Enabling audio-haptics

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To my parents

Aim

This thesis has the following aims:

1. To present usability possibilities and problems in non-visual virtual haptic (force-feedback) environments regarding: gaining an overview, navigation, and orientation.
2. To present realized applications utilizing combinations of audio and haptics, along with user tests of the applications.
3. To present possible future scenarios and research for utilizing non-visual computer interfaces for computer users with blindness or low vision.

Abstract

This thesis deals with possible solutions to facilitate orientation, navigation and overview of non-visual interfaces and virtual environments with the help of sound in combination with force-feedback haptics. Applications with haptic force-feedback, spoken and/or non-spoken audio in mono, 2D or 3D were developed and tested by users who were blind, had low vision or were sighted.

The resulting research deals in part with the blind user's representation of himself/herself in a 3D audio-haptic virtual environment, and how the user can move the virtual ears – "ears-in-hand" – with the haptic display. The "ears-in-hand" method was tested by 10 blind users in a virtual traffic environment, and by 12 sighted users in a location test.

A drawing program for visually impaired children was sonified, where the virtual drawing pen position was mapped to pitch and pan to help the user orient himself/herself on the virtual paper. A reference group of 5 blind or low vision children have evaluated the application on an ongoing basis.

Usability tests involving 25 blind users using haptic-only virtual environments are presented that show common problems in interaction and illustrate the need for sound feedback in non-visual force-feedback haptic virtual environments.

Keywords: sound feedback, force feedback haptics, sonification, interaction, usability, virtual environments, blind, low vision

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Charlotte Magnusson has since 2001 been my supervisor and nearest colleague. She is a fountain of knowledge of haptics, of programming and of mathematics and a good working friend. Thank you, Charlotte!

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Kirsten Rassmus-Gröhn, Lund, August 11, 2006

Contents

AIM **2**

ABSTRACT **3**

ACKNOWLEDGEMENTS **4**

INTRODUCTION **7**

THESIS BACKGROUND 7
RELEVANT RESEARCH PROJECTS AND FUNDING 8
RELEVANT PUBLICATIONS 10

STATE OF THE ART **13**

FEELING VIRTUAL ENVIRONMENTS 13
HEARING VIRTUAL ENVIRONMENTS 16
COMBINING HAPTICS AND AUDIO 19
USABILITY ISSUES 20

APPLICATIONS & USER TESTS **23**

HAPTIC COLLABORATIVE ENVIRONMENT WITH HAPTIC AVATARS 23
THE STEP-BY-STEP TRAINING SESSION 24
RECOGNITION OF GEOMETRIC OBJECTS 26
AUDIO-HAPTIC MEMORY GAME 27
A VIRTUAL HAPTIC-AUDIO TRAFFIC ENVIRONMENT 27
SONIFICATION OF A HAPTIC LINE-DRAWING APPLICATION 30

RESULTS **33**

THE STEP-BY-STEP TRAINING SESSION 33
UNDERSTANDING HAPTIC ENVIRONMENTS WITHOUT AUDIO GUIDANCE 34
UNDERSTANDING AUDIO-HAPTIC VIRTUAL ENVIRONMENTS 36
THE HAPTIC AVATAR AND THE EARS-IN-HAND METAPHOR 38

DISCUSSION **39**

3D AUDIO-HAPTICS 39
2D AUDIO-HAPTICS 40

CONCLUSIONS **43**

AUDIO-HAPTIC TOOLS FOR SCHOOL WORK 43
AUDIO-HAPTIC MAPS AND VIRTUAL ENVIRONMENTS 44
FROM PRESENT TO FUTURE 45

REFERENCES **47**

APPENDICES.. 51

APPENDIX 1 - THE STEP-BY-STEP TRAINING SESSION 53
APPENDIX 2 - THE SENSE OF TOUCH PROVIDES NEW COMPUTER INTERACTION TECHNIQUES FOR DISABLED PEOPLE.. 55
APPENDIX 3 - SUPPORTING PRESENCE IN COLLABORATIVE MULTIMODAL ENVIRONMENTS BY HAPTIC FORCE FEEDBACK 67
APPENDIX 4 - PHANTOM-BASED HAPTIC LINE GRAPHICS FOR BLIND PERSONS... 85
APPENDIX 5 - A VIRTUAL TRAFFIC ENVIRONMENT FOR PEOPLE WITH VISUAL IMPAIRMENTS 107

Introduction

People that are blind have benefited from the information society of today, as have all of us, and now it is easy to get hold of information that was inaccessible in the printed text era. However, there is a considerable amount of information not yet accessible for a user who cannot see, e.g. graphical information such as maps, charts, etc.

A computer user that is blind often has some form of text-to-Braille (TTB) or text-to-speech (TTS) system. This enables access to text on web pages, in the operating system and in documents. But with the development of graphic user interfaces and the focus on pictures, layout and recently also 3D models, much is still hidden for a person who cannot see. From this vantage point, the old text interfaces were much more accessible.

Both text-to-Braille and text-to-speech systems have their main drawback in the serial information channel that they provide the user. Granted, state-of-the-art TTB & TTS systems provide additional tools that, for example, display links, headings or button labels in a quite orderly fashion; still, it is almost impossible to gain an overview and to skip uninteresting sections of a web page.

The evolvement of force-feedback or haptic devices has therefore spurred the imagination of researchers and people who are blind. What if they can be used to provide a haptic overview of graphical interfaces? Can they be used for experiencing 3D environments in games, for example?

Thesis background

Haptic technology has evolved gradually from teleoperating technology (the control of robots from a distance) [1]. In the early 1990s, Thomas Massie and Kenneth Salisbury at MIT developed the PHANToM, a desktop 3D force-feedback device [2]. In 1994, Certec purchased its first PHANToM device, and with it started the development of ideas and software prototypes.

In 1997, I gradually started demonstrating the PHANToM device and making small applications, along side my other work (mostly as a teaching assistant). In 2000, I enrolled as a PhD student, and continued, in addition to my primary teaching responsibilities, working in various projects with the PHANToM. In my private life, I have been active in Student Theater as a sound technician, which is the source of my sound interface interest.

The extended nature of my doctoral studies, due in part to maternity leaves (children born 2003 and 2005), has yielded both advantages and disadvantages. Some of the research and papers that are presented in this thesis may seem outdated, but were very relevant at the time. The larger projects are based on teamwork, and because I have mainly worked part-time since 2003, I have been involved in different parts of different projects: background work, programming applications or parts of applications, and designing and conducting user tests. In the beginning, my primary assignment was to demonstrate the device.

Relevant research projects and funding

The European Union, the Swedish Road Administration, and Skåne Region (administrative area in southern Sweden) have all financed parts of my research on haptic-audio interfaces. The EU grants and those from the Swedish Road Administration have been directed to specific research projects, see table and presentation below.

Project name	Years
ENORASI, EU	2001
Traffic project, Swedish Road Adm.	2002 - 2003
MICOLE & ENABLED, EU	2004 – 2007

Table 1. Overview of projects and funding.

ENORASI, EU

The ENORASI project was aimed at developing a highly interactive and extensible haptic virtual reality (VR) system that would allow visually impaired people, especially those blind from birth, to study and interact with various virtual objects. ENORASI would also provide case studies for training through interaction, manipulation and modification of objects of complex shapes. The project was discontinued in September 2001, but a number of initial studies were conducted. Examples of user trials and applications include: recognition of objects of different complexity, texture recognition, pedagogical graph application, small virtual traffic environment, localization tests and relief drawings and maps.

My efforts in this project focused on:

- Designing a learning session to help users over the initial use threshold (the step-by-step training session)
- Implementing virtual scenes for the learning session
- Implementing a localization test – memory game with sound

- Implementing a geometry recognition and localization test
- Designing user tests

A virtual audio-haptic traffic environment, Swedish Road Administration

The goal was to investigate if and how blind persons can navigate in a dynamic virtual audio-haptic environment, i.e. a virtual environment with modeled houses, roads, pedestrian crossings, signposts, cars, bicycles, etc. The model was as haptically accurate as possible concerning the placement of objects, but utilized some possibilities to make certain simplifications in object details. The model also incorporated spoken text labels to supply information about objects and surfaces, as well as 3D sound rendering for cars and tick signals at pedestrian crossings.

Ten visually impaired users used the application for exploring the environment and learning a route, after which they traveled the route by foot in the real, original environment.

My part in the project focused on background investigations on how to use sound in the application:

- Checking 3D sound APIs
- Initial study on how to place speakers or use head phones
- Initial study on how to orient the ears of the avatar (the virtual "self")
- Design of sound effects
- Programming an interface between a sound API and the haptic application

MICOLE, EU – ongoing

MICOLE is an EU project that runs September 2004 – October 2007. In the project, computer tools and interfaces are being developed for school children who are blind or visually impaired. Virtual haptics and virtual sound as well as magnification will be used to provide access to computer models and information. Another goal is that the visually impaired children will be able to collaborate with teachers or their sighted peers.

Until April 2006 focus has been on two areas: user studies and application prototype development. A User Board has been formed consisting of pupils aged 10-16 and their parents. Various application prototypes have been developed to understand user needs and investigate possible solutions for guiding users in 3D haptic and audio-haptic virtual environments. A haptic-audio paint tool is under iterative development, and will be the focus of coming research, which will be presented in more detail in coming chapters.

My part in the project has two focus areas – sound interaction design and user involvement. These two are intertwined in an ongoing design-evaluation loop.

- Sound interaction design
    - Design of sound effects
    - Programming of sound functionality
- User involvement:
    - Requirements capture
    - User trials

ENABLED, EU – ongoing

EBABLED is a large-scale (Information Societies Technologies, IST) EU project with many partners in industry, running 2004-2007. Its major goals are the development of tools for Internet accessibility for people with visual impairment, multimodal interfaces, mobile computing and networks. The technology that is being utilized includes tactile systems, haptics and sound interfaces.

My work in ENABLED centers on requirements capture (design of questionnaire) and investigations on sound APIs.

Relevant publications

The following list of publications underscores the outstretched and somewhat diverse research agenda that has been followed:

Publication	Year	My part	Project
Conference 1	1998	Demonstrating, User testing	
Journal 1	1999	Demonstrating, User testing	
Journal 2	2000	Programming, User testing	
Journal 3, Conference 2	2001	Programming, User testing	ENORASI
Journal 4, Conferences 3 & 4	2002-2003	Background work, Programming	Haptic-audio traffic environment
Conferences 5, 6 & 7	2005-2006	Background work	ENABLED, MICOLE
Conference 8	2006	Background work, Programming, User testing	MICOLE

Table 2. Overview of journal and conference papers, and declaration of my work in each publication.

Journal papers

All are appended to the thesis.

1. The sense of touch provides new computer interaction techniques for disabled people
Calle Sjöström, Kirsten Rassmus-Gröhn
Technology & Disability (IOS Press), 1999, Vol. 10, No. 1.

2. Supporting presence in collaborative multimodal environments by haptic force feedback
Eva-Lotta Sallnäs, Kirsten Rassmus-Gröhn, Calle Sjöström
ACM Transactions on Computer-Human Interaction (TOCHI)
Dec. 2000, Vol. 7, Issue 4.

3. Phantom-based haptic line graphics for blind persons
Calle Sjöström, Henrik Danielsson, Charlotte Magnusson, Kirsten Rassmus-Gröhn
Visual Impairment Research, 2003, Vol. 5, No 1, pp 13-32.

4. A virtual traffic environment for people with visual impairments
Charlotte Magnusson, Kirsten Rassmus-Gröhn
Visual Impairment Research, 2005, Vol. 7, No 1, pp 1-12.

A selection of conference and workshop papers

1. Using a Force Feedback Device to Present Graphical Information to People with Visual Disabilities
Kirre Rassmus-Gröhn, Calle Sjöström
Second Swedish Symposium on Multimodal Communication,
Lund, Sweden, Oct. 1998.

2. Navigation and Recognition in Complex Haptic Virtual Environments – Reports from an extensive study with blind users
Charlotte Magnusson, Kirsten Rassmus-Gröhn, Calle Sjöström,
Henrik Danielsson
EuroHaptics 2002, Edinburgh, UK, July 8-10.

3. Non-visual Zoom and Scrolling Operations in a Virtual Haptic Environment
Charlotte Magnusson, Kirsten Rassmus-Gröhn
EuroHaptics 2003, Dublin, Ireland.

4. A Dynamic Haptic-Audio Traffic Environment
Charlotte Magnusson, Kirsten Rassmus-Gröhn
EuroHaptics 2004, Munich, Germany, June 5-7.

5. Virtual Reality Technology – A tool for behavioural studies involving disabled people
Gerd Johansson, Roy C. Davies, Joakim Eriksson, Jonas af Klercker, Charlotte Magnusson, Kirsten Rassmus Gröhn, Mattias Wallergård.
Measuring Behavior 2005, 5th International Conference on Methods and Techniques in Behavioral Research, Wageningen, The Netherlands, Aug. 30 - Sept. 2.

6. Audio Haptic Tools for Navigation in Non-visual Environments
Charlotte Magnusson, Kirsten Rassmus-Gröhn
ENACTIVE 2005, the 2nd International Conference on Enactive Interfaces, Genoa, Italy, Nov. 17-18.

7. Non Visual Haptic Audio Tools for Virtual Environments
Charlotte Magnusson, Henrik Danielsson, Kirsten Rassmus-Gröhn
Accepted at First International Workshop on Haptic and Audio Interaction Design, to be held Aug. 31- Sept. 1 2006, Glasgow, UK

8. User Evaluations of a Virtual Haptic-audio Line Drawing Prototype
Kirsten Rassmus-Gröhn, Charlotte Magnusson, Håkan Eftring
Accepted at First International Workshop on Haptic and Audio Interaction Design, to be held Aug. 31- Sept 1. 2006, Glasgow, UK.

State of the art

A short overview of the virtual haptic and audio display technologies is presented to lay the groundwork for the description of combining the two. A section then follows on the research persons and haptic learnability and testing issues.

Feeling virtual environments

The technology of hardware to enable a user to feel computer models has emerged from the robot industry, where there was a need to operate robots from a distance and sometimes be able to "feel" what the robot "felt" [1]. In the mid-90s, force feedback and tactile displays for desktop use were developed at such companies as Sensable Technologies [2] and Immersion Corp. [3]. Both force feedback displays and tactile displays such as Braille displays, vibro-tactile gloves or mice are often referred to as haptic displays. Tactile displays are not within the scope of this thesis.

Haptic interaction

The term haptics is used to describe different concepts related to human perception and understanding through touch [4]. The term comes from the Greek word "haptein" which means, "to touch". In [5], Hatwell writes about the close link between perception and action in haptic functioning. This means, particularly in the context of non-visual haptics that in order to perceive haptically, the user must move actively.

In computer interaction, the haptic sense is active when, for instance, writing on the keyboard and manipulating the mouse. Virtual haptic displays can provide either tactile (as in a Braille display) or kinesthetic (as in a force feedback display) information to a user.

Most displays for force feedback use motors and linkages to convey forces to a user's finger, hand or arm [4]. How the forces are computed can produce different effects. Surfaces can be modeled with different degrees of hardness, roughness, stickiness, etc. Viscosity and inertia can be modeled as well as attracting forces to provide guidance. Contact with a virtual surface is simulated by computing the appropriate force based on the current position of the end-effector. It is equally important that the device feels free and weightless when no force is applied [6].

Force Feedback displays

There are a number of different force feedback displays available today. Their performance varies from having a one-point 2D 2·2 cm² work area with small working forces, to 5-finger bi-manual use with full arm working area. The prices vary according to number of contact points, maximum forces and resolution. The table below describes a selection of different commercial force feedback devices.

Device	**Contact points**	**Degrees of freedom**	**Working area (relative to user)**	**Max force**
Wingman FF joystick	1	1	Hand movement (limited)	
Wingman FF mouse	1	2	Hand movement (2·2 cm²)	
PHANToM Premium 1.0 [2]	1	3 (+3)	Hand movement	8.5 N
PHANToM OMNI [2]	1	3 + 3	Hand movement	3.3 N
Force Dimension 3-DOF OMEGA [7]	1	3	Lower arm movement	12 N
PHANToM Premium 1.5 high-force [2]	1	3 (+3)	Lower arm movement	37.5 N
PHANToM Premium 3.0, 6 DOF [2]	1	6	Whole arm movement	22 N (translation)
Virtuose Haption [8]	1	6	Whole arm movement	35 N
CyberGrasp with CyberForce [3]	5	3	Whole arm movement	8.8 N

Table 3. A selection of force feedback haptic devices.

Among the devices mentioned, the following have been used in this research:

- Old T-model PHANToM 1.0
- A-model PHANToM Premium 1.0
- PHANToM OMNI
- Wingman FF mouse (only for user testing)
- Wingman FF joystick (only for user testing)

The PHANToM force feedback devices are mechanically built up using small step motors and wires for the force feedback. The user holds a pen or puts his index finger into a thimble.

PHANToM Premium 1.0

The PHANToM Premium is the base variant of the PHANToM devices, and provides force feedback in 3 degrees of freedom (translations in x, y and z). The 1.0 size is suitable for hand movement force feedback, with about 25·18·13 cm^3 maximum workspace with a nominal position resolution of 850 dpi and a maximum force of 8.5 N. An encoder gimbal that can measure rotational movements (pitch, roll and yaw) can be attached to the Premium when using the pen interface, and there is also a small switch on the pen. The mechanical parts are fully accessible and thus make service easy.

PHANToM Premium 1.0

PHANToM OMNI

The PHANToM OMNI is a low-cost device, with all moving parts encased in plastic cover, and a pen interface with 2 switch buttons. Its maximum work area is about 16·12·7 cm^3, with a nominal position resolution of 450 dpi and a maximum force of 3.3 N.

PHANToM OMNI

APIs for force feedback programming

The specialized nature of interfacing with force feedback displays has brought forward a number of APIs that make it possible to construct applications with objects that are possible to feel. Usually, the APIs are built up similarly to a virtual reality model, with a "scene" that within a tree-structure describes in detail what the environment consists of. A touchable model, whether it is static or dynamic, will need to be attached with properties that describe the physical, touchable behavior such as the hardness and smoothness of a surface or the weight of an object that can be picked up.

Examples of commercial or open source APIs that can be used to control the PHANToM:

- GHoST SDK
- Reachin API
- OpenHaptics
- H3D
- CHAI

The APIs that I have used in different projects are GHoST SDK and Reachin API.

GHoST SDK

The GHoST API is created and sold by Sensable Technologies (developer and manufacturer of the PHANToM). With the

GHoST API it is possible to create a haptic scene by programming in C++ by specifying geometries or haptic force effects. At the time (GHoST was used at Certec until 2001) there was no simple technique for adding a visual representation to the scene. To acquire a visual representation, the programmer had to use OpenGL programming.

Reachin workstation

Reachin API

The Reachin API is created by Reachin Technologies. The company Reachin focuses on the co-localization of haptic sensation and visual feedback, i.e. the user sees the virtual scene and his hand at the same location as the user feels the objects. The workstation that enables this can be seen in the figure in the margin.

Reachin API provides the programmer with a virtual scene graph that simultaneously creates the visual and haptic scene, which is practical in development work (if the programmer is sighted). The visual representation angle, however, does not need to be the same as the haptic representation angle, and the Reachin API can be used without the Reachin workstation with just a computer and a PHANToM.

Hearing virtual environments

The technology needed to enable a user to hear sound emerging from the computer is comprised of loudspeaker technology and sound programming APIs, resembling the framework for haptic technology. Sound reproduction from a computer, however, is more common for every computer user of today. But when sound made its entry into computer interfaces, it was limited to simple beeps that were supposed to capture the users' attention.

Audio interaction

Audio output in computer interfaces is commonly used to enhance visual output or to catch attention. Blind people commonly use screen readers along with synthetic speech to access text information. Research on auditory display investigates possible audio output techniques to provide understandable non-spoken audio information.

Auditory display

Auditory display is the term for all output sound used in human machine interfaces [9]. Auditory display can, for example, be the speech synthesis that reads the text to a blind person, the sound alert when you receive an email, or the heart beat sound that you get from the ECG machine at a hospital. Auditory display is sometimes separated into two parts – sonification of data and sonification of the interface. In certain cases, a direct translation from the data into the aural domain is called audification.

A mathematical graph can be sonified. The values of the y-axis are translated into pitch and the x-axis into time – just like a sound wave. The graph can then be heard as a compound object (see also the figure in the margin).

Auditory icons are everyday sounds in interfaces that have an iconic resemblance to the object or action that they represent [10]. A crumbling paper sound when emptying the waste basket is an example.

Earcons are synthesized (musical), non-figurative auditory cues used to display interface components or events. These can be created automatically [11].

Speech can be either recorded natural speech or synthetic speech. Synthetic speech is commonly used by blind people to access written text.

The preference of the use of sound interfaces varies with the application and the individual user. Some users find an interface with too much speech annoying; others find it hard to memorize non-speech sounds and would rather have them in spoken form. Additionally, some interfaces could function better without sound, e.g. when the applications is used to produce or edit sound – this was in fact one of the reasons why the *Moose* (a 2D haptic interface) was invented [12].

3D sound interaction

The human ear is too unreliable to use for exact localization of sound sources, and localizing simulated 3D sound is even less exact [13]. However, in modern game technology, 3D sound is used to enhance the user's perception of what he or she sees on the screen, and also to indicate that someone or something is approaching from behind.

Example – a sound based computer game

A non-visual computer game can serve as an illustrating example of an interface that utilizes many techniques for sonification. A project at The Swedish Library of Talking Books and Braille was aimed at developing sound games for blind children and has been reported in [14-16]. There are also many sound games both for children and adults available at http://www.audiogames.net/.

