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User-Centered Design of Non-Visual Audio-Haptics

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Doctoral Thesis

Certec, Rehabilitation Engineering Research
Department of Design Sciences
Faculty of Engineering
Lund University

Lund 2008

User-Centered Design of Non-Visual Audio-Haptics

Kirsten Rassmus-Gröhn

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Department of Design Sciences

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For the strength of the Pack is the Wolf,
and the strength of the Wolf is the Pack

Rudyard Kipling, The Law of the Jungle

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Kirsten Rassmus-Gröhn, Lund, October 24, 2008

Abstract

Persons who have visual impairments are still excluded from accessing certain types of information that are accessible to the general public. Today, screen reading software and Braille displays or text-to-speech systems are used for enabling access to text. For accessing graphics, and especially digital graphics, no standardized technology is in widespread use. In school education, preprinted material with relief pictures complicates teamwork in collaborative settings, making it harder for pupils with visual impairments to work together with their sighted peers and to make it possible to acquire a shared understanding of school material.

The emergence of haptic hardware and the possibility to create interfaces for non-visual audio-haptic interaction has opened a door to the access of digital graphics and 3D models. Still, the high price of high-precision haptic devices is a hindrance, as well as the lack of useworthy applications.

In relation to the design of audio-haptic interfaces, this thesis has the following aims:

- To show that the audio-haptic technology adds functionality and meaning, because the currently used technological aids cannot provide the dynamic information access that the audio-haptics can
- To show that it is possible to undertake on-site user testing of audio-haptic applications in a school environment together with children with blindness, their sighted peers and their teachers
- To describe an activity based user-centered iterative process in the development of a prototype of a non-visual drawing application for collaborative use in school (the AHEAD application)
- To emphasize the need of applying a context based, activity based and situated approach to design of artifacts for assistive use
- To exemplify the possibilities to carry out collaborative work between pupils with blindness or low vision and their sighted classmates, even when material is based on graphics

The results demonstrate the value of working close to pupils and teachers and of evaluating new applications and technology in real situations and contexts. The long-term studies also made it possible to focus more on the process than on single usability studies.

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Introduction

This doctoral thesis presents research in the field of non-visual audio-haptic application design. It consists of a collection of articles and a summary, and is focused on recent research concerning the integration of audio-haptic technology in school work.

When desktop haptic technology first entered the scene in the early to mid-1990s, an application area that seemed natural was computer interaction for people with low vision and blindness, since it added a new modality to the available ones. At the time, synthetic speech and Braille displays provided access to digital text, but the recent emergence of graphic display for computer related information introduced a problem for the community of computer users who relied on non-visual information. Since then, researchers have put interest and effort into investigating the possibilities of using audio display in combination with haptic technology for non-visual digital graphic and model access (see Figure 1). Most of the applications developed are experimental, designed to study details in interaction with audio-haptics and are not intended for widespread use.

Figure 1 A person using a haptic desktop device (the PHANToM) for editing a digital hand drawing

There are, as yet (2008), in practice no end users who are using audio-haptics for the purpose of accessing graphics and models. There can be many reasons for this but the combination of haptic precision devices being expensive and there being no audio-haptic software that reliably solves major problems of graphic access are two key issues. If audio-haptic technology is to reach a larger audience, design and development needs to shift focus from research vehicles to tools designed for practical use.

Aim

This thesis deals with one way to design useworthy tools by involving users in the process and by doing so in an arena where the cost for audio-haptics may easier be justified. A special consideration has been to support collaborative work between pupils who are blind or have low vision and their sighted class mates. In this context, this thesis has five aims:

- To show that the audio-haptic technology adds functionality and meaning, because the currently used technological aids cannot provide the dynamic information access that the audio-haptics can
- To show that it is possible to undertake on-site user testing of audio-haptic applications in a school environment together with children with blindness, their sighted peers and their teachers
- To describe an activity based user-centered iterative process in the development of a prototype of a non-visual drawing application for collaborative use in school (the AHEAD application)
- To emphasize the need of applying a context based, activity based and situated approach to design of artifacts for assistive use
- To exemplify the possibilities to carry out collaborative work between pupils with blindness or low vision and their sighted classmates, even when material is based on graphics

