environment without walls whereas the difference between the results of the different shapes was not that large.

5.1 REFERENCE POINTS

It is clear that the lack of walls and corners as reference points makes a big difference for a vast majority of the users. A few of the users do get about the same time one this test as in the reference program but all users agree that this environment is harder to handle than the one with walls. The average time for completion and number of button pushes is also considerably higher in this test than in the reference.

This test was the only test in which one user did not manage to solve the task. This user said that the difference with walls was "totally crucial".

The user had a lot of comments on the virtual environment without sidewalls, here are a few of them:

- Awkward without the walls I think…
- Hard if you loose your orientation, then you want to be able to get back to a corner.
- The buttons are good, but it's a tough job to concentrate without the walls as a security.
- This was a lot harder…
- You loose your references here.
- Especially when the buttons were gone it was hard having nothing to relate to.
- Hopeless!
- This was harder then with the walls, but not a huge lot harder.

Reference points are indeed important in all kinds of navigation but in the case of blind users in a navigation heavy virtual task it is apparent that the reference points provided by the walls and corners can make a real difference and in some cases even imply the difference between success and no success.

5.2 GRIDLINES

The test with gridlines got the highest average time for completion of all the tests. All but two users thought that the gridlines were more of a disturbance than help. Two users thought that the gridlines did help them but they both got longer times and more button pushes than in the reference program. The interesting thing about this test is that the difference in times a markedly higher than the difference in number of button pushes. Actually all users got higher times with this game but only 6 of them got more button pushes than in the reference. It seems as though the gridlines disturb the free scanning for many of the users but still help when it comes to a more mechanical use of the memory game.

Many users complain that the gridlines disturb them and that it takes more time because you do not know immediately if you are touching a line or a button.

This is a selection of the user comments on the game with the gridlines.

- It was disturbing; you couldn’t feel the difference between the different things.
- The lines disturb the scanning
- I have to look for the buttons instead of remembering the sounds.
- You think that it is a button, but then you understand that it is a gridline
- I thought that this would be good, but it was only disturbing.
- It jerks…
- Good with the lines as an orientation, you can feel if you go upp or down a row

5.3 BUTTON SHAPES

The different button shapes apparently make the least difference in the result of this task. Both the average times and number of button pushes are slightly higher with flat buttons than with the scooped button but the difference is not as large as in the other tests. Looking at the results for each user we can see that half of the users have better times with the flat buttons and half of the users have better times with the scooped buttons. The same holds for the number of button pushes. It is thus hard to tell for sure if the scooped buttons really make a difference on performance in this kind of task, even if we get an indication that it might be so.

The real difference in this test though is the user rating of the environments. 6 of the users preferred the scooped buttons, two thought that the scooped buttons were slightly better but that it did not matter in this kind of task and two thought that the flat buttons were better.

User comments on the different button shapes:

- It was quite a big difference on the buttons; the scooped ones were easier to handle even though I actually did not notice it from the start. But the rounded sides were not only good.
- The scooped buttons were better, but it’s not a huge difference.
- It was easier to handle the scooped buttons because you don’t slide away from them.
- The flat buttons were easy to slip off, the scooped ones were better in that sense.
- The scooped buttons were good because it was easy to feel what it was.
- The flat buttons work well too, once you have learned to handle them.
- The flat buttons feel more distinct

The comments “it was easy to feel what it was” and “you don’t slide away from them” indicate that this design has a better haptic affordance. Gibson discussed the term affordance in “The Ecological Approach to Visual Perception” (Gibson 1979).

Gibson writes "The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, but the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment...”

Norman gives the term a slightly different twist in “The psychology of Everyday Things” (Norman 1988). Norman writes "When used in this sense, the term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used. A chair affords ("is for") support, and, therefore, affords sitting." And in a note: ”I believe that affordances result from the mental interpretation of things, based on our past knowledge and experience applied to our perception of the things about us.”

Haptic affordance has been discussed by Arthur Kirkpatrick in his disseration ”Force plus graphics is not equal to vision plus haptics: Towards usable haptic environments” (Kirkpatrick 2000). Kirkpatrick writes that “Visual affordances tend to indicate possible actions, as for example the sight of a doorway affording the possibility of entering a room… By contrast, haptic affordances always guide action."

The way affordance is used today it often refers to a quality that indicates that an action is possible or in a subtle way help a persons to understand what an object is for.

The users comments on the scooped buttons in my test suggest that the shape of the button both indicate what this object is for and guide the user when performing that action. The haptic affordance of this button is thus not only of the kind that is suggested by Kirkpatrick, but also similar to the classic definition of affordance but communicated in a purely haptic way.

6 Conclusions

The final conclusions here is that reference points, for example in the form of corners of a room, are very important for many users and do not seem to disturb the interaction in any way. It is thus highly recommended to include flat walls (and corners) in a virtual environment, especially if the task is navigationally heavy.

Gridlines can help but seem to disturb for a majority of the users and should thus not be included if the added exactness is not needed. It is possible that a grid designed in a different way (e.g. with grooves instead of the cylinders used in this test) can give a better result, but most likely a large portion of the disturbance will still be there. In most cases I would recommend having gridlines as an option that be turned on and off by the user.