The game that serves as an example here is *The Secret of Akatella* (a Swedish, off-the-shelf non-visual computer game). The player (this is a one-player game) finds herself on an abandoned space station and is supposed to unravel the secret of the space station and find out why it was abandoned.

The game audio output used is a combination of:

- Spoken audio
- 3D sound to locate places or hit targets (for shooting)
- Moving sound to illustrate the user's own movement in the virtual world – footsteps
- Interaction sounds – to indicate, for instance, that input is needed from the user

The game is both challenging and interesting but every bit of information is presented in audio – which limits the information that can be displayed to the user simultaneously. Much of the story is presented with the spoken audio. There is no way to skip audio information in this particular game.

Sound cards and speakers

The hardware for sound reproduction can be seen as the sound card and the loudspeakers or headphones that are attached to it. A modern sound card enables reproduction of sound in different output modes. In the research presented here, these are the output modes:

- Stereo (2 speakers)
- 4-speaker surround sound
- Normal headphones
- Surround headphones

To simulate 3D sound – the localization of sound sources at different positions in a virtual room – the computer sound card needs a special transfer function, an HRTF (Head Related Transfer Function). An HRTF can be said to be a model of a person's torso and head and depending on the virtual angle between a sound and a user, the sound is filtered to resemble the characteristics of a real sound coming from that angle.

APIs for sound programming

Sound programming APIs and frameworks are continuously being developed to make it possible to reproduce sound with many different characteristics, e.g. to play classical music with just the right reverb or to hear the evil foe at your back when playing a computer game.

A sound framework or API provides a set of functions that makes it reasonably easy to play back sound files, MIDI and simple tones and to send them to the sound card to be reproduced in mono, stereo or multi-speaker mode. Sound APIs can also make it possible to place sound sources in 3D virtual environments, to model obstruction and occlusion (sound filtering when objects are placed between the virtual listener and the virtual sound source). There are, in addition, packages to set reverb to the sound. The sound frameworks and APIs that I have come in contact with in my studies are:

- OpenAL via Reachin API
- DirectSound & DirectSound3D (Microsoft DirectX)
- FMod Ex

In contrast to haptic APIs, sound APIs are often low-cost, or free – at least when using them in research.

OpenAL

The Reachin API sound is built on the OpenAL [17] framework. When making combinations of haptics and sound this is a very handy approach, since haptic objects easily can be attached with a sound source. In 2002 and 2003, the sound functions were immature, and the sound coordinate system was not consistent with the haptic coordinate system.

DirectSound & DirectSound3D

DirectSound (and DirectSound3D) are parts of the DirectX multimedia APIs that are built into Windows [18]. DirectSound plays wav files and incorporates the possibility to place sound sources in 3D and to add reverb.

FMod Ex

FMod Ex [19] is a high-level sound API that enables a programmer to play different sound files, placing them in 3D, adding reverb, model obstruction and occlusion, and more. It is available for many different operating systems and platforms. It also has functionality to create oscillating tones with different characteristics that can be adjusted in real-time.

Combining haptics and audio

With the slow maturity of haptic technology, and the recently increased interest in multimodal interfaces, there is more and more research and development aimed at combining visual, haptic and auditory display. Since 2002 there has been a conference on Haptic Audio Virtual Environments, which includes visual display in most contributions. Unfortunately, much of the work is of little or no interest when it comes to research on purely non-visual haptic audio display, since most of the work presented includes the visual modality.

Some of the haptic-audio applications attempt to make realistic object collision haptic-sound renderings [20;21], mainly focused on low-level algorithms that reproduce the sound and haptics realistically and without too much latency (time difference between haptic and audio sensation).

Blind users are the target population in applications that combine the use of audio and digitizer tablet, reported in [22;23]. These applications are sometimes referred to as audio-haptic but do not incorporate force feedback.

Applications making practical use of non-spoken audio and force-feedback haptics are, for example, those supporting mathematical display [24-28], games [29-31] non-visual image representation [32] and an audio-haptic interface [33]. Other applications for blind users are virtual environments in the form of maps combining spoken audio (synthetic or natural), non-spoken audio in 3D and haptics [29;34;35].

Usability issues

Research persons (or users) that are involved in usability evaluation influence the design of audio-haptic interfaces and environments. Therefore, it is important to consider how users can best contribute to the design process, without wearing out important user groups, such as people with blindness.

The research persons

When testing applications for people that are blind, the pool from which to draw research persons for evaluation is limited. It is therefore common to test the applications using blindfolded, sighted users. However, the potential impact of the mature audio-haptic technology and possible advantages for visually impaired users differ so much from sighted users' that we prefer to use blind research persons whenever possible. They will have different reflections on the possible use of the technology. Blindfolded sighted users can be valuable to evaluate prototypes in the first stages of the development cycle, but when the prototypes are more stable, the end users should be the key persons.

Facing issues of device learnability

When faced with haptic interaction for the first time, it is by no means obvious whether the test evaluates the usability of the device, or the usability of the application.

A common technique to overcome problems with testing applications for novel devices is to let the research persons have a short training session first. It can be a simpler form of the actual test task and it improves the efficiency in the later haptic interaction [36]. Often, the training session is limited in time, giving the research person only a short time to familiarize him or herself with the device. In fact there is a certain "learning threshold" that the research person must reach to begin using the device in any productive way. This threshold differs quite a lot between users.

Usability in a more relevant long-term perspective requires other kinds of tests or trained expert users.

Trained expert users

Since there is a limited number of a blind research person to contact, some of the evaluating participants in the projects described here are the same. As a side effect, these persons have learned to use the PHANToM quite well, and thus need little or no training to test new applications. This is an advantage that both saves time for the research person and for the researcher.

It can be argued that we also face the risk of having research persons who are too familiar with the technical and interface solutions, which bear some similarity to one another since they may be programmed by the same researcher. The expert user can also be too tuned into how the programmer thinks to be as good an evaluator as a new research person [37].

Our goal, however, is to try to foresee what audio-haptic technology can yield in the long run when used by people that may benefit from it. Therefore it is an obvious advantage to be able to use blind expert users in evaluation work. It is similar to the apparent advantage for all of us with new Windows applications that look more or less like every other Windows application.

It may even be so that to fully capture the benefits of haptic devices for blind computer users, long-term use is needed, as is also the case with Braille reading.

Applications & user tests

Application Programming Interfaces (APIs) have gradually improved from 1997 to 2006. I have attempted to balance between keeping in touch with new APIs and using simpler ones that are stable and familiar. The applications I have been involved in are developed with different APIs both for haptics and sound.

Application	**Haptic API**	**Sound API**	**Years**
8QB	GHoST	-	2000
Memory	GHoST	Windows	1998-2001
Training session	GHoST	Windows	2001
Geometry test	GHoST	-	2001
Traffic pre-study I	Reachin	Reachin / OpenAL	2002
Traffic pre-study II	Reachin	DirectSound	2003
Traffic app.	Reachin	DirectSound	2003
Line drawing app.	Reachin	FMod	2005-2006

Table 4. Applications developed and APIs used.

The applications have been under evaluation by either sighted users or users who are blind or have low vision, see Table 5.

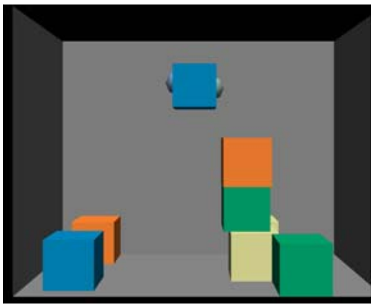
Application	**Sighted users**	**Blind/visually impaired users**
8QB	28	
Memory		23
Training session		23
Geometry test		23
Traffic pre-study	4	
Traffic application		10
Line drawing application		3-5

Table 5. User trials

What follows is a presentation of the parts that I have done the major work on. They are presented in consecutive order.

Haptic collaborative environment with haptic avatars

The application enables two individuals placed in different locations to simultaneously feel and manipulate dynamic objects



Screen dump of the collaborative environment

in a shared desktop virtual environment. The environment consists of 8 cubes that can be moved in space: pushed and lifted and placed on top of each other. The users can lift the cubes in collaboration by placing their PHANToM pens on opposite sides and lifting upwards together.

The user's avatars are 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 an object (i.e. the cubes and walls) from that of another person in the environment, a slight vibration was added to the avatars. Furthermore, the users can hold on to each other by pressing the PHANToM switch – a feature originally implemented to enable the users to virtually "shake hands." 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 application was run on a single host computer, with two PHANToM devices and two screens attached to it. Thus, the two users always had exactly the same view of the environment.

This work was done in collaboration with Eva-Lotta Sallnäs at KTH, Stockholm, who performed a presence study on the application, and also came up with the idea. Together with Calle Sjöström, I did the implementation of the virtual environment, and I also served as test leader in some user test sessions.

The work has also been presented in the article: *Supporting Presence in a Collaborative Multimodal Environments by Haptic Force Feedback* [38].

The Step-by-step training session

For a large-scale feasibility test for the ENORASI EU project in 2001 the *step-by-step training session* was created. This technique has not been reported before, although it has been mentioned in the articles: *Phantom-based haptic line graphics for blind persons* [25] and *Navigation and recognition in complex haptic virtual environments – reports from an extensive study with blind users* [30].

The idea for this approach has its roots in the extensive experience that the author and others at Certec have in demonstrating and letting end users try out haptic devices (primarily the PHANToM). If the research person has problems solving test tasks, it may be impossible to discern whether the problem originates in the handling of the device as such or whether the problem is to solve the test task. Therefore, the training-session in the ENORASI project feasibility test was carefully considered and planned. The research persons were allowed to spend as much time as they needed with the pre-test tasks.

The individual steps for the training session are based on a stepwise introduction to more and more complex virtual environments. The training session consisted of 3 parts: simple static environments, dynamic environments and complex environments.

Static environments

The limiting box (a haptic room metaphor) was used to restrict the user to the optimal working space for the PHANToM and to prevent them from penetrating the maximum workspace of the PHANToM arm. The limiting box walls, floor and ceiling should also provide the user with a non-changing reference.

The objects placed in the virtual room were moved stepwise:

1. A cube adjacent to a wall on the floor
2. A half sphere in the middle of the floor
3. A cube in free space

Only haptic feedback was used during the tasks, but the user was also provided with a short verbal description of the layout of the virtual environment.

Dynamic environments

The following three environments consisted of dynamic objects that were placed in different positions, designed to help the user exercise haptic scanning and to be able to manipulate dynamic objects such as buttons, sliders and a moving object. The virtual environments were designed with a stepwise increase in complexity and consisted of:

4. A single cylindrically shaped button attached to a wall
5. A cube that could be slid around on the floor
6. 2 sliders and 2 buttons with different shapes attached to a wall

Four and 6 (but not 5) had audio feedback when buttons and/or sliders were manipulated.

Complex environments

The last part of the training session was to introduce the users to tasks similar to those that were to be solved in the real test session.

7. Floor plan with audio description of rooms
8. VRML model of a guitar

A detailed description of the applications and tests can be found in Appendix I.

Participating research persons

The research persons that participated in the feasibility study were 11 blind users from Sweden and 12 blind users from Italy, see Table 6.

Age	Gender	Age at onset of blindness	Occupation
37	F	0	Telephone operator
55	M	0	Consultant
24	M	0	Student
50	F	22	Telephone operator
27	M	0	Student
73	M	55	Professor – retired
63	F	0	Teacher
25	F	0	Student
48	F	4	Telephone operator
47	M	2	Telephone operator
19	M	0	Student
85	F	64	Librarian – retired
52	M	23	Student
45	M	25	Educational consultant
52	F	5	Telephone operator
43	M	0	
12	F	0	Student
34	M	23	Computer technician
12	M	0	Student
15	F	6	Student
22	M	0	Student
22	M	0	Student
28	M	2	Student

Table 6. Participating research persons in feasibility test by age, gender, onset of blindness and occupation. A "0" for "age of onset of blindness" means blind from birth.

Recognition of geometric objects

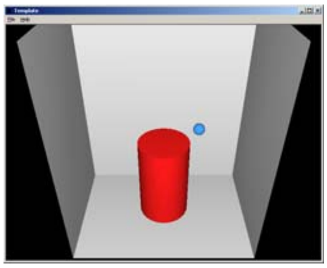
In the feasibility test mentioned above, haptic object recognition was also investigated. The recognition of standard geometrical shapes was tested along with recognition of more complex objects, such as 3D VRML models of a grand piano and a satellite, and 2D relief drawings. There were 2 parts of the test: one was to recognize a single shape, and the other was to recognize 3 shapes and to correctly build a copy with real building blocks. This has also been presented in the article: *Navigation and recognition in complex haptic virtual environments – reports from an extensive study with blind users* [30].

Recognizing single shapes

For this, a number of applications containing static geometrical shapes were implemented:

- Cylinder, diameter 3 cm, height 6 cm
- Box, 3·3·6 cm^3
- Box, 1.5·3·6 cm^3
- Box, 1.5·3·9 cm^3
- Cube, 3·3·3 cm^3
- Sphere, diameter 4 cm
- Half cube (roof shape), 3cm·4cm with 2 cm height
- Half cylinder, diameter 3 cm, height 3 cm

The task was to match the geometrical object to real children's building blocks. The user was supposed to choose the real block which resembled the virtual one the most.

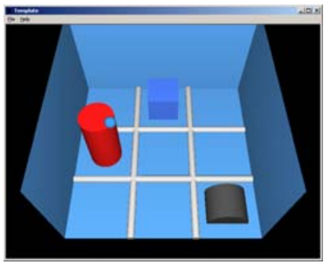


Virtual geometrical shape

Real shapes to compare with

Interpreting a virtual scene with 3 geometrical objects

A virtual environment with 3 geometrical shapes in a grid was constructed. The task was for the user to build a copy using children's building blocks and a box with a grid. All research persons were presented with the exact same virtual environment.

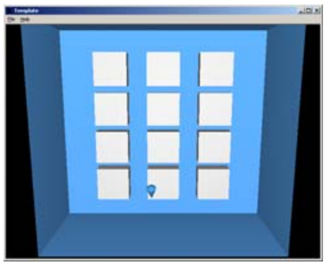


Geometrical objects in a grid

Real shapes to build a copy with

Audio-haptic memory game

Task completion times for solving an audio-haptic memory game were also measured in the feasibility test mentioned above, and reported in [25;30]. Audio-haptic memory games have previously been investigated by Calle Sjöström [39], but not in such a large-scale test. The functionality of the memory game is as follows: 6 or 12 haptic buttons are placed on the far wall of a virtual room. When a button is pressed, its corresponding sound is played. Every button has a pair button with the same sound attached to it. When pressed in direct succession, it is considered to be a match and both buttons are erased from the wall. When all buttons are gone, the game is finished. The research persons started by playing the 6-button variant, and then played the 12-button variant. The completion times were automatically logged, as well as the number of button pushes.



12-button audio-haptic memory game

A virtual haptic-audio traffic environment

The virtual environment in the study is a model of a real traffic environment in Lund, Sweden, and includes 484 static objects and 35 dynamic objects (cars and bicycles). All objects are attached with spoken caption sounds and cars and pedestrian crossings are attached with sound sources, which give the user a sound experience in 3D. Before the final application, reported in [34], a couple of minor studies were conducted that have not been reported previously.

Programming of sound software interface

The traffic environment application is coded with the Reachin API. This enables the import of VRML models to facilitate the building of the whole environment. As described above, the Reachin API includes a sound module, which is based on Open AL. During the initial investigations on how to attach sounds to haptic objects and to move the virtual listener position, it turned out that the coordinate systems were not compatible, and that it was impossible to change OpenAL parameters through Reachin. Therefore, the Reachin API was used only for haptics, and the DirectSound API was used for sound.

To simplify the sound handling, a wrapper class was written with the needed functions to place sound sources and to play them. Additionally, a wav file reading and buffer handling wrapper class that was originally written by Björn Breidegard[1] was adapted to the application.

User pre-study: 3D sound – speaker placement

The final application was supposed to render 3D sound information informative to the user. The idea was that the user should be able to hear a car approaching, and to hear the position of a pedestrian crossing with a tick signal in the virtual environment. Therefore, a small study on sound localization was conducted. In order to investigate the functionality of the Reachin API in combination with the sound wrapper class, a virtual world was realized with a sound source that changed its position by keyboard commands. The test was conducted with 2 different sounds: a pink noise and a pedestrian crossing tick signal sample.

Four (4) speakers attached to the sound card were set up around the user chair, and the chair was placed in the "sweet spot" where sound reproduction is most favorable. The chair was an ergonomic stool without back- or headrest to interfere with the sound. The test task was to point out the apparent direction of a sound when it was played. The sound was placed in 8 random positions in at least 10 iterations. Four sighted users participated in this test.

[1] bjorn.breidegard@certec.lth.se

User pre-study: Virtual ear orientation

In addition to the sound localization study, an orientation study was conducted with the same users. To be able to place oneself (the avatar) in a virtual environment, the user moved the virtual listener object by moving the PHANToM pen, with the avatar nose pointing in the direction of the PHANToM pen tip. When the user had chosen a spot to place the listener, the user pressed a key on the keyboard. This made it possible to place the listener/avatar freely in a virtual environment, and to rotate the avatar "head" (and thus ears) freely. The sound was reproduced once again with 4 speakers, and the user was not allowed to see the screen.

The user was presented with a series of tasks on localization and placement of the avatar in a virtual environment with a car model, and a road with a sidewalk. To begin with, the user could investigate the model with the PHANToM. Then, a sound source placed in the center of the car was started, and also a moving animation of the car. The sound followed the car path and when the car reached the end of the road the animation started from the beginning again (looped). The user was asked about the apparent trajectory of the car based on the sound feedback, and also the apparent distance to the car. Then, the user was asked to move the virtual listener position (the avatar) with the PHANToM pen, and listen to the car sound from the new position. As a last task, the user was asked to move the avatar so that it was placed with its back to the road and to listen to the car sound from that position. The users were asked to "think aloud" during the whole test. In some cases, users drew sketches to illustrate how they perceived the sound trajectories.

Final user study: Exploring and learning a route

Ten severely visually impaired users tried out the virtual haptic-audio traffic environment for exploring and learning a route in the final evaluation of the application. The test was divided into three subtasks. First, the user was asked to explore the environment in order to find a number of hidden treasures. That task was intended to familiarize the user with the environment. Next, the user was asked to explore and describe a suitable route in the virtual environment from a given start point to a given end point. Last, the user was driven to the real traffic environment and was asked to walk the path that he or she had explored in the virtual environment. Charlotte Magnusson conducted this user study.

Sonification of a haptic line-drawing application

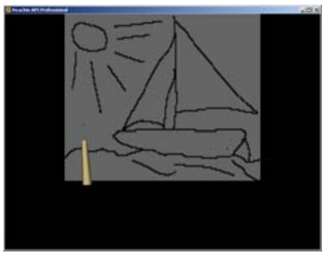
From the very beginning of Certec's work on the PHANToM for blind children, making drawing and painting applications for non-visual use have been a focused interest. When planning for the MICOLE project, we wanted to find an application that was "multi-purpose", i.e. one that blind pupils could use in different school subjects rather than developing a tailor-made application for a specific subject. This development is an ongoing process in various stages of prototyping, but the initial application was a relief line-drawing program with sound enhancement that was able to import ready-made graphics.

The work is also presented in the article: *User evaluations of a virtual haptic-audio line drawing prototype* [40].

Hardware and software

In the MICOLE project, the main technology focus is making use of the PHANToM haptic device together with Reachin software. Therefore, the application is written with the Reachin programming API for the haptics. However, when starting the project, the sound module for the API did not incorporate the needed sound rendering features, and thus, the FMod programming API has been used for the sound. Reachin API is a high-cost commercially available API while FMod is free for research purposes.

Description of prototype application



Screen dump of a drawing application with positive relief.

This prototype is an application for making black & white drawings and tries to incorporate improvements suggested by the work in [41]. The application consists of a room with a virtual paper sheet, which a user can draw a relief on. When the PHANToM pen touches the virtual paper the user can draw on it while pressing the PHANToM switch. The haptic image is produced as a positive or negative relief depending on which alternative is selected. The relief height (depth) is 4 mm. The drawing can be seen on the screen as a grayscale image – a positive relief is seen as black and a negative relief is seen as white. The paper color is gray.

When the user draws, the haptically touchable relief is updated every time the user releases the switch on the pen. There is (as of April 2006) a problem in letting the user feel the exact line that is drawn, since this causes instability in the PHANToM. However, the user can feel the previously drawn lines while adding new parts to the image.

A png file ("portable network graphics", a lossless compressed file type for graphics [42]) import function has been included. The files imported must be grayscale and a multiple of 256·256 pixels. A complete grayscale is actually translated into different relief heights, which makes it possible to import any grayscale image and get some haptic information from it. Images not adapted to haptic/tactile reading for blind users are very hard to understand. However, the grayscale can be used to smooth out relief lines, for example. Non-speech sound information is provided to the user about:

- PHANToM pen position
- Application mode
    - Draw mode (in touch with paper, PHANToM switch pressed)
    - Feel mode (in touch with painting)
    - Free space mode (not in touch with painting)
- Contact with limiting box

For the positioning, a pitch and pan analogy is used. When the PHANToM pen moves up and down the pitch of a position, tone changes, brighter upwards, and mellower downwards. When the PHANToM pen moves from left to right the stereo balance changes accordingly. The mode information is conveyed by the volume and timbre of the tone. In free space, a pure sine wave is used. When the user is in contact with the virtual drawing paper (when not pressing the PHANToM switch) the volume is louder. And when the user is drawing (and thus pressing the PHANToM switch) the tone is changed to a saw-tooth wave.

The walls of the limiting box produce contact sounds when touched.