Personal research background and declaration of work

I have been able to follow the development of the haptic force-feedback technology from the first not-quite-stable PHANToM device to the consumer affordable Novint Falcon for a period of about 13 years. At the same time, computer sound systems have evolved from reproducing stereo (at the most) to providing 3D sound as in computer games. During the very first years I was occupied with other research and work. I began to participate in the initial haptic work in 1998 by demonstrating, testing and programming haptic concept applications. These early applications were designed to assess whether a haptic device with an appropriate application or model could at all be used to access information. Would people understand the models or the dynamic applications and be able to use them as intended? Was it at all fruitful to continue designing haptic applications for non-visual use? This initial work is presented in the article:

The Sense of Touch Provides New Computer Interaction Techniques for Disabled People
Calle Sjöström, Kirre Rassmus-Gröhn
Technology & Disability (IOS Press) Volume 10, Number 1, 1999

The next step was a large-scale feasibility study where 23 users with blindness or low vision participated in evaluating non-visual use of haptic 3D models, textures, line drawings and dynamic applications such as simple games and maps. I was responsible

for the programming of 3 of the environments that were tested and co-designing the evaluation and the post-test analysis. This is explained in more detail in my licentiate thesis and two articles:

Enabling Audio-Haptics
Kirsten Rassmus-Gröhn
Licentiate Thesis, Certec 2:2006, Department of Design Sciences, Lund University, September 2006, Lund, Sweden

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, July 8-10, 2002, Edinburgh, UK
Appended to this thesis, see also "Selection and summary of publications"

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

One of the application ideas evaluated in the large-scale study mentioned above was a small dynamic traffic environment with houses, sidewalks and moving cars. The application idea appealed to the users and the project that followed aimed at designing and evaluating a more realistic traffic environment and also evaluating it for use in learning routes and safe behavior in traffic situations. The research concerned many aspects of design in virtual audio-haptic environments, and I conducted pilot studies on 3D sound use in haptic environments and on avatar orientation. These are presented in my licentiate thesis (listed above). I also participated in designing a pilot study on design of scroll and zoom in haptic virtual environments that extend beyond the reach of the device arm. This and the final evaluation of the completed virtual traffic model in a learning situation in which the 10 participants first used the model and then walked in the real traffic environment are reported in:

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

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

For the last three years my main focus has been on a long-term user-centered iterative design process of a learning tool for school use. Throughout the process, I have had close contact with a group of five youths, their parents and teachers. The youths are blind or have low vision and attend integrated classes in compulsory school and high school. It was during this time that I co-developed AHEAD: an audio-haptic editor

and explorer for 2D drawings for use in education. My main responsibility was sound programming and auditory icon design. Most design decisions concerning the interaction were made collaboratively. I also conducted evaluation meetings regularly with the user group, and field studies in the schools of the youths. The evaluation meetings incorporated interviews with parents and youths, and informal and formal test sessions evaluating the AHEAD application or other applications relevant to the design process. At the meetings, my main responsibility was to focus on sound design evaluation. I was also responsible for and conducted two special evaluations: a semi-formal study where three of the five youths in the user group participated, and a formal study with 11 adults, presented in:

User Evaluations of a Virtual Haptic-Audio Line Drawing Prototype
Kirsten Rassmus-Gröhn, Charlotte Magnusson, Håkan Eftring
Workshop on Haptic and Audio Interaction Design, August 31-September 1, 2006, University of Glasgow
Appended to this thesis, see also "Selection and summary of publications"

The complete design process right up to but not including the final evaluation was presented in:

Iterative Design of an Audio-Haptic Drawing Application
Kirsten Rassmus-Gröhn, Charlotte Magnusson, Håkan Eftring
CHI 2007 Work In Progress, April 28-May 3, 2007, San Jose, California, USA
Appended to this thesis, see also "Selection and summary of publications"

The iterative design process of the AHEAD application came to an end in the spring of 2007, and the final application was evaluated at five schools. For every person in the user group, I designed the material for the lessons, and collaborated with the teacher(s) in choosing tasks and material to fit the curriculum and subject. I also conducted the final evaluations with my colleagues and carried out post-test analysis of video material and interview results. Preliminary results of the complete post-test analysis were presented in the article:

AHEAD – Audio-Haptic Drawing Editor and Explorer for Education
Kirsten Rassmus-Gröhn, Charlotte Magnusson, Håkan Eftring
HAVE 2007 – IEEE International Workshop on Haptic Audio Visual Environments and their Applications, Ottawa – Canada, 12-14 October 2007
Appended to this thesis, see also "Selection and summary of publications"