The shape of the haptic widget does not seem to make a very big difference on performance in this kind of task but the scooped and rounded buttons are indeed better liked by a clear majority of the users. Widget design can thus make a real difference and there is a need for improvements on this point. Haptic affordance is also an area where further research is needed.

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Appendix 7

List of Articles and Presentations at Scientific Conferences

Journal Articles
Haptic Representations of 2D Graphics for Blind Persons
Calle Sjöström, Henrik Danielsson, Charlotte Magnusson, Kirsten Rassmus-Gröhn
Submitted to Haptics-E, the Electronic Journal of Haptics Research, 2002

Navigation and Recognition in Complex 3D Haptic Virtual Environments
Charlotte Magnusson, Calle Sjöström, Kirsten Rassmus-Gröhn, Henrik Danielsson
Submitted to Haptics-E, the Electronic Journal of Haptics Research, 2002

Supporting Presence in Collaborative Multimodal Environments by Haptic Force Feedback
Eva-Lotta Sallnäs, Kirre Rassmus-Gröhn, Calle Sjöström
ACM Transactions on Computer-Human Interaction (ToCHI), Volume 7 Issue 4, December 2000

The sense of touch provides new computer interaction techniques for disabled people
Calle Sjöström, Kirre Rassmus-Gröhn
Technology and Disability Vol. 10, No 1, 1999, pp 45-52, IOS Press.

Scientific Conference Presentations
Haptic Line-Drawings for Blind Persons
Calle Sjöström, Henrik Danielsson, Charlotte Magnusson, Kirsten Rassmus-Gröhn
Presented at the 7th International Conference on Low Vision – Vision 2002, Göteborg, Sweden

Designing Haptic Computer Interfaces for Blind People
Calle Sjöström
Presented at the 6th IEEE International Symposium on Signal Processing and its Applications – ISSPA 2001, August 13 – 16, 2001, Kuala Lumpur, Malaysia

Virtual Haptic Search Tools
Calle Sjöström
Presented at the 6th European Conference for the Advancement of Assistive Technology - AAATE 2001, Ljubljana, Slovenia, September 3 - 6, 2001

Using Haptics in Computer Interfaces for Blind People
Calle Sjöström
Presented at the ACM SIGCHI Conference on Human Factors in Computing Systems - CHI 2001, Seattle, USA, March 31 - April 5, 2001

Haptic Feedback in Virtual Environments
Eva-Lotta Sallnäs, Kirsten Rassmus-Gröhn, Calle Sjöström
Poster presented at the 6th European Conference on Computer Supported Cooperative Work - ECSCW´99. Copenhagen, Denmark.

Support for the Touch Modality in Collaborative Distributed Environments
Eva-Lotta Sallnäs, Kirsten Rassmus-Gröhn, Calle Sjöström
Presented at the third Swedish symposium on Multimodal Communication - SSOMC´99. Linköping, Sweden.

Using a Force Feedback Device to Present Graphical Information to People with Visual Disabilities
Kirre Rassmus-Gröhn, Calle Sjöström
Presented at the Second Swedish Symposium on Multimodal Communication – SSOMC 98, Lund, Sweden, Oct 1998

The Phantasticon - the Phantom for Blind People
Calle Sjöström
Presented at the Second PHANToM Users Group, Dedham, MA, Oct 1997

To Use the Sense of Touch to Control a Computer and the World around You
Calle Sjöström, Bodil Jönsson
Presented at the 4th European Conference for the Advancement of Assistive Technology - AAATE -97, Thessaloniki, Greece, Sep 1997

Haptics is the area of research dealing with the feedback we receive through our sense of touch. Developments in this area have been of great interest to the computer games industry in recent years. But the potential of this technology for providing access to graphical computer interfaces for people who are blind is obvious. The Haptics Group at Certec has been carrying out research, development and testing since 1995 when it acquired its first haptic interface device, the Phantom™.

This dissertation presents the results in the form of guidelines and applications to be used in the design of non-visual haptic interaction. Extensive testing with people from the intended user group has been a central element in the process. Their reported experiences, reactions and suggestions have contributed significantly to the ongoing development.

The five general design guidelines are accompanied by more detailed explanations and examples based on eighteen computer programs developed and described here by the author. Inspiration has come from the fields of design, usability engineering, software development and human-computer interaction.

The overall aim of the research is to improve the possibilities for blind people to use computers, to reduce the problems that arise in developing and using graphical user interfaces and to develop new applications and application areas.

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Certec is a division in the Department of Design Sciences at Lund University. Our research and education has a clearly expressed purpose: that people with disabilities be given better opportunities through a more useworthy technology, new design concepts and new individual forms of learning and searching. While both the process and results are often of a genuinely technical nature, our work begins and ends with the individual.

We have 20 staff members and an annual budget of approximately 12 million Swedish crowns. The major portion of our funding comes from Region Skåne, the southernmost province in Sweden, and Lund University. Project funding is also provided by the European Union and several other contributors.

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