User evaluations

The gradually emerging application prototypes were first tested informally during the summer and fall of 2005 by a reference group that is participating in the MICOLE project. The design work was iterative and the users were presented with new features and changes in the prototype at every meeting. The first two evaluations were of an informal nature, with few and loosely formulated test tasks. An open discussion took place in which children and their parents or other close relations and the researchers discussed topics triggered by the prototypes tested.

The third pilot evaluation with the reference group incorporated some formal test tasks. An evaluation with formal tasks with sighted participants was also conducted.

Research persons

A reference group of visually impaired children have tested all prototype versions, although not all children have tested all versions. The reference group consists of five (5) children, aged 10 to 16. Two (2) of the participants are blind from birth, and three (3) participants have various forms of low vision. All of them read Braille and are integrated in normal schools in southern Sweden.

The 11 sighted research persons that participated in the formal study were adults (aged 25 – 72).

Prototype design issues and user tests

Since the application has been gradually developed, hypotheses and design questions have changed during the process, and each prototype version has been evaluated. The basic navigation and interaction issues that have been investigated are:

- Optimization of the work area with respect to:
    - Ergonomics
    - Sound feedback mapping
    - Virtual paper size and shape
    - Size of limiting box
- Design of relief
    - Depth
    - Positive versus negative
    - Smoothness
- Placement of user input interaction controls
    - Virtual buttons
    - Keyboard buttons
    - Other input
- Design of position and mode feedback sound
- Recognition and reproduction of figures (geometric, curve drawings, road signs) for different use cases:
    - Negative vs. positive relief
    - Presence and absence of sound field

Results

The applications and user trials with evaluations have led to diverse result clusters. The step-by-step training session is in itself a result, since it is based on usability problems that are observed for first-time users of virtual haptic environments. Both design considerations and some user test results from the training sessions are reported here.

Results concerning the use of haptic-only virtual environments are presented, as well as results concerning haptic-audio environments. A separate section on haptic avatars and the ears-in-hand metaphor completes the results section.

The Step-by-step training session

The training session had a duration of about half an hour for some users, and for others it could be as long as 1.5 hours. The goal was to bring users to a more "equal level" before beginning the formal evaluation study.

The static environments in the step-by-step training session were designed to help the users gradually learn to expand their haptic search space, and to learn to find objects placed in different positions. All 25 users were able to handle these environments. One noteworthy (but occasional) comment was about the problem of distinguishing the object from the limiting box – especially for the first task where a cube was in contact with the wall and floor.

The dynamic environments in the step-by-step training session were designed to help the user exercise haptic scanning and to be able to manipulate dynamic objects. The virtual environments were designed with a stepwise increase in complexity. All 25 users were able to handle these environments. Three out of 7 users (observation notes were made for only some of the users) were reported to have some trouble with the cube that could be pushed around on the floor.

The haptic floor plan with audio information in the step-by-step training session was designed to introduce the user to 2D maps and to the technique of pressing the floor in a room to get audio feedback. All 25 users were able to handle this environment, although there were users that got lost when they went outside of the floor plan since the outside lacked audio information.

The VRML model of a guitar in the step-by-step training session was an introduction to recognition tasks. All users were able to feel and recognize the object as a guitar or a violin, which shows that the overall shape was understood. However, the narrow neck caused trouble for some users. One out of 7 users had documented problems with the lack of a limiting box around the object, and ran into the physical boundaries of the PHANToM workspace, which led to an assumption that there was an object at the limit. In similar cases, the lack of a limiting box has also led other research persons to believe that there was an object at the maximum reach of the PHANToM arm.

Understanding haptic environments without audio guidance

Our studies have shown that blind users can handle quite complex virtual haptic-only environments, especially when these are models of real objects. But sometimes, the haptic perception is disturbed by the lack of haptic experience, pre-conceptions or a heavy reliance on other senses such as vision.

Possibility: Handling realistic environments

The results from the large-scale study within the ENORASI project (reported in the paper *Navigation and recognition in complex haptic virtual environments – reports from an extensive study with blind users*) show that detailed single-object models can be handled and used for feeling shapes and referencing to details. A model with 3 abstract geometrical shapes placed in a grid turned out to be more difficult to handle, although it was comprised of fewer surfaces. This shows that virtual environments with realistic models in some cases appear easier to understand than abstract environments with geometrical shapes. This result highlights the importance of context, and thus the need to provide information in addition to the purely haptic, e.g. audio. Another factor observed to be important is haptic scanning strategy. Although users had undergone the step-by-step training session where a scanning strategy was practiced, they failed to scan efficiently and missed parts of the environment, particularly under time pressure.

Further, all except one of the research persons that participated in the test completed the audio haptic memory game with 12 buttons that also was tested during the study, and all completed the memory game with 6 buttons.

Problem: Illusion falls apart

This problem is most apparent for sighted users; however, it has also been found in some blind users. In the early days of virtual haptic technology, there was no screen image to display the virtual model. Therefore, the user had to feel the virtual model without any help of visual feedback. When users were told to close their eyes, the haptic virtual model became more apparent, but it disappeared as soon as the user opened his/her eyes again. After some training, users could still keep the illusion even though there was nothing to see where the objects could be felt.

A similar problem was encountered once among all blind research persons. This person relied very much on using both hands to feel objects, and kept stretching out the non-dominant hand to confirm the sensation in the dominant hand. And when the person felt nothing with the other hand, the user's perception of the virtual environment was disturbed. It actually seemed as if the user stopped believing in the haptic sensations of the dominant hand when the other hand experienced nothing.

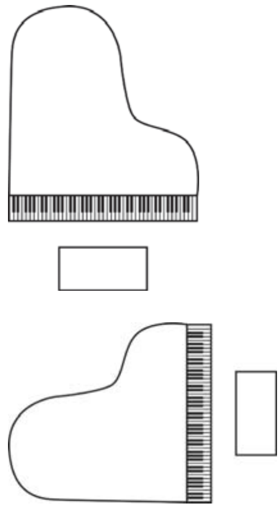
Problem: Visual perception takes over

A problem that is very closely related to the above (illusion falling apart), is that when confronted with a system that displays 2D visual feedback and 3D haptic feedback, the user will let visual input take over. In fully sighted users this has been seen to limit the haptic scanning strategy to 2D. The same problem is not as apparent when using a co-located 3D haptic and 3D visual system (such as the Reachin display).

Moreover, this focus on the visual input has also been seen to limit the user's hand movements, and as negatively affecting the scanning strategy as a whole, since the user looks closely at the screen, and expects to feel something, and then does not. This has been observed both in users with residual vision and fully sighted users.

Problem: User's preconception disturbs the understanding

A user's preconception can hinder the user from experiencing and understanding a haptic model. One problem occurred for a user when navigating a VRML model. The user was informed that the model represented a grand piano and a stool and was asked to point at the different parts of the grand piano (keyboard, lid, etc.). This particular user had imagined the representation being oriented with the keyboard towards the user (see figure to the right), and since it was oriented the other way, the user had great trouble finding the parts. When the user understood, the user said: "Oh, it's oriented that way, now I understand." Then, the user also correctly pointed out the different parts.



The user imagined the grand piano oriented like the figure on the top when in fact it was oriented like the figure to the bottom.

Understanding audio-haptic virtual environments

Using a combination of audio-haptic feedback improves understanding of and interaction with non-visual virtual environments. Perhaps, for some users, the addition of audio to a haptic environment will make the difference between not understanding at all and understanding.

3D sound – speaker placement and choice

The pre-study to the traffic project on speaker placement showed that a multi-speaker approach is much too sensitive to the exact speaker placement and to the room dimensions and reverb. None of the 4 users that participated in the pre-study correctly placed all of the sound sources. The mean success rate for the 4 persons was 52% for the pink noise sound and 69% for the tick signal sample sound. The most common errors were that the users thought that the sound came from one of the positions nearest the correct position, or that sounds were correctly placed left or right, but switched front and back. Moving sounds were generally thought to travel a curved trajectory when they in fact were following a straight line from left to right.

This resulted in headphones being used in the later study with the completed traffic environment. The drawback is that the user loses the advantage of being able to move his/her head freely to aid localization.

Complex audio-haptic traffic environment

Eight of the ten users were able to handle the virtual audio-haptic traffic environment, and the same users also succeeded in navigating the real traffic section from which the virtual environment was modeled. The users navigating the virtual world most easily were those that also were very good at navigating with a mobility cane.

Two different approaches to exploring the virtual environment were identified. Some users requested (by clicking the PHANToM switch button) sound information more or less continuously and did comparatively little haptic exploration in between requests, while others explored haptically for longer periods and clicked for sound information less often.

Audio-haptic drawing program

The reference group test users were able to use the application as intended. Task result differences seem to match personal differences in fine motor skills and the ability to remember images. Two of the 3 users could draw a square and a number, two could recognize the Arabic numbers and all three could recognize simple geometric shapes.

Users were helped by the difference in sound character to know which program mode they were in. This helped especially one user who previously had had considerable problems releasing the switch to feel the painting. The sounds did not disturb the users very much, although one musically trained user found them somewhat irritating. That same user also indicated the similarity of the sound to the aiming sound used for non-visual target shooting. Another reference group user expressed great enjoyment with the sound and spent much time playing with it.

Ten of 11 sighted users in the formal test were able to complete it, although a few test tasks had to be cancelled due to time restraints. In general, the geometry recognition tasks were found to be the easiest and the examination times were shorter than the time to examine curves and road signs. There are also indications that negative relief is to be preferred over positive relief, both subjectively and by time measure.

In the curve recognition and reproduction tasks, there appears to be no major difference between results concerning positive or negative relief, nor concerning subjective measures nor time measures.

Eight of the 10 test users reproduced (i.e. drew with the drawing program) more than half of the curve figures reasonably correctly. The most common type of major error was that part of the figure was missing. This occurred particularly when the figure contained separate parts or when there was an intersection inside the figure. This occurred in the case of a single line when the figure contained sharp directional changes. The drawings illustrate the need for better feedback during drawing, since minor mistakes with regards to exact/relative positions and shapes were quite common – most users drew the figures from memory (as if drawing in the air) and would easily lose their orientation within the virtual environment.

The road sign recognition test was considered difficult: the mean rating was 4 on the 1 to 5-difficulty scale. However, despite the obvious problems the users had in examining and reproducing most of the signs (which was done with pencil and paper), they still pointed out the correct road sign on average 3 out of 4 times when presented with a chart of 24 different road signs.

None of the three subtasks shows any significant difference concerning examination times or subjective difficulty rating between the cases with present or absent sound field. Two users had suggestions for improving the sound feedback design. One suggested that the sound feedback should convey information about the placement of the center of the paper rather than the height of the PHANToM pen. Another user suggested that the sound information adjusted with a larger pitch range and better stereo effect might give information about the size of objects or relative shape of similar objects (like a sphere and an ellipse, for example).

The haptic avatar and the ears-in-hand metaphor

Results concerning the avatar design in the application for collaborative work have not been reported previously. All test users that underwent the test in the haptic variant (half of the users) used the holding function to shake hands and to lead each other along a route. In a pre-test, when the avatar function was being designed, a user commented that the vibration as well as the possibility to hold on to another avatar was almost too intimate, but in the final test, users appeared not to be bothered

The pre-study on the avatar placement in a virtual traffic environment demonstrated that it was indeed possible to use the PHANToM pen to place the avatar and thus the virtual ears freely in a virtual environment. However, it appeared to be too complex a task to place the head exactly with the pen. Moving (translating) the head in x-y-z with fixed gaze forward in the virtual world was intuitive, as was the rotation of the head around the neck. Tilting the head up and down did not seem to be important, and tilting the head sideways by rotating the PHANToM pen was too complex. Initially, this presented considerable problems for the users until the test leader presented a strategy to handle it.

In the traffic environment study [34] with a large number of static and dynamic objects, the results of the pre-test were utilized so that the gaze of the avatar was fixed in a front-facing position, regardless of the rotation of the PHANToM pen. This technique was later labeled as “ears-in-hand” [31]. At the time of the traffic environment study it was not possible to let the user hear the changing sound in real-time while moving the PHANToM pen. The user was forced to move his/her ears stepwise by pressing the PHANToM switch. Later, with faster computers and smaller models in the 3D-sound tests described in [31], the user could hear the sound in real-time.

Discussion

When a user cannot use the visual sense, it seems natural to use the remaining modalities to present information in as great detail as possible. Users are different, and their preferences vary. Some prefer to use Braille displays for text reading; others would rather use speech synthesis. Some like spoken information in interfaces, while others prefer non-spoken audio messages.

Keeping in mind that access to virtual environments and computer interfaces needs to be flexible and adaptable to personal preferences, the findings on enabling audio-haptics are discussed in the next section under two headings: 3D audio-haptics and 2 audio-haptics.

3D audio-haptics

When generation of audio-haptic 3D models of the real world (such as the traffic model) can be performed in a more efficient manner, user responses in interviews show that there is a demand for these kinds of environments. There is also a wish for more schematic, map-like environments. Such environments have already been suggested by different authors [30;43].

Users who appear particularly good at navigating with a mobility cane are fast and accurate in exploring and navigating virtual audio-haptic environments. This becomes interesting if it can also work the other way around, i.e., if practicing in an audio-haptic virtual world improves navigational skills in the real world. A haptic device like the PHANToM is not exactly like a mobility cane, but strategies as well as the ability to create a mental model of an environment using limited sensory input can be compared and possibly improved through training in virtual environments. Adding simulations of contact sounds could further enhance the similarities of the mobility cane and the audio-haptic display.

Different users seem to utilize the sensory modalities differently. As seen in the traffic study, some users appear to rely mainly on the audio feedback, and request sound information very often. Such users may benefit from a continuous change of the position of the avatars ears in the environment as the haptic device position changes (i.e. ears-in-hand). Other users employ haptic exploration more often, and use the sound labels more as confirmation. For such a user, it may actually be beneficial to be able to put the avatar in a specific position and then to explore haptically around that position, which was also stated by one of the users in the traffic environment test. Thus, it is important to consider both users relying primarily on sound and those relying primarily on haptics when designing audio-haptic virtual environments. Individual preferences concerning the use of spoken audio vs. non-spoken audio should also be observed.

Simulated 3D sound has some limitations, and the use of regular headphones for reproduction makes it impossible for a user to use slight head movements to aid sound source localization. A possible way to overcome this problem technically is to attach a head tracker on top of the user's head and let the information from the tracker affect the 3D sound field in the virtual environment. Another idea is to let the user move his/her head and ears with the haptic display (like in the pre-study to the traffic project).

2D audio-haptics

The need and practical use for a non-visual computerized drawing program has been questioned. However, Kamel[44], Kennedy [45] and others [46] give sufficient support to the thought that some blind people are interested in drawing. As is also the case for sighted users without much drawing skill, a drawing application can enable blind users to produce neat drawings by providing helpful tools for making curves, rectangles and circles, for instance. In school, such an application could also be used to produce figures for mathematic education (e.g. geometry).

The background idea for the sound feedback was that the pitch and pan changes perhaps would enhance the perception of location of the pen (and hand). The implementation of the sound information in the drawing application implemented seemed not to affect the examination times and recognition accuracy, and therefore not add to the usability. In the case of recognition (although the results are not strictly comparable), Pakkanen and Raisamo [47] have previously shown that exact recognition of geometrical objects using a combination of vibro-tactile feedback and audio is hard to achieve.

Some users expressed annoyance with the sound, whereas others enjoyed it despite its artificial quality. One user suggested that the sound feedback should convey information about the placement of the center of the paper rather than the height of the PHANToM pen. Another user suggested that the sound information adjusted with a larger pitch range and better stereo effect might give information about the size of objects or relative shape of similar objects (like a sphere and an ellipse for example).

On two occasions, the absence of sound field feedback did have an impact on a single user's results. Due to technical problems, the contact sound with the walls stopped working after a while, which affected the examination times in the test cases without sound field feedback, since the user mistook the edges along the limiting walls for lines. With the sound field feedback present, the limiting wall contact sound was not as crucial.

The apparent failure of the audio feedback strategy may depend on the user test tasks chosen, the pitch and pan range or unaccustomed users. As also stated above, pitch is indeed a common way to sonify a graph [9], for example, and has been shown to be useful. Perhaps users need more practice interpreting sonified data, by a structured training session similar to the step-by-step training session for haptic environment use.

It may also be interesting to try an approach where the height information is coded in a combination of pitch and timbre, and where the left-right position information could be enhanced by adding reverb (as in [48]), or by making a two-tone sonification (one for height and one for left-right).

Conclusions

What about possible future benefits of audio-haptic interfaces and environments for blind users? People who are blind already have a lot of specialized equipment to handle, e.g. magnifying equipment, talking calculators, Braille books, speech synthesis, etc. Can audio-haptic computer access add sufficient benefits to be worth the bother?

Only a handful of those 50 individuals I have met have been uninterested or negative to the audio-haptic technology as such. Rather, there has been widespread enthusiasm about the possibilities and the feedback from users has been closely related to their interest in the field of application. The slow progress in developing useful applications is considered the greatest problem. In principle, all audio-haptic (with force feedback) applications are still in a prototype stage, and together with the relatively high cost of haptic equipment there are no (to me) known end users who are interested in purchasing the equipment on their own.

In the first stage, specialized applications that capture the interest of pioneer users need to be developed – "killer apps". But to reach the everyday, normal user, the audio-haptic interface needs to become secondary to the task, just a tool to reach the goal that the user wants to achieve. The two following scenarios, both on the frontline of research and beyond, might contribute to this.

Audio-haptic tools for school work

Consider a pupil who is blind and who is integrated in a normal school, attending 7th grade. She uses a laptop with Braille display, speech synthesis and an audio-haptic device to access school material and control her computer. The audio-haptic device is used for accessing graphics or virtual worlds for experimenting with science. The following examples are a selection of school related audio-haptic applications:

In mathematics, the class is working with planar geometry. The teacher is solving a problem on the whiteboard, and the class is following. The pupil follows the problem solving on her laptop that is connected via the wireless network to the whiteboard. She can trace the outline of the geometric figure with her audio-haptic device, and the teacher's handwriting is interpreted and presented with speech synthesis. She uses a geometry drawing program with a measuring tool to solve geometry exercises.

In physics, the class is working with a computerized tool to experiment with electrical circuits. The pupil who is blind has a specialized audio-haptic tool that enables her not only to build a virtual circuit, but also to experience it by tracing the wiring and following the electrical current. A resistor in the circuit maker her feel as though she were moving through a sluggish fluid, while simple wiring will have no resistance at all. The audio feedback can render the names and values of the different electrical components or reinforce the haptic sensation by adding audio effects corresponding to the components' behavior.

In art class, the pupils are working on an art project for an exhibition. Our pupil is not very fond of working with real clay, and has chosen to work with an audio-haptic virtual clay tool to design a 3D-sculpture. The sculpture will be exhibited on a computer screen with stereo, enabling her classmates to see it, but also to hear it in audio and touch it with the haptic system.

In geography, the pupil uses her audio-haptic system with a plug-in to "Google Earth" that enables her to feel maps with different details and satellite pictures. She also has specialized software for learning geography that provides audio-haptic feedback for experiencing different ground features (e.g. plains, mountains, streams), country information, language samples, etc.

Our pupil also uses the audio-haptic tool in any subject that requires her to take part in what the teacher draws on the white board. Every drawing will be sent to the audio-haptic device for her to experience if she likes. When the teacher draws or points at the drawing on the whiteboard, the position of the pointing will be sent to the audio-haptic device. The pointing position will be modeled in the audio-haptic system as a weak pulling force that enables the pupil to easily find the spot. The pupil can thus follow the teachers drawing or pointing and in this way be helped to trace a figure. She also has an audio-haptic 2D drawing program that she uses for subjects in which she needs to produce figures or drawings.

Audio-haptic maps and virtual environments

A computer programmer who is blind is on a business trip to Glasgow. He has been on several business trips and is well acquainted with his local airport, but he has never been to Glasgow before. He prefers to plan ahead and uses his audio-haptic system to acquire information about the airport. At the airport website he can find an outline map of the airport that his audio-haptic system can display for him. However, this does not get him all the needed information, so he accesses a special database with maps and models of buildings. He finds the Glasgow Airport, and downloads a model of it. He can now use the model to go on a virtual tour of the airport with spoken information and audio effects. He can also enter map mode and choose different levels of detail to acquire information about gate numbers, kiosks and toilets for instance. He will be taking the shuttle bus to central Glasgow and will then be walking to his hotel. He has a talking GPS system that works well, but he still wants to orient himself in advance. He uses the GPS maps with an audio-haptic plug-in in his computer to be able to haptically trace his walking route and to check nearby places in addition to getting a GPS data simulation.

On another occasion he is about to go on a vacation to Crete. He is interested in history, and will be travelling to Knossos by tourist bus. He wants to familiarize himself with the Cretan geography and the route they will be taking, as well as learn about Knossos. He uses an audio-haptic plug-in to "Google Earth", to experience the geography, and to trace the road to Knossos. He also accesses the Knossos website to read about its history and to trace the outline map.

From present to future

The examples above illustrate how the audio-haptic tool can be used in many different school subjects as well as being a powerful map accessing and planning tool. The frequent use and the different applications' useworthiness for the individual can make the audio-haptic device transparent, enabling the user to concentrate on the task and not the device. When and if this goal is reached, an audio-haptic device can be a valuable computer access tool in addition to screen readers, Braille displays and speech synthesis.

This and similar research can contribute to the future goal by investigating and analyzing details of audio-haptic usability that will result in guidelines. Also, ad hoc use of audio-haptic prototype applications by reference groups, for example, can render new ideas and show the end user group that this technology is available and possible to develop further. This can hopefully stimulate potential end users to initiate ideas and projects.

References

[1] Burdea, G.C. *Force and Touch Feedback for Virtual Reality.* John Wiley & Sons, New York, USA, 1996.

[2] Sensable Inc. company homepage. 2006. www.sensable.com

[3] Immersion Corp. company homepage. 2006. www.immersion.com

[4] Ruspini, D.C. *Beyond the looking glass: the haptic exploration of virtual environments*. PhD thesis, Dept. of Computer Science, Stanford University, CA, USA, 2003.

[5] Hatwell, Y., Streri, A., Gentaz, E. (Eds.) *Touching for knowing.* John Benjamins Publishing Co., Amsterdam, The Netherlands, 2003.

[6] *OpenHaptics Toolkit*, Programmer's Guide. Sensable Technologies.

[7] Force Dimension company homepage. 2006. www.forcedimension.com

[8] Haption company homepage. 2006. www.haption.com

[9] Kramer, G. (Ed.) *Auditory Display: Sonification, Audification and Auditory Interfaces.* Addison-Wesley, Reading, MA, USA, 1994.

[10] Gaver, W.W. Using and Creating Auditory Icons. In Kramer, G. (Ed.) *Auditory Display – Sonification, Audification, and Auditory Interfaces.* Addison-Wesley, Reading, MA, USA, pp. 417-446, 1994.

[11] Brewster, S. *Providing a structured method for integrating non-speech audio into human-computer interfaces*. PhD thesis, Human-Computer Interaction Group, Dept. of Computer Science, University of York, England, 1994.

[12] O'Modhrain, S. and Gillespie R.B. The Moose: A Haptic User Interface for Blind Persons. In *Proceedings of the Sixth World Wide Web Conference: Access Track.* Santa Clara, CA, USA, 1997.

[13] Wenzel, E.M., Wightman, F.L., and Kistler, D.J. Localization with non-individualized virtual acoustic display cues. *Proceedings of the SIGCHI Conference on Human factors in computing systems: Reaching through technology* ACM. New Orleans, LA, USA, 1991.

[14] Eriksson, Y. and Gärdenfors, D. *Computer Games for Partially Sighted and Blind Children*. The Swedish Library of Talking Books and Braille (TPB). Enskede, Sweden, 2004. Available online at: www.tpb.se/barnens_tpb/spel/projekt/report.html (accessed 19 Aug. 2006).

[15] Gärdenfors, D. Designing Sound-Based Computer Games. *Digital Creativity*, vol. 14, no. 2, 2003.

[16] Gärdenfors, D. *Auditory Interfaces – A Design Platform*. Design Sounds, Sweden, 2001. Available online at: www.designsounds.net/auditoryinterfaces.pdf (accessed 19 Aug. 2006).

[17] OpenAL organization homepage. 2006. www.openal.org

[18] Microsoft DirectX homepage. 2006. www.microsoft.com/directx

[19] FMod organization homepage. 2006. www.fmod.org

[20] DiFilippo, D. and Pai, D.K. The AHI: An Audio and Haptic Interface for Contact Interactions. In *Proceedings of the 13th annual ACM symposium on User interface software and technology.* San Diego, CA, USA, 2000.

[21] Yano, H., Igawa, H., Kameda, T., Muzutani, K., and Iwata, H. Audiohaptics: audio and Haptic rendering based on a physical model. In *Proceedings of HAPTICS '04 Haptic Interfaces for Virtual Environment and Teleoperator Systems.* San Diego, CA, USA, 2004.

[22] Vanderheiden, G.C. Use of audio-haptic interface techniques to allow nonvisual access to touchscreen appliances. In *Proceedings of Human Factors and Ergonomics Society Annual Conference*, 1996. Available online at: trace.wisc.edu/docs/touchscreen/chi_conf.htm

[23] Winberg, F. and Hellström S.O. Designing Accessible Auditory Drag and Drop. In *Proceedings of the 2003 Conference on Universal Usability CUU*. Vancouver, BC, Canada, 2003.

[24] Bussell, L. Touch Tiles: Elementary Geometry Software with a Haptic and Auditory Interface for Visually Impaired Children. *EuroHaptics 2003,* Dublin, Ireland, 2003.

[25] Sjöström, C., Danielsson, H., Magnusson, C., and Rassmus-Gröhn, K. Phantom-based haptic line graphics for blind persons. In *Visual Impairment Research*, vol. 5, no. 1, 2003.

[26] Yu, W., Ramloll, R., and Brewster, S.A. Haptic Graphs for Blind Computer Users. In *Proceedings of the First International Workshop on Haptic Human-Computer Interaction*. Glasgow, UK, 2000.

[27] Yu, W., Brewster, S., Ramloll, R., and Ridel, B. Exploring computer-generated line graphs through virtual touch. In *Proceedings of Sixth International Symposium on Signal Processing and its Applications*, vol. 1. Kuala Lumpur, Malaysia, 2001.

[28] Yu, W., Kangas, K., and Brewster, S. Web-based haptic applications for blind people to create virtual graphs. In *Proceedings of Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS 2003.* Los Angeles, CA, USA, 2003.

[29] Iglesias, R., Casado, S., Gutierrez, T., Barbero, J. I., Avizzano, C. A., Marcheschi, S., and Bergamasco, M. Computer graphics access for blind people through a haptic and audio virtual environment. In *Proceedings of Haptic, Audio and Visual Environments and Their Applications, HAVE 2004.* Ottawa, ON, Canada, 2004.

[30] Magnusson, C., Rassmus-Gröhn, K., Sjöström, C., and Danielsson, H. Navigation and Recognition in Complex Haptic Virtual Environments – Reports from an Extensive Study with Blind Users. *EuroHaptics 2002,* Edinburgh, UK, 2002.

[31] Magnusson, C. and Rassmus-Gröhn, K. Audio haptic tools for navigation in non visual environments. *ENACTIVE 2005, the 2nd International Conference on Enactive Interfaces*. Genoa, Italy, 2005.

[32] Roth, P., Richoz, D., Petrucci, L., and Pun, T. An audio-haptic tool for non-visual image representation. In *Proceedings of Sixth International Symposium on Signal Processing and its Applications*, vol. 1. Kuala Lumpur, Malaysia, 2001.

[33] Ramstein, C., Martial, O., Dufresne, A., Carignan, M., Chassé, P., and Mabilleau, P. Touching and Hearing GUI's: Design Issues for the PC-Access System. In *Proceedings of the second annual ACM conference on Assistive technologies.* Vancouver, BC, Canada, 1996.

[34] Magnusson, C. and Rassmus-Gröhn, K. A Virtual Traffic Environment for People with Visual Impairments. *Visual Impairment Research*, vol. 7, no. 1, 2005.

[35] Wood, J., Magennis, M., Arias, E. F. C., Gutierrez, T., Graupp, H., and Bergamasco, M. The Design and Evaluation of a Computer Game for the Blind in the GRAB Haptic Audio Virtual Environment. *EuroHaptics 2003.* Dublin, Ireland, 2003.

[36] Jansson, G. and Ivås, A. Can the Efficiency of a Haptic Display Be Increased by Short-Time Practice in Exploration? *Haptic Human-Computer Interaction Workshop*. Glasgow, UK, 2000.

[37] Nielsen, J. *Usability Engineering.* Morgan Kaufmann, San Francisco, CA, USA, 1993.

[38] Sallnäs, E-L., Rassmus-Gröhn, K., and Sjöström, C. Supporting Presence in Collaborative Multimodal Environments by Haptic Force Feedback. In *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 7, no. 4, 2000.

[39] Sjöström, C. *Non-Visual Haptic Interaction Design – Guidelines and Applications.* PhD thesis. Dept. for Design Sciences, Lund University, Faculty of Engineering, Lund, Sweden, 2002.

[40] Rassmus-Gröhn, K., Magnusson, C., and Eftring, H. User evaluations of a virtual haptic-audio line drawing prototype. *Workshop on haptic and audio interaction design*. Glasgow, UK, 2006.

[41] Hansson, C. Haptic Drawing Program. Master thesis. Design Sciences, Lund University, Faculty of Engineering, Lund, Sweden, 2003.

[42] PNG organization homepage. 2006. www.libpng.org/pub/png/

[43] Van Scoy, F. L., Baker, V., Gingold, C., Martino, E., and Burton, D. Mobility Training using a Haptic Interface: Initial Plans. *Fourth Annual PHANTOM Users Group.* Dedham, MA, USA, 1999.

[44] Kamel, Hesham M. *The Integrated Communication 2 Draw (IC2D)*. PhD thesis. Electrical Engineering and Computer Sciences Department, University of California, CA, USA, 2003.

[45] Kennedy, J.M. *Drawing and the Blind – Pictures to Touch.* Yale University Press, New Haven and London, 1993.

[46] Axel, E.S. and Levent N.S. (Eds.) *Art Beyond Sight.*Art Education for the Blind, Inc. and AFB Press, New York, USA, 2003.

[47] Pakkanen, T. and Raisamo, R. Perception strategies in modal-redistributed interaction. In *Proceedings of the 31st Annual International Symposium on Computer Architecture.* München, Germany, 2004.

[48] Winberg, F. and Hellström S.O. Qualitative Aspects of Auditory Direct Manipulation: A Case Study of the Towers of Hanoi. In *Proceedings of the 7th International Conference on Auditory Display.* Espoo, Finland, 2001.

Appendices

Appendix 1

The Step-by-step training session, detailed description of applications and user tests. March 2006.

Appendix 2

Journal paper:
The Sense of Touch Provides New Computer Interaction Techniques for Disabled People
Calle Sjöström, Kirsten Rassmus-Gröhn
Technology & Disability (IOS Press), Vol. 10, No. 1, 1999

Appendix 3

Journal paper:
Supporting Presence in Collaborative Multimodal Environments by Haptic Force Feedback
Eva-Lotta Sallnäs , Kirsten Rassmus-Gröhn, Calle Sjöström
ACM Transactions on Computer-Human Interaction (TOCHI), Vol. 7, Issue 4, Dec. 2000

Appendix 4

Journal paper:
Phantom-based Haptic Line Graphics for Blind Persons
Calle Sjöström, Henrik Danielsson, Charlotte Magnusson, Kirsten Rassmus-Gröhn
Visual Impairment Research, pp 13-32, Vol. 5, No. 1, 2003

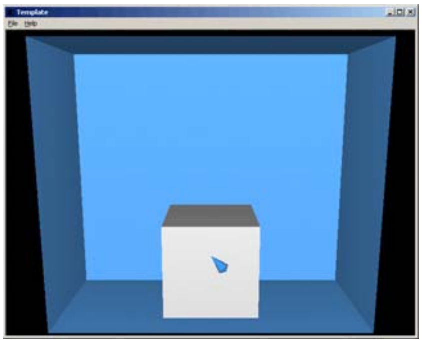
Appendix 5

Journal paper:
A Virtual Traffic Environment for People with Visual Impairments
Charlotte Magnusson, Kirsten Rassmus-Gröhn
Visual Impairment Research, pp 1-12, Vol. 7, No. 1, 2005

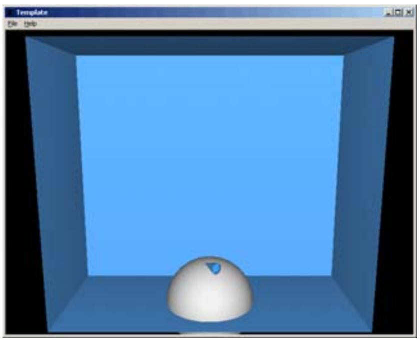
Appendix 1 - The Step-by-step training session

In a large-scale feasibility test for the ENORASI project in 2001 the author created the *step-by-step training session*. The focus on test tasks and the pre-tests was to let the research persons explore and experience virtual objects and be able to recognize them and communicate about details in objects. The research persons were allowed to spend as much time as they needed with the pre-test tasks.

The pre-test applications 1 to 6 were written in the GHOST API framework, and the models were hard coded in C++. All were built on a template model of a limiting box and modified according to each special application. The author of this thesis implemented all these test applications.



Pre-test task 1



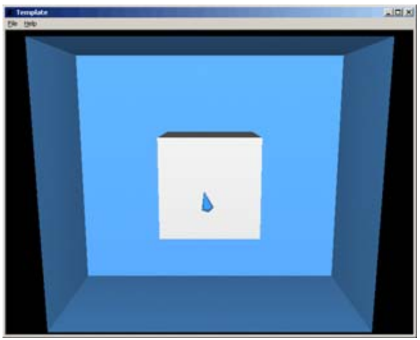
Pre-test task 2

Introduction to the test

All research persons performed the tests without any visual feedback. First, the research person was supposed to familiarize him or herself with the device. That included a verbal description of the system and free explorations of the hardware – i.e. the research person could feel the PHANToM arm and the base. Any questions about the technology were also answered.

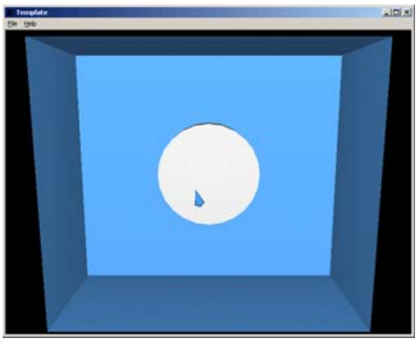
Pre-test tasks 1, 2 and 3

The VE consisted of a 3D room (16•14•6.5 cm³) with limiting walls, floor and a ceiling. This limiting box is necessary to give visually impaired users a reference and to prevent them from reaching the maximum workspace of the PHANToM arm. In certain cases the lack of a limiting box has led some research persons to believe that there is an object at the maximum reach of the PHANToM arm.



Pre-test task 3

The first VE contains a single static cube that is in contact with the floor and rear wall. In the second VE, a half-sphere is positioned in the middle of the floor of the limiting box. And finally, in the third VE, there is a cube suspended in air. These three pre-test tasks gradually encourage the user to explore the 3D space in all dimensions and get used to the limiting box and its size.

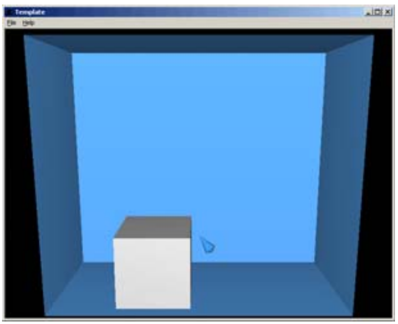


Pre-test task 4

Pre-test task 4

This VE consists of the limiting box with dimensions described above with a cylindrically shaped button mounted on the middle of the wall opposite of the user. The user's task was to find the button and to press it into the wall. A bird twitching sound was played when the user succeeded in pressing the button.

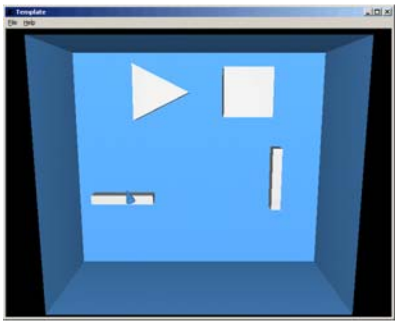
Pre-test task 5



Pre-test task 5

This VE has the same limiting box as above with one cube that can be pushed around with the PHANToM arm. The cube and the room have very limited dynamics, and the cube rests firmly on the floor and can be pushed sideways and back and forth, but cannot be rotated. It can be questioned whether this pre-test was necessary for the coming tests, since no dynamic haptic objects (other than buttons and sliders) were supposed to be manipulated by the users in the main test.

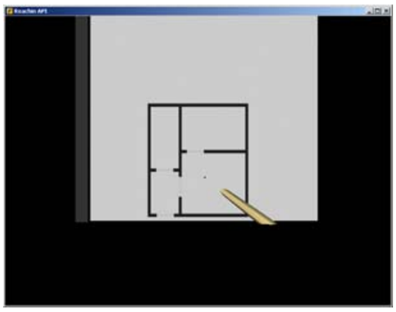
Pre-test task 6



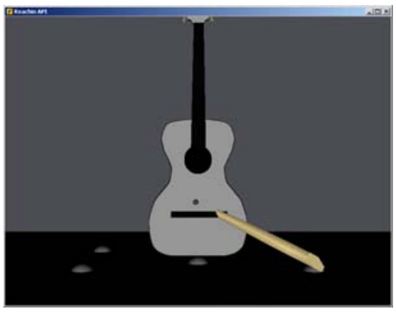
Pre-test task 6

The VE is a virtual haptic radio or tape player, with music controls on the wall opposite the user, one play button shaped like a triangle, one stop button shaped like a square, and two slider controls, one for volume (sliding up and down) and the other for panning left and right (sliding left and right).

Pre-test tasks 7 and 8



Pre-test task 7



Pre-test task 8

These two applications were built with the Reachin API and also use the possibility to load VRML models into that framework.

The VE in pre-test 7 consisted of a floor plan of a small apartment. The walls were modeled as high ridges and the doorways as very low ridges. In each room the user could press the floor to hear the name of the room. The screen dump seen to the right shows a top view of the VE; in fact the model was horizontal. This VE did not have a limiting box. Calle Sjöström implemented this application.

Pre-test 8 was a 3D complex object – a VRML model of a guitar, entirely without sound feedback information. The user was informed that it was an instrument and was supposed to identify it. This VE did not have a limiting box. Charlotte Magnusson implemented this test application.

Appendix 2 - The Sense of Touch Provides New Computer Interaction Techniques for Disabled People

Calle Sjöström, Kirsten Rassmus-Gröhn

Technology & Disability (IOS Press), Vol. 10, No. 1, 1999

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

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Abstract

Windows and the World Wide Web are two of the keys to the IT-explosion that we are all caught up in. Computers can do more and more and 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

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 and even to 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 thing that could change it all: 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” (Massie, 96). 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 at the same time *feel* some of the things the robot is doing.

The PHANToM

Figure 1, The PHANToM (photo by SensAble Technologies Inc.)

The PHANToM (Figure 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 haptic scene is a collection of separate haptic objects with different behaviors and properties.

When activated, the PHANToM coacts with the computer to interpret the user’s 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.

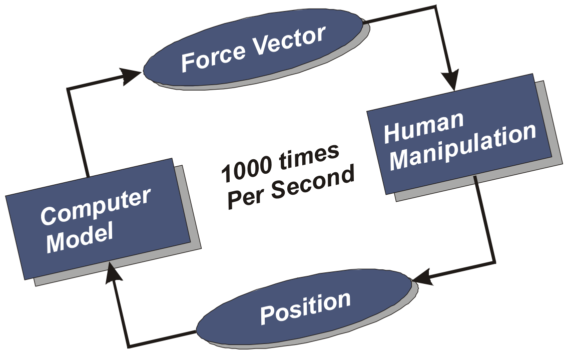

Figure 2, The control loop

This process (Figure 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 (Massie, 96).

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.

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 (Figure 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.

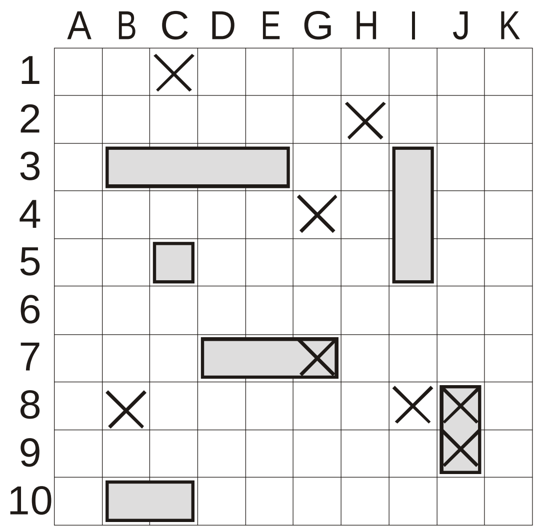

Figure 3. A paper-based battleship game

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)
?? Bombed, hit part of a submarine - vibrations
?? 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 most games do nowadays. It has been tested by a lot of people - both sighted and blind. 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 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, 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.

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 (Fritz, Barner, 96).

Touch Windows

Computers are becoming everyday technology for more and more people. Computers have 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. This is done in real time and in addition to being much more flexible it also saves space compared to books with Braille-text on paper. But, at present, that is about as good as it gets for computer users with visual impairments.

Nowadays there is 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, however, 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 nowadays 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. The good thing is that 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 was good enough. 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 will be much easier to exchange documents and they will also be able to help each other when things don't work as they should.

Our goal in the "Touch Windows" project is to make the haptic Windows system 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 so big that we have chosen this strategy rather than making a new haptic user interface tailored to the needs of blind users.

In the haptic Windows system that we are designing right now we want to use haptic interaction mainly to provide an overview of the system. The idea is to make window-frames, buttons, menus, icons etc. touchable via the haptic interface and that should provide the overall information in a similar way as the graphical widgets 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.

This dividing of 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 and that means that it is 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".

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* (Figure 4). The Memory House (Sjöström, 97) is a haptic/audio memory game. The 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.

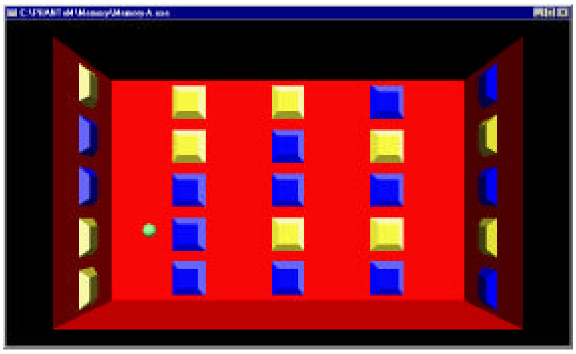

Figure 4, The Memory House (original version)

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 user 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 (Figure 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 (Figure 5).

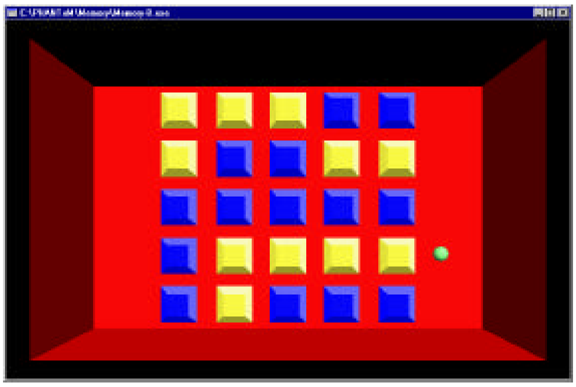

Figure 5. The Memory House (version B)

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 (Figure 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.

Figure 6, A virtual model of a house

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

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

2D force feedback devices

The PHANToM is a high performance force feedback device with many benefits, but 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 (Rosenberg, 1997), for example, may 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.

Figure 7, The FEELit Mouse (photo by Immersion Corp.)

Force feedback devices using only two dimensions are sufficient for working in 2D environments like Windows. But since, unfortunately, the FEELit mouse (Figure 7) is not yet available on the market, we have done no tests with this hardware. However, we know that Immersion themselves have held a couple of try-out 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 (Figure 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.

Figure 8. The Microsoft Sidewinder Force Feedback Pro joystick (photo by Certec)

Certec is collaborating with two scientists who are working on the Microsoft Sidewinder Force Feedback Pro device (Johansson, Linde, 98) 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 (Figure 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.

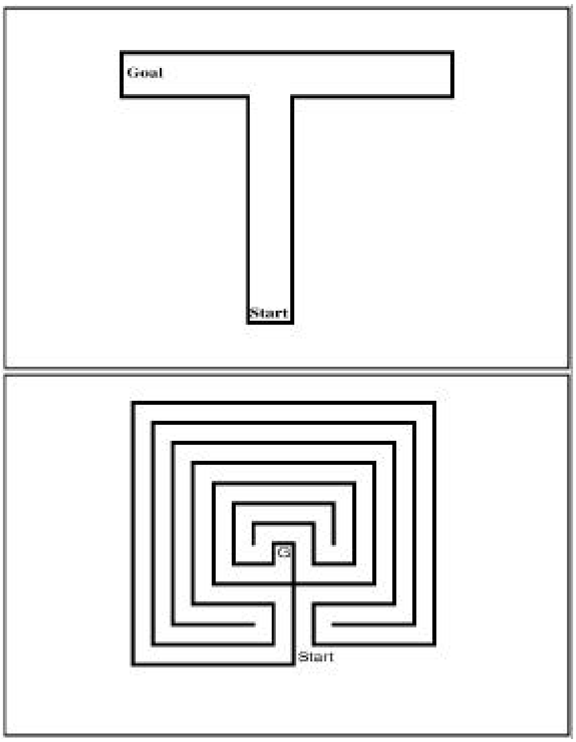

Figure 9. Mazes (image by Anders Johansson)

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.

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 (Bolmsjö, Eftring, Neveryd, 95). 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 user's movements as well as how much force is exerted against the finger.

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

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References:

Bolmsjö G, Eftring H, Neveryd H: Robotics in rehabilitation. IEEE Transactions on Rehabilitation Engineering, vol 3, no 1, pp 77-83, March 1995.

Fritz J, Barner K: Design of a haptic graphing method. Paper presented at RESNA '96 Annual Conference, Salt Lake City UT, June 1996.

Johansson A, Linde J: Using Simple Force Feedback Mechanisms to Visualize Structures by Haptics. Paper presented at the Second Swedish Symposium on Multimodal Communication, Lund, Sweden, Oct 98.

Massie T H: Initial Haptic Explorations with the Phantom: Virtual Touch Through Point Interaction. Master's Thesis, MIT, MA, Feb 96.

Rosenberg L B: FEELit mouse: Adding a realistic sense of FEEL to the computing experience. URL: http://www.force-feedback.com/feelit/white-paper.html.

Sjöström C: The Phantasticon - Haptic interfaces give new possibilities for blind people. Master's Thesis (only the abstract is available in English), Certec, Lund University, Sweden, Oct 1997.

Appendix 3 - 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.

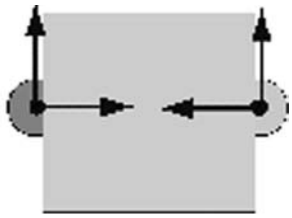

Fig. 5. Two users collaborate to lift a cube. The users press into the cube from opposite sides and lift it upward simultaneously.

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

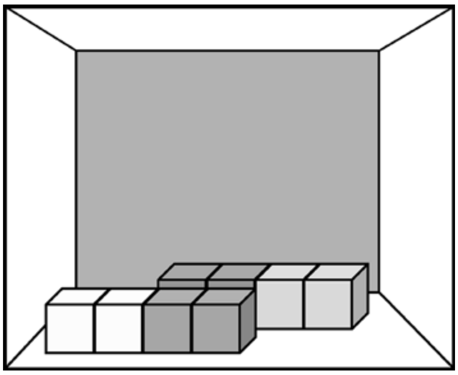

Fig. 6. Task B.

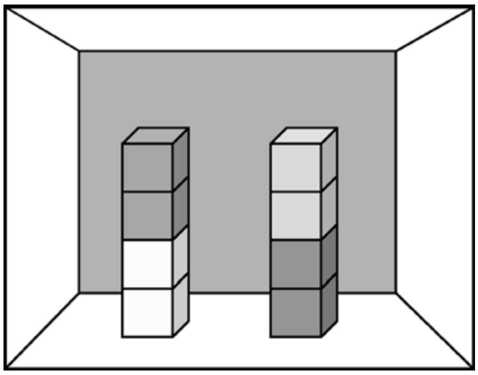

Fig. 7. Task C.

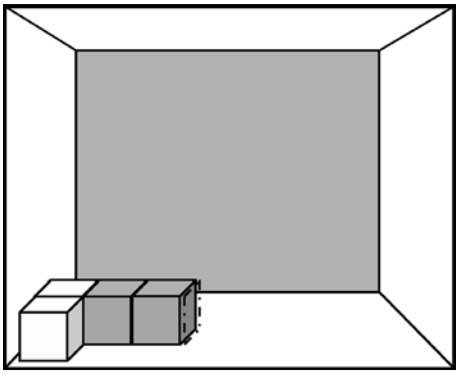

Fig. 8. Task D, person 1.

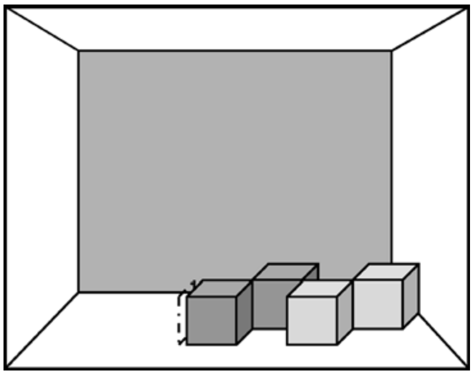

Fig. 9. Task D, person 2.

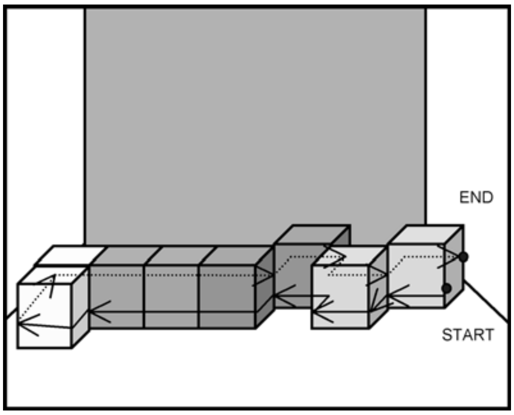

Fig. 10. Task E.

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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REFERENCES

APPELLE, S. 1991. Haptic perception of form: Activity and stimulus attributes. In *The Psychology of Touch*, M. Heller and W. Schiff, Eds. Lawrence Erlbaum Associates Inc., Hillsdale, NJ, 169–188.

BASDOGAN, C., HO, C., SLATER, M., AND SRINIVASAN, M. A. 1998. The role of haptic communication in shared virtual environments. In *Proceedings of the Third Workshop on Phantom User Group* (Dedham, MA, Oct. 3-6). http://www.ai.mit.edu/conferences/pug98

BURDEA, G. C. 1996. *Force and Touch Feedback for Virtual Reality*. John Wiley and Sons, Inc., New York, NY.

DAFT, R. L. AND LENGEL, R. H. 1986. Organizational information requirements, media richness, and structural design. *Manage. Sci. 32*, 5 (May), 554–571.

DURLACH, N. AND SLATER, M. 1998. Presence in shared virtual environments and virtual togetherness. In *Proceedings of the British Telecom Workshop on Presence in Shared Virtual Environments* (Ipswich, Suffolk, June 10–11).

GUPTA, R., SHERIDAN, T., AND WHITNEY, D. 1997. Experiments using multimodal virtual environments in design for assembly analysis. *Presence: Teleoper. Virtual Environ. 6*, 3, 318–338.

HASSER, C. J., GOLDENBERG, A. S., MARTIN, K. M., AND ROSENBERG, L. B. 1998. User performing a GUI pointing task with a low-cost force-feedback computer mouse. In *Proceedings of the Conference on ASME Dynamics and Control Division*. 151–156.

HELD, R. M. AND DURLACH, N. I. 1992. Telepresence. *Presence: Teleoper. Virtual Environ. 1*, 1 (Winter), 109–112.

HENDRIX, C. AND BARFIELD, W. 1996. The sense of presence within auditory virtual environments. *Presence: Teleoper. Virtual Environ. 5*, 3, 290–301.

HOFFMAN, H. G., HOLLANDER, A., SCHRODER, K., ROUSSEAU, S., AND FURNESS, T. 1998. Physically touching and tasting virtual objects enhances the realism of virtual experiences. *Virt. Real. 3*, 226–234.

HURMUZLU, Y., EPHANOV, A., AND STOIANOVICI, D. 1998. Effect of a pneumatically driven haptic interface on the perceptional capabilities of human operators. *Presence: Teleoper. Virtual Environ. 7*, 3, 290–307.

ISHII, M., NAKATA, M., AND SATO, M. 1994. Networked SPIDAR: A networked virtual environment with visual, auditory, and haptic interactions. *Presence: Teleoper. Virtual Environ. 3*, 4, 351–359.

KATZ, R. AND TUSHMAN, M. 1978. Communication patterns, project performance, and task characteristics: An empirical evaluation in an R&D setting. *Org. Behav. Hum. Perf. 23*, 139–162.

MASSIE, T. H. 1996. Initial haptic explorations with the phantom: Virtual touch through point interaction. Master's Thesis. Massachusetts Institute of Technology, Cambridge, MA.

MCLEOD, P. L. 1996. New communication technologies for group decision making: Toward an integrated framework. In *Communication and Group Decision Making*, R. Y. Hirokawa and M. S. Poole, Eds. Sage Publications, Inc., Thousand Oaks, CA, 426–461.

RICE, R. E. 1993. Media appropriateness: Using social presence theory to compare traditional and new organizational media. *Hum. Comm. Res. 19*, 4, 451–484.

SHORT, J., WILLIAMS, E., AND CHRISTIE, B. 1976. *The Social Psychology of Telecommunications*. John Wiley and Sons, Inc., New York, NY.

SJÖSTRÖM, C. AND RASSMUS-GRÖHN, K. 1999. The sense of touch provides new computer interaction techniques for disabled people. *Tech. Disab. Res. & Dev. 10*, 1, 45–52.

Slater, M. and Wilbur, S. 1997. A framework for immersive virtual environments (Five): Speculations on the role of presence in virtual environments. *Presence: Teleoper. Virtual Environ. 6*, 6, 603–616.

Witmer, B. G. and Singer, M. J. 1998. Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoper. Virtual Environ.* 7, 3, 225–240.

Appendix 4 - Phantom-based Haptic Line Graphics for Blind Persons

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Phantom-based haptic line 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, in this case the Phantom from SensAble Technologies, can be used to give blind persons access to 2D graphics and similar computer-based graphics. User tests were carried out with 24 blind users from Sweden and Italy. The tests included mathematical curves, 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. 72% of the users managed to solve the applied mathematical problem that was the task for the mathematics program. The results for the picture reliefs were highly dependent on contextual information: 33%–66% 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 use the haptic floor plans.

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

Key words Haptic; line graphics; blind; navigation; The Phantom

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 studying the use of haptic interfaces since 1995,

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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 to blind persons. To be able to develop useful applications for this group, however, it is important to gather information about the ability of blind users to interact with different haptic virtual environments. Thus a user test study including 24 blind users using the Phantom haptic device from SensAble Technologies[1] was carried out. This paper concentrates on the parts of the study that consider different kinds of 2D graphics.

Three different applications that present 2D graphical 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 was tested was 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 affects the ecological system on the island.

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

The third 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.

This study included only users who were blind because it was desired to study haptic technology and to test interaction design ideas with potential users of the system.

ACCESS TO VISUAL INFORMATION FOR PEOPLE WHO ARE BLIND

To blind and nearly blind persons, computer access is severely restricted due to 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 based on the user being able to gain an overview of the system through visual input. Even so, 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 research on graphics for blind persons uses tactile touch whereas this study concerns haptic touch. The arguments for that will be given shortly, but first the definition of haptics: Haptic sensing is defined as the use of motor behaviors in combination with touch to identify objects.[2]

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.

Many of the haptic touch interfaces that have been developed in recent years use one-point haptic interaction with the virtual world. The effect resembles tracing the outline of an object with your index finger in a thimble or holding a pen and recognizing it through this information alone. In virtual haptic interaction, the touch sensations are often transmitted in exactly that way, via, for example, a thimble or a pen that is suspended or connected to a force-generating mechanism. The only skin receptors affected by the haptic interface are those that are in contact with the pen or thimble.

The kind of haptic interaction used in the present study is often referred to as 'active touch', since to user has to move around in the virtual world to feel things. 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 which is also present 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.

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 (though 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.[3,4] The main problem with this technology is obtaining 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, different ways to access graphical information dynamically, via the sense of touch and a haptic computer interface, are investigated. The haptic interfaces that are available today have very high resolution and are becoming more and more robust. Haptic interfaces also have the possibility of rendering 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 confronted 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 information access for blind persons.[5–9]

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.[10,11] 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.[12] designed a haptic data visualization system to display different forms of lines and surfaces to a blind person. Instead of grooves and ridges, Fritz uses a 'virtual fixture' to let the user trace a line in 3D with the Phantom. This program and the present authors' original program (mentioned above) are the first mathematics programs for the Phantom in the literature.

Later, Van Scoy, Kawai, Darrah and Rash[13] created a mathematics program with a function parser that is very similar to the mathematics program in the present study, but which includes the possibility to input the function via a text interface. The functional graphs are rendered haptically as a groove in the virtual back wall, as in the present authors' original program. However, the technical solution is completely different.

Ramloll, Yu, Brewster et al.[9,14] have also presented an ambitious work on a line graph display system with integrated auditory feedback as well as haptic feedback. This program can make use of either the

Phantom or the Logitech Wingman Force Feedback Mouse. The haptic rendering is 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 (similar to the virtual fixtures used by Fritz above).

Finally, Minagawa, Ohnishi and Sugie[3] 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 get access to mathematic information. For the present study, the groove-rendering method was chosen, since it has been found very effective. The original implementation was changed to a polygon mesh implementation that is more fitted for today's haptic application programming interfaces.

Ramloll et al.[14] report on a low level of interest in haptic mathematics and graph display systems among teachers of blind persons. In unpublished work by Sjöström, Danielsson, Magnusson and Rassmus-Gröhn, a questionnaire was answered by 36 persons who were blind or visually impaired. The ability to learn mathematics was rated lowest of six possible areas where assistance of a haptic device was desired (mean of 2.3 on a scale from 1 to 5, whereas none of the other alternatives had means below 3.6). One argument for us to include graphs in the study despite this result was that it is difficult for the user to know before trying if he or she actually wants this particular assistance. Another argument from a democratic point of view is that it is not justifiable to exclude blind persons from parts of society that require access to graphs and diagrams. Moreover, for this study the authors wanted to take the mathematics application closer to a real learning situation. Therefore, the mathematical graphs were put 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 it is still an important step towards use in a real learning situation.

Tactile and haptic imaging Way and Barner[15,16] describe the development of a visual-to-tactile translator called the TACTile Image Creation System (TACTICS). This system uses digital image processing technology automatically to 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.[17] 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, etc. The program developed for the present study works very well with black and white line drawings, which is basically the output of the TACTICS system. This means that technology like TACTICS can be used in conjunction with the technology presented in this paper to make an even more efficient haptic imaging system.

Eriksson et al.[18–20] have presented several reports and practical work on how tactile images should be designed to be understandable by blind readers. 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[21] 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[22] with tactile imaging in mind. Although the Pantograph is a haptic interface (like the Phantom) it has only 2 degrees of freedom. The 3 degrees of freedom of the Phantom is an advantage in image access, since lines can be rendered as grooves or ridges as described above, and it might also lower the need for image simplification.

Roth, Richoz, Petrucci and Puhn[23] have developed and studied 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. Even though audio can be a very good complement to haptics, the present study is concentrated on haptic interaction. A design criterion for the present system was that it should ultimately be handled by a blind person alone, and that excludes a descriptor/explorer scheme.

Kurze[24] has developed a guidance 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 in a circle and the idea is to give the user directional hints that he can choose to follow or not. Kurze[25] 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 (our 'virtual search tools' is a similar idea.)[26]

Shinohara, Shimizu and Mochizuki[4] have developed a tactile display that can present tangible relief graphics for visually impaired persons. The tactile surface consists of a 64×64 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 it can be argued that a tactile display can provide a slightly more natural touch interaction than haptic displays, the resolution of current tactile displays is still far lower than the resolution of haptic displays like the Phantom.

Probably the closest report to the present one is a report on an 'image to haptic data converter' by Yu et al.[27] 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. 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 very similar to the idea in the present program for image access. However, Yu is using a technique that includes automatic image tracing, which is not used in the program for the present study. Both methods have their strong and weak points, and one cannot say that one method is always better than the other. In the long run it could be good to let the user choose a rendering and/or simplification method depending on the kind of picture he or she wants to feel.

One important use of tactile imaging is tactile maps. The benefits of interactive tactile maps are pointed out by Arditi, Holmes, Reedijk and Whitehouse.[28] They found that there were significantly fewer errors and significantly more errorless way-finding trials when the blind person planned a route with an interactive tactile map compared to route planning using directions from a 'bystander'. Holmes and Arditi[29] have also investigated the relative usefulness of 'wall-style' and 'path-style' maps for route planning in a building. The wall map shows barriers, including walls, whereas the path map instead shows possible routes in the building. The study showed that significantly more time was spent planning the route to a goal using the wall map compared to when using the path map. Even so, the path map was rated more difficult than the wall map both for planning a route and for building up a meaningful cognitive map of the route. In general, the wall map received higher acceptance among the test participants. We chose to use 'wall style' maps in the present study both because of their good results for blind users and since this style is used in standard floor plans, which is important from a production point of view.

In sum, previous research on tactile imaging and tactile maps suggests the need to investigate an imaging program and maps such as those involved in the present study. This study uses a 3D haptic device because of its high resolution and its ability to render easily updateable graphics. The image-rendering method 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 study was to see if and how a haptic interface, in this case the Phantom by SensAble Technologies, can be used to give blind persons access to line drawings and similar computer-based graphics. Three specific areas are investigated in this study. The areas have been chosen in cooperation with professionals at 'Horisont' in Sweden who work with computer adaptations and solutions for blind school children in Sweden. Each of the three areas represents a task which often requires help from a seeing person to be carried out, but could be done more independently using haptic technology. The three tests also represent areas where the flexibility of a solution based on a dynamic haptic display can be very important for the blind user. We have also used a questionnaire to obtain input about the interest in different areas from potential users of the system.

1. 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 can comprehend line graphs that are haptically represented. It was therefore decided to design and test a haptic graphing program that displays a mathematic phenomenon in a natural science context.

2. Can drawings be haptically rendered 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 presented line graphs, and that makes it interesting to test how haptically presented pictures can be understood by blind persons.

3. Can maps and floor plans be represented haptically and used by blind persons?

It is known that tactile maps can be understood by blind persons and that better access to maps is requested by many blind persons. The question is how haptic maps should be designed for access by a blind person and whether the maps can be understood. It is also interesting to test whether the knowledge gained via the haptic map can be used for real-life orientation.

Material and methods

PARTICIPANTS 24 blind persons, 13 from Italy and 11 from Sweden, carried out the test. Eight of them were female, 16 were male. 13 were blind from birth. Their age varied from 12 to 73 years with a mean of 37 and standard deviation of 17. They had varying professional backgrounds, but there were more students and telephone operators than in an average population. All of the participants had limited or no experience in using the Phantom. All the participants were, as the representative from the Italian organization for the blind expressed it, 'blind in practice'. This means that the participants' vision varied from no light perception at all to severely limited residual vision. None of the participants could use their vision for any kind of image recognition. For a detailed presentation of the individual subjects, see Tables 1 and 2.

The Swedish participants were recruited in association with 'Horisont' (presented above), and the Italian participants by the Italian Organization for the Blind. When recruited, they were informed of the purpose of the study, and told that they could choose not to continue participating in the test at any time. This information was repeated before the test started.

APPARATUS The hardware that was used for the haptic interaction was the Phantom from SensAble Technologies[1] (See Fig. 1). 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.[30] Two Phantoms were used in parallel for

TABLE 1. Test persons, Italy.

Age	Sex	Blind from birth	Profession
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

TABLE 2. 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	Unemployed
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

Fig. 1. The Phantom.

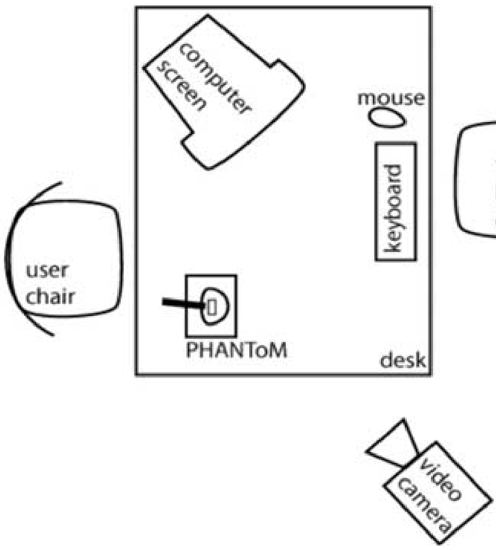


Fig. 2. The test set-up used.

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, 7 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 some 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 2. This set-up makes it possible to record the 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. A discrete scale from 1 to 5 was used, with 5 being the most challenging. The users responded to a questionnaire on the test experience afterwards.

In the mathematics tests, the keyboard was handed over to the 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.

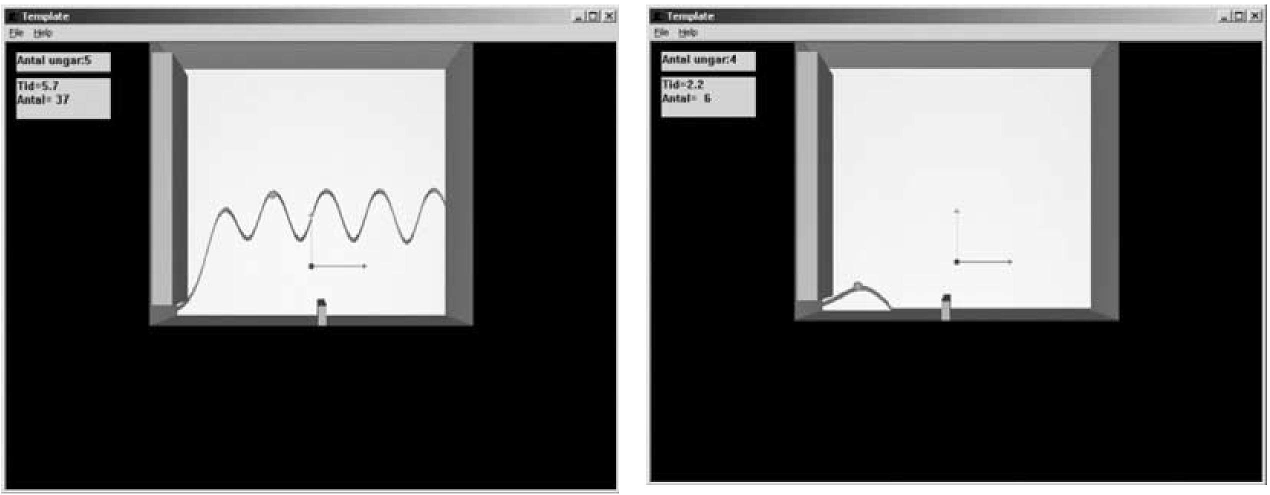


Fig. 3. The mathematical environment with herbivore fertility set to 5 and 4 births per time unit respectively.

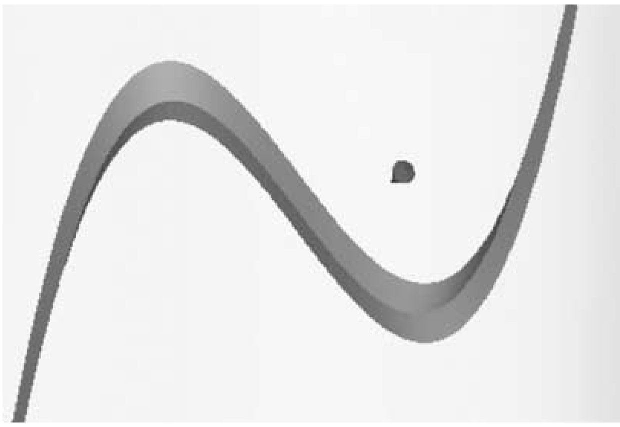


Fig. 4. Close up of a groove in the mathematics environment.

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.

The graph in the system is rendered as a groove in the back wall of the virtual environment (see Figs. 3 and 4). 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 via, for example, 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 virtual wall with an engraved path. The system with a groove in the back wall was also used in the authors' original mathematics program,[10,11] but at that time it was easier to calculate the forces directly

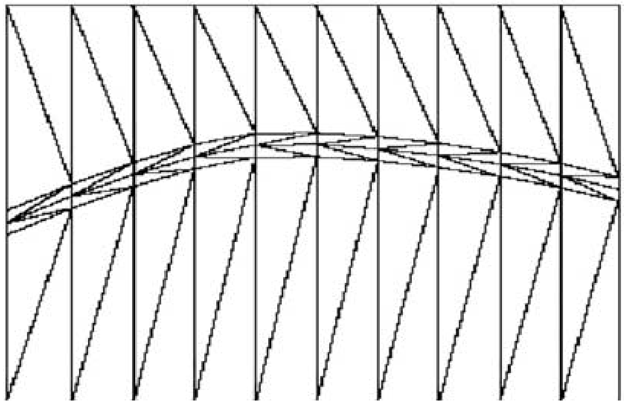


Fig. 5. Schematic picture of the polygon mesh used to render the groove.

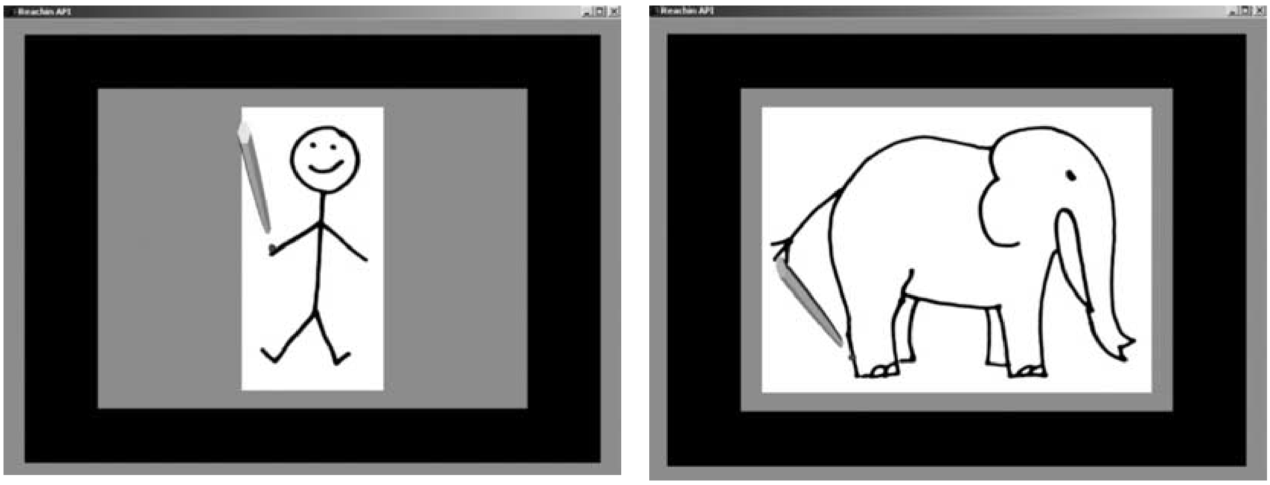


Fig. 6. The two line drawing environments used in the test.

than via a polygon representation. With today's object-oriented haptic programming interfaces, it is easier to construct the groove as a polygon mesh, as is 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 Figure 5.

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 who 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, the trunk or the tail.

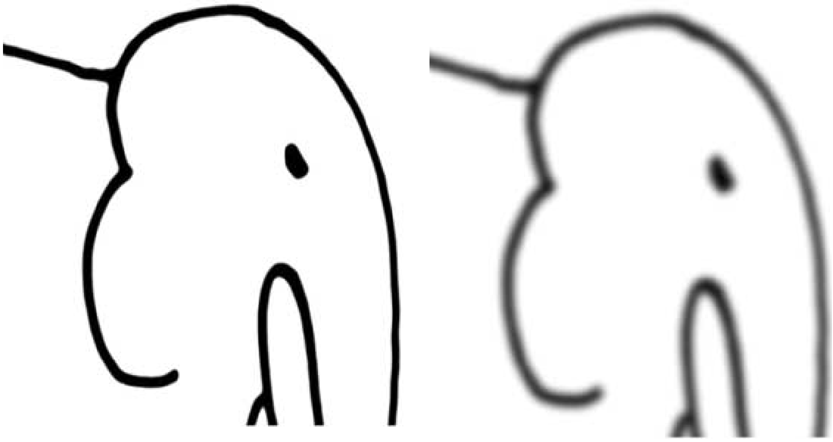


Fig. 7. Part of one original image and the corresponding blurred version used for the haptic interaction.

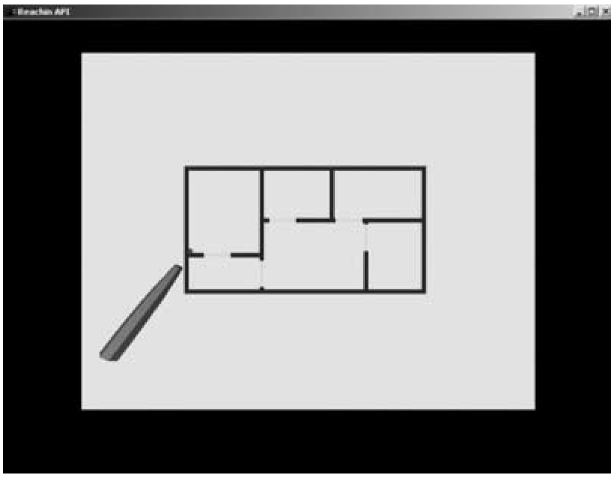
The haptic relief was rendered from scanned black and white images. The process of transforming the images to haptic reliefs was performed manually for these tests, but since the steps are rather straightforward in this case it is possible to carry them out automatically for any line drawing.

The process steps are:

1. Scan the image to a grayscale file
2. Apply gaussian blur
3. Render the image lines haptically raised (as ridges), or recessed (as grooves). Gray areas (from the blurring) are rendered less extreme in height than black areas.

The 'BumpmapSurface' from the Reachin API was used to render the image haptically. The BumpmapSurface node takes an image in PNG-format as an input to render a height-mapped surface on any object in the virtual environment. For this test, a map height of 4 mm was used. The blurring of the image is necessary to make the relief feel 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 rather uncomfortable. (See Fig. 7.)

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, feeling 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 it seems that it works very well in haptic reliefs. To move between the rooms,



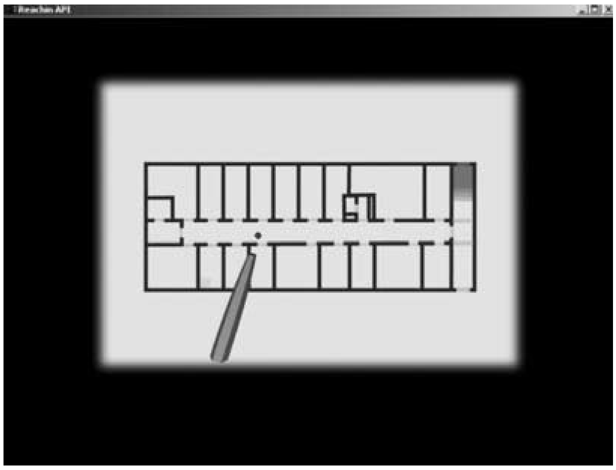


Fig. 8. The two different floor plan environments used in the test.

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 participants.

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 Fig. 8). 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 locate physically the room with the treasure in the real corridor. The second part of the floor plan test was only carried out in Sweden, since a map of the test site in Italy could not be finished in time for the tests.

Results

HAPTICALLY REPRESENTED MATHEMATICAL GRAPHS All the 24 users 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 (*SD* = 0.46) on a scale from 1 to 5, 5 being the most challenging. 72% managed to solve the ecological problem. The overall challenge of this test was rated as 2.2 (*SD* = 1.0) on average.

In the after-test questionnaire, 71% of the test participants said that they wanted to have a program like this. They said they wanted to use this kind of program for understanding sociological phenomena, checking their bank accounts, checking the stock market, feeling sound waves, etc. Today, 50% of the users said, they have the opportunity to feel curves, typically through the use of some kind of swell paper or plastic relief.

LINE DRAWINGS 62% could identify the stick man. Three of the users who failed thought it was a flower or a tree. 88% could identify parts of the line drawing 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 (SD = 1.4).

33% could identify the elephant. 83% could identify parts of the line drawing (such as the trunk and the tail) once they knew it was an elephant. The challenge of this test was judged as 4.0 (SD = 1.0) on the average.

The task of identifying parts of the line drawing was significantly easier than identifying what was depicted ($t(23) = 4.98$, $p < 0.05$).

HAPTIC MAPS AND FLOOR PLANS 83% of the users could count the right number of rooms in the apartment (6 rooms). No one answered more than one room too many or too few. 83% could find the specified room (only one user failed both tasks). The challenge for these tasks on the average was judged as 1.4 (SD = 0.63), respectively 1.4 (SD = 0.81).

Six of seven (86%) users could find the treasure on the corridor map. Of these six, five 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 (SD = 1.2).

GENERAL RESULTS

No significant differences between the total number of successfully completed tasks and the user characteristics of country, age, blindness from birth, job and type of manipulandum could be found, but men may have performed slightly better than women, ($t(22) = 2.01$, $p < 0.10$). This tendency was not related to any specific test; in other words the interaction test by sex was not significant.

Discussion and conclusions The following discussion of our results and their implications for future research will consider four topics: (1) the use of haptically represented mathematical graphs; (2) haptical realizations of drawings; (3) haptical representations of maps and floor plans; (4) transfer of haptically gained knowledge to real-life situations.

1. CAN HAPTICALLY REPRESENTED MATHEMATICAL GRAPHS ADD TO BLIND PERSONS' UNDERSTANDING OF THE UNDERLYING PHENOMENON? Haptically represented applied mathematics apparently functions quite well. 72% of the users did manage to solve the problem, and to do so they had to understand the underlying phenomena. The rather complex scientific phenomenon was chosen on purpose to see if the representations could really stand a difficult test. This strengthens the case that haptically represented mathematics is feasible, and we

also conclude that haptically represented mathematical graphs can provide blind persons with an understanding of underlying scientific phenomena, which is an important criterion for using a system like this in a real learning situation.

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.

2. CAN DRAWINGS BE HAPTICALLY RENDERED 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. In an application using haptic image rendering, contextual information can be given via any additional channel to enhance the probability for a correct understanding of the drawing. One example could be to use the ALT-text of an image on a web page transmitted via standard text access methods together with haptic rendering of the image itself.

The indication that contextual information is very important is also interesting compared to Kamel and Landay's[31] report on a Study of Blind Drawing Practice. 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 is a lot to be done in this area.

It was apparent during the test that part of the problems with the haptic drawings originate in some participants' limited familiarity with outline pictures in general. Also, limited familiarity with the objects depicted seemed to give problems for some of the users. For example, one of the participants said that he did not have any idea about what an elephant looks like, so it would be impossible for him to identify one on a picture.

Some of the users commented that the program should have used ridges for the elephant and grooves for the stick man. This is probably a good idea, 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.

It is concluded that this kind of haptically represented drawing is feasible but not always easily understandable. Contextual information is very important and seems to be working as a starting point that can lead to understanding of the whole picture.

3. CAN MAPS AND FLOOR PLANS ABE REPRESENTED HAPTICALLY AND BE USED BY BLIND PERSONS? It was quite evident that the maps worked well for a majority of the users. The fact that more than 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 usable information about environments such as the apartment represented in this test. Over 80% of the users also managed to

find the treasure on the considerably larger and more detailed map. This means that the size and the amount of details were not critical parameters for the ability to manage the map.

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.

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 surrounding area.

One of the important functions of a map or drawing is to give an overview. Because the sense of touch only works at one or a few points at a time, tactile and haptic maps require that the user actively scan the surface in order to understand what is felt and 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 that maps in different scales and with different amounts of detail should be supplied, as is the case with maps for sighted people. To achieve this technically does not require a significant expansion of our system; the problem lies in making the interaction in such a way that the user can maintain orientation and overview in the system even while zooming and scrolling. This is an area that would benefit from more research.

4. 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, a strong indication that the map information was really understood and that the knowledge is transferable to a real situation is clear. The only test participant who failed to find the room with the treasure, in spite of the fact that she had found it on the map, had interpreted the map correctly but misinterpreted the real environment, and 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. It would be most interesting to follow up this result with a study using more participants and several different maps.

GENERAL OBSERVATIONS 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 a negative relief 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. 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.)

FUTURE APPLICATIONS AND RESEARCH 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.

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.)[32] 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.

There are reasons to believe that training could improve the results, as it did in, e.g., Jansson and Ivås's[33] study on haptic identification of objects and a study on production and interpretation of perspective drawings by Heller et al.[34] To conclude, the 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.

References

1 The Phantom. Product Information from SensAble Technologies. Available at: http://www.sensable.com/products/phantom_ghost/phantom.asp. Accessed June 18, 2003.

2 Appelle S. Haptic perception of form: activity and stimulus attributes. In: Heller M, Schiff W, editors. *The Psychology of Touch*. Hillsdale, NJ: Lawrence Erlbaum Associates Inc., 1991;169–188.

3 Minagawa H, Ohnishi N, Sugie N. Tactile-audio diagram for blind persons. *IEEE T Rehabil Eng*. 1996; 4:431–437.

4 Shinohara M, Shimizu Y, Mochizuki A. Three-dimensional tactile display for the blind. *IEEE T Rehabil Eng*. 1998;6:249–256.

5 Holst A. Making the Windows environment touchable – feedback that really makes a difference. *Proceedings of CSUN Technology and Persons with Disabilities Conference*. 1999.

6 Jansson G, Fänger J, König H, Billberger K. Visually impaired person's use of the phantom for information about texture and 3d form of virtual objects. *Proceedings of the Third Phantom Users Group Workshop*. 1998.

7 Sjöström C. The Phantasticon – haptic interfaces give new possibilities for blind people [only the abstract is available in English]. Lund, Sweden: Certec, Lund University; 1997.

8 Sjöström C, Rassmus-Gröhn K. The sense of touch provides new computer interaction techniques for disabled people. *Technol Disabil*. 1999;10:45–52.

9 Yu W, Ramloll R, Brewster S. Haptic graphs for blind computer users. *Proceedings of the Haptic Human-Computer Interaction Workshop*. Glasgow, UK: University of Glasgow, 2000;102–107.

10 Sjöström C. Fantomaten – The Phantom för handikappade barn (The Phantom for handicapped children). Lund, Sweden: Certec, Lund University; 1996.

11 Sjöström C, Jönsson B. The Phantasticon – to use the sense of touch to control a computer and the world around you. *The 4th European Conference for the Advancement of Assistive Technology (AAATE)*. 1997.

12 Fritz J, Barner K. Design of a haptic data visualization system. *IEEE T Rehabil Eng*. 1999;7:372–384.

13 Van Scoy F, Kawai T, Darrah M, Rash C. Haptic display of mathematical functions for teaching mathematics to students with vision disabilities: design and proof of concept. *Proceedings of the Haptic Human-Computer Interaction Workshop*. Glasgow, UK: University of Glasgow, 2000;78–81.

14 Ramloll R, Yu W, Brewster S, Riedel B, Burton M, Dimigen G. Constructing sonified haptic line graphs for the blind student. *Proceedings of the Fourth International ACM Conference on Assistive Technologies (ASSETS)*. 2000;17–25.

15 Way T, Barner K. Automatic visual to tactile translation I: human factors, access methods, and image manipulation. *IEEE T Rehabil Eng*. 1997;5:81–94.

16 Way T, Barner K. Automatic visual to tactile translation II: evaluation of the TACTile image creation system. *IEEE T Rehabil Eng*. 1997;5:95–105.

17 Hernandez S, Barner K. Tactile imaging using watershed-based image segmentation. *The Fourth International ACM Conference on Assistive Technologies (ASSETS)*. 2000;26–33.

18 Eriksson Y. How to make tactile pictures understandable to the blind reader. *Proceedings of 65th IFLA Council and General Conference*. 1999 August 20–28.

19 Eriksson Y, Strucel M. Reliefbildsframställning på svällpapper (Relief image production using microcapsule paper, our translation). *The Swedish Library of Talking Books and Braille (TPB)*, 1994.

20 Tellgren A, Norberg A, Strucel M, Eriksson Y. Getting in touch with Stockholm – city guide for visually impaired people. *The Swedish Library of Talking Books and Braille (TPB)*, 1998.

21 Pai D, Reissel L-M. Haptic interaction with multiresolution image curves. *Comp Graph*. 1997;21:405–411.

22 Siddique J, Barner KE. Wavelet-based multiresolution edge detection. *Proceedings of International Conference on Image Processing*. 1998;550–554.

23 Roth P, Richoz D, Petrucci L, Pun T. An Audio-haptic tool for non-visual

image representation. *Conference Proceedings CD-ROM of the Sixth International Symposium on Signal Processing and its Applications (ISSPA)*. 2001.
24 Kurze M. Rendering drawings for interactive haptic perception. *Proceedings of the CHI 98 Conference on Human Factors in Computing Systems*. 1998;423–430.
25 Kurze M. TGuide – a guidance system for tactile image exploration. *Proceedings of the Third International ACM Conference on Assistive Technologies (ASSETS)*. 1998;85–91.
26 Sjöström C. The IT potential of haptics – touch access for people with disabilities. Lund, Sweden; Certec, Lund University. 1999.
27 Yu W, Guffie K, Brewster S. Image to haptic data conversion. *Proceedings of Eurohaptics*. 2001.
28 Arditi A, Holmes E, Reedijk P. Whitehouse R. Interactive tactile maps, visual disability and accessibility of building interiors. *Vis Imp Res*. 1999;1:1–21.
29 Holmes E, Arditi A. Wall versus path tactile maps for route planning in buildings. *J Visual Impair Blin* 1998;93:531–534.
30 Reachin Technologies AB. Company web site. Available from:URL: http://www.reachin.se. Accessed June 18, 2003.
31 Kamel H, Landay JA. A study of blind drawing practice: creating graphical, information without the visual channel. *The Fourth International ACM Conference on Assistive Technologies (ASSETS)*. 2000;34–41.
32 Nomad Mentor. Product information from Quantum Technologies. Available from:URL: http://www.quantech.com.au/products/quantum_products/tactile/nomad.htm. Accessed June 18, 2003.
33 Jansson G, Ivås A. Can the efficiency of a haptic display be increased by short-time practice in exploration?. *Proceedings of the Haptic Human-Computer Interaction Workshop*. Glasgow, UK; University of Glasgow, 2000;22–27.
34 Heller MA, Calcaterra JA, Tyler LA, Burson LL. Production and interpretation of perspective drawings by blind and sighted people. *Perception* 1996;25:321–334.

Appendix 5 - A Virtual Traffic Environment for People with Visual Impairments

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A Virtual Traffic Environment for People with Visual Impairment

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ABSTRACT This article reports results from a study in which ten severely visually impaired users used a virtual haptic-audio traffic environment for exploring and learning a route. The virtual environment was a model of a real traffic environment in Lund, Sweden, and included 484 static objects and 35 dynamic objects (cars and bicycles). Eight of the ten users were able to handle this large and complex environment, and the same users also succeeded in navigating the real traffic section from which the virtual environment was modeled. The users navigating the virtual world most easily were those that also were very good at navigating with a cane. Further results such as the identification of two different exploration strategies in the virtual model, different usages of this kind of model and the importance of relevant initial information are also discussed.

KEYWORDS Audio, haptic, interface, virtual reality, visual impairment

BACKGROUND AND INTRODUCTION

Although there are few studies on traffic accidents involving visually impaired people, there is some indication[1,2] that they suffer more accidents in the traffic environment compared to sighted people.

People with visual impairments often feel insecure in the traffic environment, and will often avoid situations that are perceived as insecure and dangerous. This results in limited accessibility not only to the traffic environment as such, but most environments outside the home.

Of course much can be done in the actual physical environment with tactile signs, sound signals, etc. But other measures, which provide information about the traffic situation and the traffic environment, can be equally important. In the study 'Traffic security, accidents and prevention among visually impaired persons in Umeå,[1] some users requested maps containing traffic and accessibility information. Furthermore, the need for an increased understanding among sighted persons is pointed out.

In this project, we investigate if and how virtual traffic environments can be made useful for blind users with the help of haptics and sound. With a virtual traffic environment, a blind user could safely investigate different traffic settings and situations. In 1999, Van Scoy et al.[3] suggested a similar project. Within our project, different ways of moving/scrolling the haptic world, preliminary zooming,[4] the design of sound feedback and environmental sounds are investigated in separate user tests. As a final test, a virtual model of a limited

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section of a real traffic environment was built, and the way users interacted with this environment was tested. The present article reports the outcome of this final test.

STATE OF THE ART

Haptic sensing is defined as the use of motor behaviors in combination with touch to identify objects.[5] There are a number of force feedback devices on the market today that make use of haptics to provide a computer user with a sense of touch. The simplest forms of force feedback devices are force feedback steering wheels for racecar computer games or force feedback joysticks for various other game playing. However, these devices have quite low resolution and small output forces. In research and medical applications, better-performance devices are used. These can be either onepoint or multi-point devices, i.e. provide a single touching point for one finger or up to several touching points for all fingers on one hand. In a one-point device the user usually holds a pen-like manipulator or perhaps uses a thimble on the index finger to sense the force, while a multi-point device is attached to a person's arm and fingers. The onepoint devices have the advantage of being cheaper and usually also have a better resolution and performance.

It has been shown possible to use one-point haptics alone to recognize basic shapes and textures.[6–8] Furthermore, haptics or haptics combined with sound have been used to interact with mathematical graphs, diagrams and maps.[3,9–14] Fairly complex environments involving large memory games,[13] explorative games[14] and traffic environments[4,14] have also been investigated.

Nevertheless, using one-point haptic VR is not the same as touching and manipulating objects with your own two hands. As pointed out in Jansson et al.,[6] the single contact point leads to problems when it comes to getting an overview or finding relevant parts of an object. Also, the contact point and the resolution of the device will put a limit on how the user perceives textures.[7,8] This puts particular demands on the design of the haptic virtual environment[13,15] as well as on guidance[13,16] and training,[17] and the need for fusing haptics with other modalities, particularly in more complex environments.[14]

Haptic interfaces and haptic-audio interfaces have been investigated to some extent, but a significant amount of work remains to be done. Mappings to the different modalities (here: sound and haptics) and the interplay between modalities need to be investigated in more detail, i.e. how do you optimize the mapping and what information should be present in the different modalities (or both). Also, the level of complexity present in the virtual environment needs to be increased to investigate the potential limits of systems and the usefulness of complex virtual environments.

The present study is one step on the road to increased complexity, since such a large haptic-audio environment has not previously been studied with blind users.

GOAL OF THE STUDY

The present study was designed to investigate how blind or severely visually impaired users can navigate and understand a large, complex haptic-audio virtual environment based on one-point haptics combined with 3D sound. The study was performed in an explorative manner; user comments, ways of interacting and navigating both the virtual and real world were observed and recorded.

TEST DESIGN

The test started with a short interview, after which the user was introduced to the virtual world. The different available methods of controlling the world were explained, and a short standardized verbal overview of each world segment was given. The description for the first segment was: 'In this part of the world there is one road, Malmövägen, going from south to north. Parallel to it is another road, Järnåkravägen.' The descriptions for the other segments were of a similar nature.

The test was divided into three subtasks. In subtask 1, the user was asked to explore the environment in order to find a number of hidden treasures. This task was really only intended to familiarize the user with the environment and thus help would be given if the treasures were too hard to find.

In subtask 2 the user was asked to describe/show a suitable route in the virtual environment from the bus stop (indicated by a cross in Figure 1) to the top of the rocket by the rock music concert hall 'Mejeriet' (indicated by a circle in Figure 1).

To test only haptic and sound feedback, the computer screen was turned away from the user during these tests.

Subtask 3 consisted of going out into the real world and walking the route described in subtask 2. The user

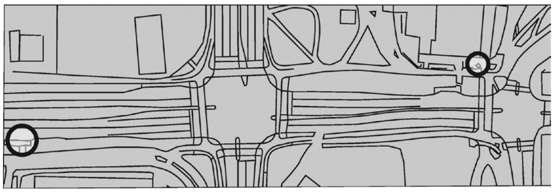

FIGURE 1 Map of the environment (north to the right).

was led to the bus stop, informed in which direction north lay, and then had to find the way on his or her own. During the test the test leader walked just behind the user, not to show the way, but close enough to be able to intervene in case of danger.

The entire test took between 2 and 2.5 hours to complete.

VIRTUAL MODEL

The virtual model contained 484 objects, making it considerably larger than models in other reported studies.[4,14,18,19] We used the ReachIn API for the haptic interaction and the static world objects were designed in 3DStudioMax and then imported into our program as VRML. Dynamic objects such as cars and bicycles were programmed directly in the ReachIn API. Due to problems with OpenAL (used by ReachIn) we used Direct3DSound for the implementation of the three dimensional sounds. Headphones were used for sound feedback.

All virtual world objects had surfaces with friction. Vegetation had a somewhat rougher surface compared to other objects, but to save processing power, more elaborate surfaces (such as bumpmap surfaces) were not used. The world was contained within walls as if it were in a box to stop the user from accidentally sliding off. These walls were slippery (without friction) to distinguish them from the world objects. Both walls and world objects were given sound labels which could be activated by touching them with the PHANToM stylus and pressing the PHANToM button. This action would also position the avatar (the user representation in the virtual world) at the position currently pointed to by the PHANToM stylus. The avatar was always positioned facing forwards just as the user was sitting facing forwards in front of the PHANToM. To a non-sighted user, the physical boundaries provided by the PHANToM may give the illusion of virtual objects, and thus the workspace was limited by a box from inside the program. Pressing the sides of this box was also used as an alternative way of scrolling/moving the world model.[4] The sides of this box emitted a short sound upon being hit to distinguish them from the world objects.

The dynamic objects within the world were cars and bicycles. They moved along pre-defined paths, but

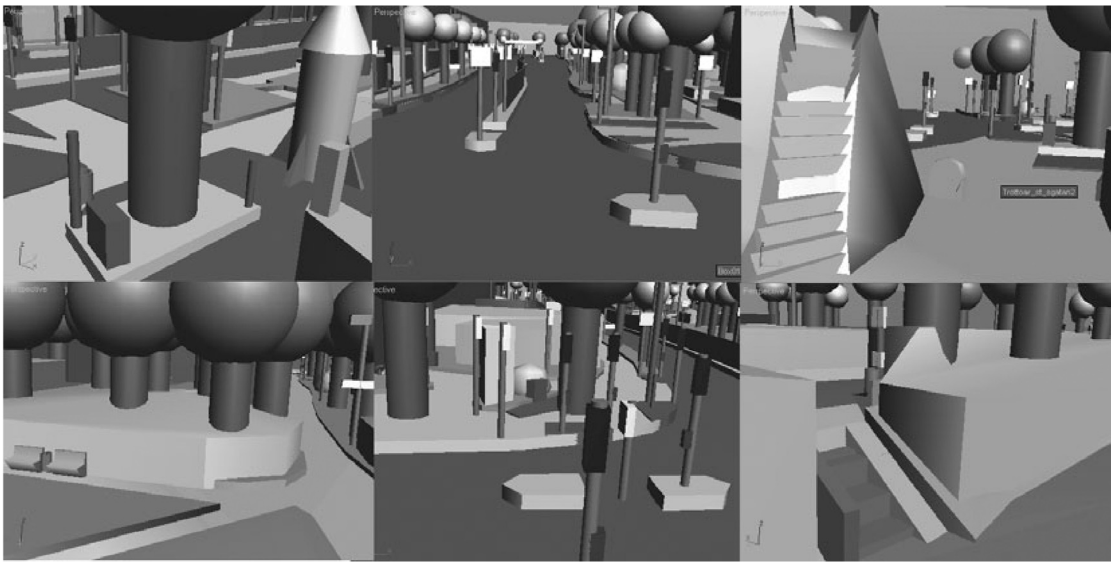

FIGURE 2 Six screen shots from the 3D model produced with 3DStudioMax. The bus stop by the top of the stairs in the lower right image was the starting point of subtask 2 while the roof of the rocket in the top left image was the goal (this rocket advertises a concert hall).

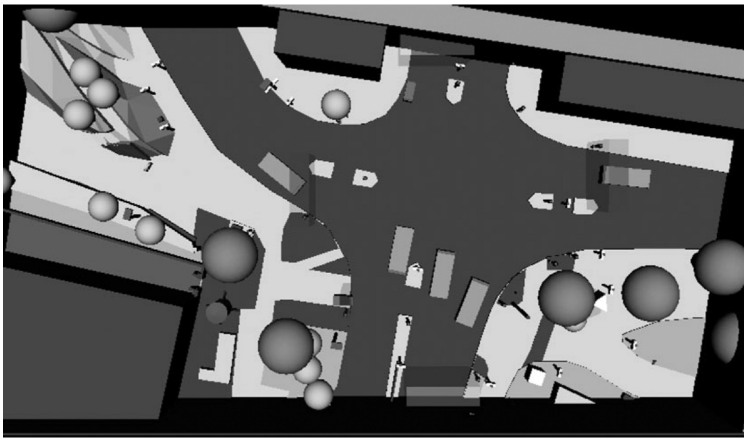

FIGURE 3 **A birds-eye screen-shot from a section of the haptic virtual world. Cars and bicycles are modeled as boxes since the one-point interaction makes it unnecessary to make more detailed models for dynamic objects. Also, the focus was on the traffic environment, therefore houses and trees were only schematically modeled. The semi-transparent boxes by the traffic lights show the state of the traffic light and allow the test leader to keep track of it. The static 3D model is the same as in Figure 2.**

stopped at traffic lights. Collision detection was also implemented between the dynamic objects to keep them from running into each other. These objects had a collision zone at the front (red in Figure 3), and if the user hit this part of the object, the car or bike would stop momentarily and emit a collision sound. Attached to each car was an engine sound consisting of 'brown' noise. Initially sounds from a real engine were tried, but the artificial noise produced a more realistic 'swishing' sound as the cars passed by in the virtual world. When the car hit the user, a sound of a bump followed by screeching tires was emitted. The bicycles were silent as they moved, but would emit a bicycle bell ring when hit. It should be noted that with a one-point interaction there is no need to use more elaborate dynamic objects than the simple boxes of this test application. The illusion produced by a simple box hitting the finger works just as well as a more complex shape.

The traffic lights in the virtual world controlled the flow of cars and bicycles, but they also emitted realistic ticking sounds when pedestrians were allowed to cross just as real world traffic lights do. As in reality, this sound was located in the box on the traffic light pole.

The world model could be scrolled/moved by using the keyboard arrow keys or by hitting the sides of the limiting box. The environment allowed zooming, but this function was rarely used.

Due to limited processing power, the world had to be divided into five segments. The test leader took care of switching between these segments at requests from the user. The limited processing power had the unfortunate side effect of influencing the way in which scrolling could be implemented, and we had to resort to fairly short scrolling steps which then did not work very well with pressing the sides of the limiting box as a way to initiate scrolling (for this type of scrolling you typically want a longer scrolling step). This biased the users towards using the keyboard for scrolling, which in this case worked better as they could keep pressing the arrow keys. To keep pressing does not work well in the case of the limiting box as the user quickly loses track of his or her position in the world–when using the keyboard this is not such a big problem as the user can put the PHANToM stylus close to a reference object and follow the world along.

We expect these problems to disappear with better processing power and the possible use of, for example, an octree space partitioning structure to exclude world objects far away from the PHANToM point.[20,21]

OBSERVATIONS

USER 1 Age 16. Female

Severely visually impaired since birth, but uses vision to navigate. Does not use a cane. Has tried the PHANToM once before. Rates her ability to navigate in unknown surroundings as 3.5 on a scale from 1 (poor) to 5 (good). This user is not accustomed to using maps and has not been in the Lund traffic environment modelled by the virtual environment.

The user has good exploration technique when using the PHANToM, and uses small careful movements to navigate. Despite her complaints about not understanding what the world looks like, with hints such as, 'It's on the other side of the road,' she produces adequate responses. The user could not complete subtask 2 without assistance, and also had problems with subtask 3, which she would not have been able to complete without guidance. When navigating in the real world, it seems as if loss of direction combined with great difficulty remembering the map are the main problems.

Subtask 1 and 2 are both rated as 4 on a difficulty scale ranging from 1 (easy) to 5 (hard).

This user comments that the reality was very different from the model.

USER 2 Age 29. Female

Can see light/darkness but does not use vision for navigation. Blind since birth. Uses a cane, and appears generally to be very good at navigating. Has tried the PHANToM once before. Rates her ability to navigate in unknown surroundings as 5 on a scale from 1–5. This user is very accustomed to using maps and has not been in the relevant part of the Lund traffic environment.

This user navigates the virtual model easily. She appears to have a good idea of what the environment looks like and, for example, finds the traffic lights and waits for the ticking signal to indicate green light before crossing the road. She can also apparently hear the cars coming, and jumps out of the way before being hit. This user describes the route in subtask 2 in a very detailed manner, and checks out which side of a pavement will be the best to follow with the cane, for example. She has no problem completing subtask 3 successfully.

Subtask 1 and 2 are both rated as 1 on a difficulty scale from 1 to 5.

This user comments that she would like to use both hands–or at least one finger from the other hand, to be able to keep track of reference points. She also comments that the virtual model was very good, and she really found nothing to complain about. She spontaneously rated subtask 3 as 0.5 difficult on a scale from 1 to 5. This user thinks models like this could be really useful particularly if information such as timetables, maps of stations, and train tracks is included.

USER 3 Age 57. Male

Can see light/darkness but does not use vision to navigate. Blind for the last 30 years. Uses a cane and appears to be generally quite good at navigating. Has tried the PHANToM once before. Rates his ability to navigate in unknown surroundings as 4 on a 1 to 5 scale. This user is not accustomed to using maps and has been in the relevant part of the Lund traffic environment.

This user initially has great problems with the virtual model due to the fact that a road he expected to run east/west runs north/south in the model. The road in question makes a 90-degree turn which the user was not aware of, and the discrepancy between his mental model of reality and the way the model showed it initially disturbed him very much. The problem was easy to observe, as he initially appeared to just jump around very much in the model. Once he had sorted out how the roads ran, his mode of exploration changed and he became much more systematic. After the initial problems, this user appeared not to have any great problems navigating the virtual world. He completed subtasks 2 and 3 without difficulty.

Subtask 1 and 2 were both rated as 2 on the 1 to 5 difficulty scale.

This user comments on the lack of overview. He wants a larger model, but also a larger working area (otherwise the bit you work with is too small). He also wants a whole model, and comments on the poor ergonomically designed working position (suggesting some external support for the arm used to interact with the PHANToM). This user thinks that this kind of model would be useful for learning about an unknown environment, but also for getting to know a familiar environment better. Despite the fact that he is well acquainted with the environment, he finds an unknown telephone box and some buildings and learns about the road he initially had problems with.

When discussing the complexity of the model he suggests that the number of trees and poles could be reduced–only keeping those necessary for navigation. He would also have preferred to move the world using the PHANToM and not the keyboard.

USER 4 Age 23. Male

Severely visually impaired but has some help from his vision. Uses a cane. Good at navigating. Has used the PHANToM once before. Rates his ability to navigate in an unknown environment as 3 on the 1 to 5 scale. He is fairly used to maps and is familiar with the relevant part of the Lund traffic environment (he lives nearby).

This user navigates the model better after a while. It is hard to say if this is due to training or because he is more familiar with the latter part of the environment. He completes subtasks 2 and 3 successfully.

Subtask 1 is rated as 3.5 and subtask 2 as 2 on the 1 to 5 difficulty scale.

This user comments that we should show where one can expect to encounter parked cars. He also does not want the moving cars. He thinks this program could be really good for indoor navigation, like finding a lecture hall and the things in it. He also suggests more sketchy maps, or a model of the train station where it is possible to feel the trains coming in. He would like more information connected to objects—he would like to touch the concert hall and find out the program for the evening, for example. He also thinks the kind of model tested may be good for training.

USER 5 Age 29. Male

Completely blind since 1975. Uses a cane and appears to be very good at navigating. Has tried the PHANToM once before. Rates his own ability to navigate in an unknown environment as 5 on a 1 to 5 scale. He is accustomed to using maps and has not been in the relevant part of Lund before.

This user appears to find it quite easy to navigate in the model. One example is that he stops at the traffic lights and waits for the green light. He uses small hand movements and is very systematic. He has no problems completing subtasks 2 and 3.

He rates subtask 1 as 4 and subtask 2 as 3 on the 1 to 5 difficulty scale.

This user comments that he finds the one point interaction a bit hard. He would like to feel with his hands, which is particularly apparent when it comes to deciding the absence of objects. He would like to have maps in this technology, possibly with different layers such as vegetation, traffic, roads, buildings, etc. He also comments that this could be good for learning/training.

USERS 6 and 7 Both are 23

User 6 is male and user 7 female. User 6 is severely visually impaired but uses vision for navigation. User 7 sees some color but does not use vision for navigation. User 7 uses a cane. User 6 leads user 7 when they are navigating together. User 6 has used the PHANToM three times earlier, while user 7 has only used it once before. Both rate their ability to navigate in an unknown environment as 2 on the 1 to 5 scale. User 6 is accustomed to using maps, while user 7 is not. Neither has been in the relevant part of Lund before.

These two users took the test together, sitting one at a time at the computer. They then walked together during subtask 3.

User 6 is a bit confused by the map initially but after a while he becomes more systematic. During subtask 2 he is initially confused by the absence of pavement along Malmövägen. After the initial confusion he successfully completes the subtask. User 7 explores the environment systematically. User 7 is also initially confused in the same way as user 6, but then manages to show the correct way. She has some problems right at the end (the sound does not work as it should) and manages to slip past the goal (the rocket). As she did show the correct way in general, she is given some hints on how to find the goal. User 6 and 7 complete subtask 3 together in pouring rain (user 6 leads). At one point they are about to walk a different way compared to the one they had indicated on the computer. They are then told, 'Now you are not walking the way you showed on the computer,' and they immediately correct themselves.

Both rate subtask 1 as 3 and subtask 2 as 2 on the 1 to 5 difficulty scale.

USER 8 Age 14. Male

Visually impaired but uses his vision for navigation. Does not use a cane. Has used the PHANToM roughly ten times before. Rates his ability to navigate in an unknown environment as 4 on the 1 to 5 scale. He is not accustomed to using maps and has not been in the relevant part of the Lund environment before.

This user jumps about quite a lot and often gets impatient when exploring the virtual model.

After a while he gets more systematic. He completes subtask 2 sucessfully although he loses track of the way for a while in the middle. He also completes subtask 3 successfully although he has to be stopped from walking out right in front of the cars at the beginning of the subtask.

He rates subtask 1 as 4 and subtask 2 as 2 on the 1 to 5 difficulty scale.

This user wants higher edges on the pavements and higher poles. He also thinks the virtual benches were hard to feel.

USER 9 Age 45. Male

Can see light/darkness but does not use vision for navigation. Visually impaired since childhood. Uses cane and dog. Very good at navigating. Has used the PHANToM once before. Rates his ability to navigate an unknown environment as 5 on the 1 to 5 scale. He is accustomed to using maps and has not been in the relevant part of the Lund environment.

This user does not appear to have any problems with the virtual environment. He actually discusses the accessibility of different solutions in the traffic environment by showing good/bad solutions to the test leader and explaining and demonstrating with the PHANToM why they are good/bad. He waits for the traffic lights and generally gives the impression of haveing a very good understanding of the environment. He successfully completes both subtasks 2 and 3 without problem (he does not use the dog for subtask 3).

He rates subtask 1 as 3 and subtask 2 as 4 on the 1 to 5 difficulty scale. The high rating on subtask 2 is motivated by the poor design from an accessibility perspective of the real environment (which is reflected by the model).

He spontaneously comments,'This was better than I thought–it actually feels as if I have walked here before,' when walking in the real environment. He also thinks this is so good we should contact people working with navigational training for visually impaired persons.

In addition, he would like more maps, possibly with different layers with varying content. And he points out that it is also important with details outside the 'right' way, as these may be needed in case one gets lost.

USER 10 Age 13. Female

Blind from birth. Uses a cane, but her father usually leads her and she has problems navigating independently. Has used the PHANToM about six times before. Rates her ability to navigate in an unknown environment as 2. Is not accustomed to using maps and has not been in the relevant part of the Lund environment.

This user has problems understanding the environment and jumps about quite a lot. She cannot complete subtask 2 and the test leader describes the way to her instead. She cannot complete subtask 3 independently, but it is interesting to see how she and her father communicate about the environment by referring to the virtual model.

She rates both subtask 1 and 2 as 5 on the 1 to 5 difficulty scale.

Her father feels that this could be very useful for training. He also suggests that the model should show suitable ways of getting to different places.

The results are summarized in Table 1.

It should also be pointed out that the users who found the virtual world most easy to navigate (users 2, 3, 5 and 9) were also the ones who appeared to be best at navigating with a cane. None of these users utilized vision for navigation.

EXPLORATION PATTERNS

In addition to the above observations, the program logged the way the user interacted with the program. These log files show interesting patterns in that they reflect some of the explorative behaviors of the users. In the following figures, a small dot indicates a click on the PHANToM pen button, which will provide the user with spoken sound information about the surface in that particular point (e.g. grass). Such a click also moves the avatar (the virtual person) ear position, as it was

TABLE 1 **Overall Test Results.**

User nr	Age	Uses vision as help for navigation	Has been in the environment before	Map experience	Uses cane	Subtask 2 completed successfully	Subtask 3 completed successfully
1	16	X					
2	29			X	X	X	X
3	57				X	X	X
4	23	X	X	(X)	X	X	X
5	29		X	X	X	X	X
6	23	X		X	X	X	(X)
7	23				X	(X)	(X)
8	14	X				X	(X)
9	45			X	X	X	X
10	13						

User 9, task 2

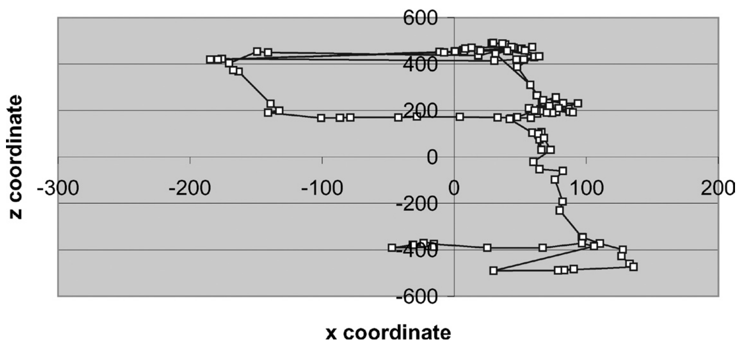

FIGURE 4 **PHANToM stylus position in z-x plane at sound label requests during subtask 2 (user 9).**

computationally impossible to let the virtual ears continually follow the exploration point. The lines between the dots do not exactly show the exploration path, but are only straight lines between dots to show in which order sound information was requested.

If we look at the log file from subtask 2 for user 9, for example (as is shown in Figure 4 below), we see that the user appears to have a rather clear picture of where he is heading, and that sound labels (or ear movements) are requested as confirmation along the way. Some exploration takes place occasionally, but generally this user appears to have a good idea of where to go. Figure 4 thus confirms the observations made during the test.

If we look at the log file for the exploration task (subtask 1) for the same user the picture is different. The x-z position for the PHANToM stylus at sound label requests (Figure 5) shows a pattern which indicates fairly few requests and a systematic exploration. Again, this confirms the observations made during the test.

This can be contrasted with, for example, the log files for user 8. In Figure 6 the log file for subtask 2 is shown for this user, and considerably more sound label requests are seen, together with more jumping about behavior along the route.

The same picture can be seen in the log file from subtask 1. Significantly more sound label requests are made and the exploration covers much of the available area. This again confirms the observations made during the test.

That the data from the log file must be treated with caustion and supplemented with observations during the test is shown by user 2. Just from looking at the log file as it is shown in Figure 8 it may appear as if this user was jumping about a lot. This was not the case, however. Instead, this user was extremely careful in her exploration, and she investigated the path, and

User 9, task 1

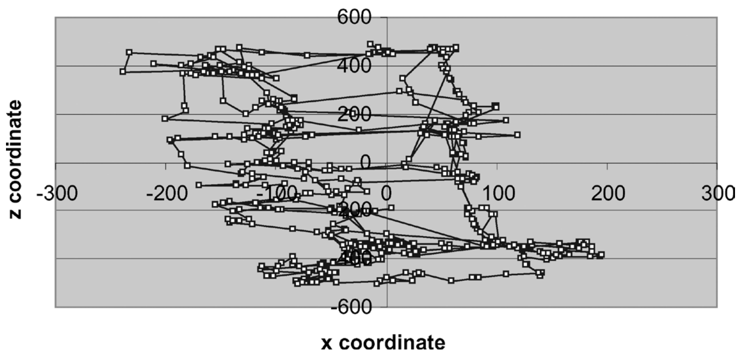

FIGURE 5 **PHANToM stylus position in z-x plane at sound label requests during subtask 1 (user 9).**

C. Magnusson and K. Rassmus-Gröhn 8

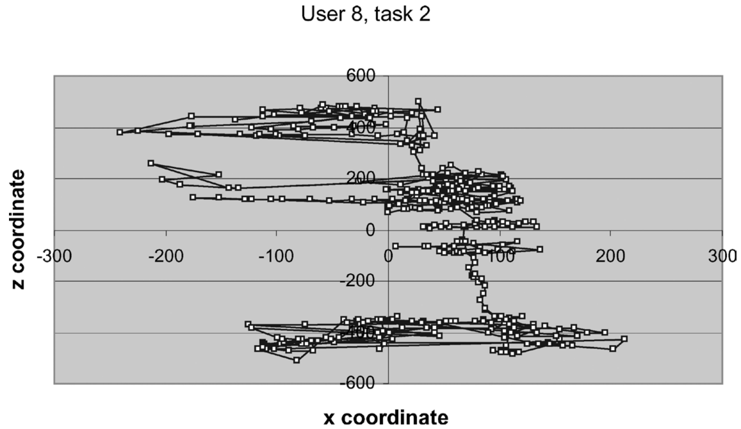

FIGURE 6 PHANToM stylus position in z-x plane at sound label requests during subtask 2 (user 8).

the objects around it, with much more detail than both the previous users.

In a sense these figures also reflect the two types of exploration behavior that were seen during the tests. Some users relied mainly on the haptic information and clicked to obtain sound information on the basis of what they could feel haptically. Others clicked to obtain sound information almost all the time, and gave the impression of using sound rather than haptics as their primary input.

This can also be reflected by the number of objects touched in between two clicks, as well as the total number of clicks, which are seen in Table 2. The total number of clicks is also influenced by how carefully the user explores the environment. User 2, for example, explored the world in great detail as was already mentioned.

It is interesting as well to look a little more in detail at how theses clicks are distributed. If we compare subtask 2 for user 7 (low average and standard deviation) to user 9 (high average and standard deviation), we see that user 9 appears to explore a lot more haptically between clicks for sound information and thus uses considerably fewer clicks (Figure 9).

DISCUSSION

The results of this test show that most of the users were able to understand and navigate in this fairly complex virtual model. It was interesting to note that the users who seemed particularly good at navigating with a cane also appeared good at exploring and navigating the virtual world using the PHANToM. This particularly becomes quite interesting if it can also be shown to work the other way around, i.e., if practicing in a virtual world using the PHANToM can be shown to improve navigational skills in the real world. The PHANToM

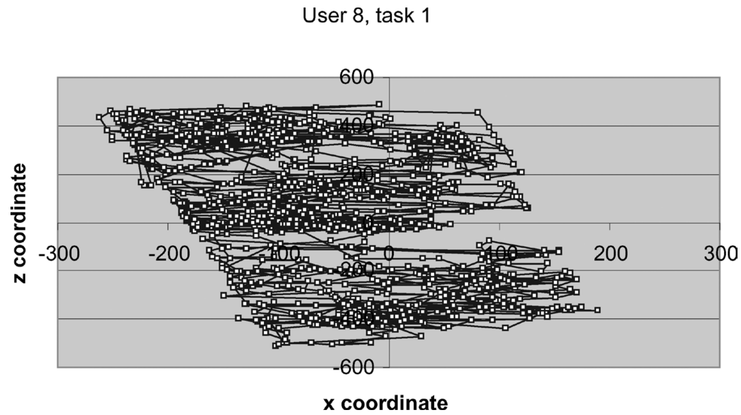

FIGURE 7 PHANToM stylus position in z-x plane at sound label requests during subtask 1 (user 8).

User 2, task 2

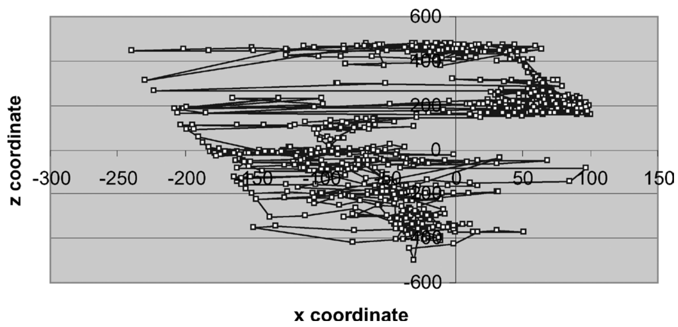

FIGURE 8 PHANToM stylus position in z-x plane at sound label requests during subtask 2 (user 2).

is not entirely unlike a cane in that it provides limited contact with the world, so possibly strategies as well as the ability to create a mental model of an environment using input from limited sensory input could be trained. Of course, information about environmental properties could also be learned. Such possible training effects need to be the subject of further studies.

The amount of work needed to produce the present type of model is somewhat prohibitive to the immediate production of large numbers of user specific environments like the route to school for a certain student. When and if the generation of 3D models of the real world can be performed in a more efficient manner, the user responses show that there is a demand for these kinds of environments. The user responses also show a demand for more schematic, map-like environments. Such environments have already been suggested by different authors[3,14] and the results of this test strengthens this suggestion.

A further utilization of such a model already apparent in the present test was as a means of communication between a sighted and a blind user. This is a way for the accessibility of different designs to be visualized/articulated and discussed.

The present study contained both haptics and sound. It was interesting to note that different users utilized the sensory modalities differently. Some users appeared to rely mainly on the audio feedback, and would click for sound information very often. Such users would have benefited from a continous change of the avatar position–i.e., the position of the user's ears in the environment changing as the PHANToM position changes (with the computer capacity available, this was not possible to implement). Other users employed haptic

TABLE 2 Average Number of Objects Touched in Between Clicks for Sound Information. (—) Signifies Missing Data, While (*) Indicates that this User was Guided Through the Exploration Process

User nr	Average nr of objects touched, subtask 1	Standard deviation, subtask 1	Total number of clicks, subtask 1	Average nr of objects touched, subtask 2	Standard deviation, subtask 2	Total number of clicks, subtask 2
1	2.4	5.0	1490	—	—	—
2	3.4	6.8	2171	3.1	5.8	1213
3	—	—	—	—	—	—
4	2.5	4.1	1975	1.3	2.2	648
5	2.7	6.7	1993	3.6	7.8	637
6	—	—	—	2.2	3.5	312
7	—	—	—	1.3	1.9b	421
8	3.8	7.1	1605	3.3	5.7	533
9	4.7	10.9	985	5.6	8.7	149
10	2.8	4.8	2357	2.5*	4.3*	232*

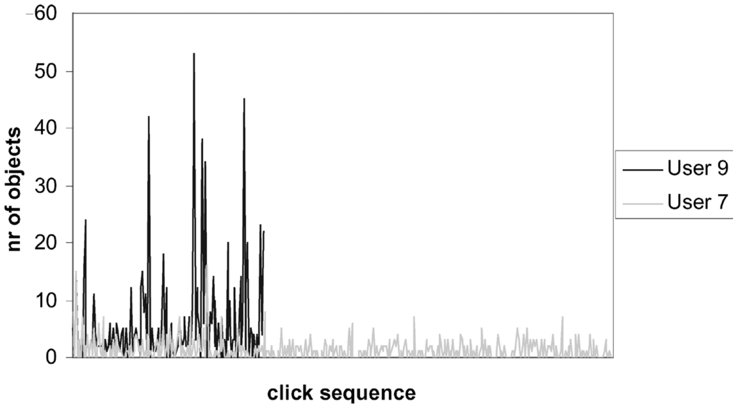

FIGURE 9 **Number of objects touched in between clicks for sound information for user 7 and user 9.**

exploration more often, and used the sound labels more as confirmation. For such a user it is actually beneficial to be able to put the avatar in a specific position and then to explore haptically around that position (this was also explicitly stated by user 9 in reply to the suggestion that the sound should change continously). Thus, it is important to consider both users relying primarily on sound and those relying primarily on haptics when designing these types of virtual environments.

The scrolling or moving of the world was possible to perform both by using the arrow keys on the keyboard and by pushing the sides of the limiting box.[4] The drag function implemented in Magnusson et al.,[4] was omitted as the PHANToM button was needed for the placement of the avatar. Unfortunately, computer problems made it necessary to implement the scrolling function with a very short moving distance. This reduced the usefulness of the pushing of the limiting box function, and most users used the keyboard to move the world (with the keyboard it was easier to keep pressing a key and thus to move the world a longer distance faster).With a single virtual model and with a longer moving distance, we expect more users to make use of the pushing function which also was the preferred one for navigation in Magnusson et al.[4]

The problems experienced due to the limited processing power of the test computer highlights the need for some kind of space partitioning structure[20,21] for larger world models.

Finally the test results confirm the observations made in[14] that the expectations of the user heavily influence the results. Several users had problems with the fact that the route from the bus stop at Malmövägen was unusual. They kept looking for pavement or a pedestrian crossing for a long time before they realized that they had to go down the stairs at the back and follow Järnåkravägen instead. A similar effect is seen for user 3 where his erroneous image of the environment initially made the virtual environment very hard for him to understand.

CONCLUSION

A majority (80%) of the test users were able to handle the present large complex haptic-audio virtual environment. The users appearing to navigate the virtual world most easily were the same users who seemed very good at navigating with a cane. From this we infer that some similarities appear to exist between cane navigation and PHANToM navigation, and it is suggested that this effect could be used in the other direction (i.e., for training). A further use of this type of model is as a visualization/articulation tool for discussing accessibility. Two different explorational modes were identified, one apparently relying more on sound and one relying more on haptics. Interfaces of this type need to cater to both these explorational strategies.

The study shows a demand both for the investigated detailed 3D models as well as more schematic, map-like environments. It also indicates a need for more automatized ways of creating such environments. The test confirms the importance of initially providing the user with relevant environmental information. During the test the test leader provided this initial information verbally, but this could easily be included as recorded verbal descriptions. Finally, the processing problems encountered during the design of the virtual world, indicate that some kind of space partitioning structure (such as an octree) may be needed to exclude irrelevant objects from the haptic loop.

REFERENCES

[1] Lundälv J. *Trafiksäkerhet, skadehändelser och prevention bland synskadade i Umeå stad*. 1999:Umeå.

[2] Gallon C, Fowkes A, Edwards M. *Accidents Involving Visually Impaired People Using Public Transport or Walking*. 1995, Transport Research Laboratory: Crowthorne.

[3] Van Scoy FL, Baker V, Gingold C, Martino E, Burton D. *Mobility Training using a Haptic Interface: Initial Plans*. in *Fourth Annual PHANTOM Users Group*. 1999. Dedham, MA.

[4] Magnusson C, Rassmus-Gröhn K. *Non-visual Zoom and Scrolling Operations in a Virtual Haptic Environment*. in *Eurohaptics*. 2003. Dublin, Ireland.

[5] Appelle S, *Haptic perception of form: Activity and stimulus attributes*, in *The Psychology of Touch*, M. Heller, Schiff,W, Editor. 1991, Lawrence Erlbaum Associates Inc: Hillsdale, NJ. pp. 169–188.

[6] Jansson G, Fänger J, Konig H, Billberger K. *Visually Impaired Persons' Use of the PHANToM for Information About Texture and 3D Form of Virtual Objects*. in *PHANToM Users Group Workshop*. 1998. Dedham, MA.

[7] Jansson G, Petrie H, Colwell C, Kornbrot D, Fänger J, König H, Billberger K, Hardwick A, Furner S. *Haptic Virtual Environments for Blind People: Exploratory Experiments with Two Devices.* International Journal of Virtual Reality, 1999.

[8] Penn P, Petrie H, Colwell C, Kornbrot D, Furner S, Hardwick A. *The Haptic Perception of Texture in Virtual Environments: An Investigation with Two Devices*. in *Haptic HCI*. 2000. Glasgow, UK: Springer.

[9] Fritz JP, Barner KE. *Design of a Haptic Data Visualization System for People with Visual Impairments.* IEEE Transactions on Rehabilitation Engineering, 1999. 7(3).

[10] Yu W, Brewster SA. *Comparing Two Haptic Interfaces for Multimodal Graph Rendering*. in *Haptics 2002—IEEE VR2002, 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. 2002. Florida, USA.

[11] Yu W, Ramloll R., Brewster SA *Haptic Graphs for Blind Computer Users*. in *First Workshop on Haptic Human-Computer Interaction*. 2000. Glasgow, U.K.: Springer.

[12] Van Scoy FL, Kawai T, Darrah M, Rash C. *Haptic Display of Mathematical Functions for Teaching Mathematics to Students with Vision Disabilities: Design and Proof of Concept*. in *Haptic HCI*. 2000. Glasgow, Scotland: Springer.

[13] Sjöström C, *The IT Potential of Haptics—touch access for people with disabilities*, in *Dept. for Design Sciences*. 1999, Lund University: Lund.

[14] Magnusson C, Rassmus-Gröhn K, Sjöström C, Danielsson H. *Navigation and Recognition in Complex Haptic Virtual Environments—Reports from an Extensive Study with Blind Users*. in *Eurohaptics*. 2002. Edinburgh, UK.

[15] Challis BP, Edwards ADN *Design Principles for Tactile Interaction*. in *First International Workshop on Haptic Human-Computer Interaction*. 2000. Glasgow, U.K.: Springer.

[16] Fänger J, König H, Schneider T, Strothotte G, Weber G. *Guided and Free Haptic Exploration of 3D Models*. in *7th International Conference on Computers Helping People with Special Needs (ICCHP 2000)*. 2000. Karlsruhe, Germany.

[17] Jansson G, Ivås A. *Can the Efficiency of a Haptic Display Be Increased by Short-Time Practice in Exploration*. in *Haptic HCI, First Workshop on Haptic Human- Computer Interaction*. 2000. Glasgow, U.K.: Springer.

[18] Wood J, Magennis M, Arias EFL, Gutierrez T, Graupp H, Bergamasco M. *The Design and Evaluation of a Computer Game for the Blind in the GRAB Haptic Audio Virtual Environment*. in *Eurohaptics*. 2003. Dublin, Ireland.

[19] Jansson G, Larsson K. *Identification of Haptic Virtual Objects with Different Degree of Complexity*. in *Eurohaptics 2002*. 2002. Edinburgh, UK.

[20] Raymakers C, Coninx K. *Improving Haptic Rendering of Complex Scenes using Spatial Partitioning*. in *Eurohaptics*. 2003. Dublin, Ireland.

[21] Aamisepp H, Nilsson D. *Haptic Hardware Support in a 3D Game Engine*, in *Computer Science*. 2003, Lund University: Lund.

This thesis deals with possible solutions to facilitate orientation, navigation and overview of non-visual interfaces and virtual environments with the help of sound in combination with force-feedback haptics. Applications with haptic force-feedback, spoken and/or non-spoken audio in mono, 2D or 3D were developed and tested by users who were blind, had low vision or were sighted.

The resulting research deals in part with the blind user's representation of himself/herself in a 3D audio-haptic virtual environment, and how the user can move the virtual ears – "ears-in-hand" – with the haptic display. The "ears-in-hand" method was tested by 10 blind users in a virtual traffic environment, and by 12 sighted users in a location test.

A drawing program for visually impaired children was sonified, where the virtual drawing pen position was mapped to pitch and pan to help the user orient himself/herself on the virtual paper. A reference group of 5 blind or low vision children have evaluated the application on an ongoing basis.

Usability tests involving 25 blind users using haptic-only virtual environments are presented that show common problems in interaction and illustrate the need for sound feedback in non-visual force-feedback haptic virtual environments.

This thesis can also be found on the Internet:
www.certec.lth.se/doc/enablingaudiohaptics

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