The work presented above is the backbone of my research. I have also participated in smaller studies and written portions of articles on research that is closely related. These can be found in my publications list online (Rassmus-Gröhn, 2008).
In this thesis, the iterative design process of the AHEAD application comprises a large proportion of the content in the summary section, and three out of five of the appended publications. I have chosen to do so because the final evaluation of the

AHEAD application convincingly demonstrates the value of working close to pupils and teachers in the design process, and that new applications and technology should be evaluated in real situations and real contexts. The iterative design process also made it possible to see progress over time, and to focus more on process than on single usability studies. The longitudinality and school integrated nature of the AHEAD study more obviously reveals user relevant and new knowledge than does my previous work which was more focused on traditional artificial and one-shot usability studies.

Background

This chapter describes the background technology of haptic and audio interaction and some aspects on interaction design. I will also present the background of non-visual access to graphic material.

State of the Art – audio-haptic interaction

Haptic desktop technology has been available since the mid-1990s. Still, the technology has not spread widely. Therefore, the section on haptic interaction is written at an overall, introductory level. For more detailed descriptions about haptic technology, application areas and devices, see McLaughlin, Hespanha, & Sukhatme (2002) for example.

Haptic interaction

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" (Burdea, 1996). In the mid-90s, force feedback and tactile displays for desktop use were developed at, for example, Sensable Technologies (2006) and Immersion Corp (2006).

The term haptics is used to describe different concepts related to human perception and understanding through touch (Ruspini, 2003). The term comes from the Greek word *haptein* which means, *to touch*. In *Touching for Knowing* (Hatwell, Streri, & Gentaz, 2003), 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, for example, the haptic sense is active when 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. Although the word *haptics* encompasses all aspects of touch, force feedback displays are more often referred to as *haptic displays*. I will in this thesis use *haptic display* and *force feedback display* as synonymous expressions.

Haptic / Force-feedback displays

Most displays for force feedback use motors and linkages to convey forces to a user's finger, hand or arm at one single point. The single-point interaction, in a non-visual context, also forces a user to actively create a mental picture of a model by exploring it, and thus receiving information serially.

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 and repelling forces. Contact with a virtual surface is simulated by computing the appropriate force based on the current position of the end-effector and the virtual model of the object. The force calculation (the "haptic loop") needs to be updated at least at a 1000 Hz to provide a force rendering that the user perceives as accurate and stable (as a comparison, the graphic

loop for computers is rarely faster than 100 Hz). This puts a special demand on computer performance. It is equally important that the device feels free and weightless when no force is applied (Sensable Technologies, 2005).

There are a number of different force feedback displays available today. A large number of the devices have been developed by research institutes and universities. These are naturally not possible to purchase as easily as those in the open market. For researchers who do not develop their own devices, the PHANToM haptic interfaces are commonly used. The PHANToM is available in different sizes and designs, but here I present the ones we have been using. I also describe the Novint Falcon, a consumer device that came on the market in 2007. It is compatible with the AHEAD drawing application.

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. A PHANToM Premium costs about 140 000 SEK (in 2008). See Figure 2.

PHANToM OMNI

The PHANToM OMNI is the most low-cost device of the PHANToMs (20 000 SEK in 2008), with all moving parts encased in a plastic cover, and a pen interface with 2 switch buttons. Its maximum workspace is about 16·12·7 cm^3, with a nominal position resolution of 450 dpi and a maximum force of 3.3 N. See Figure 2.

Figure 2 The PHANToM Premium, the PHANToM OMNI and the Novint Falcon devices

Novint Falcon

The Novint Falcon is a new haptic device aimed directly at the consumer market, especially the game market, with a price that can be compared to other gaming devices (2000 SEK in 2008). The maximum work space is 10·10·10 cm^3, the

resolution 400 dpi and the maximum force 8.9 N. Instead of a pen grip, the Falcon has a "ball" with 4 buttons. See Figure 2.

Audio interaction

Sound reproduction from a computer is more common than force-feedback haptics for computer users of today. But when sound made its entry into computer interfaces, it was limited to simple beeps that were supposed to capture the user's attention. Still today, audio output in computer interfaces is most commonly used to enhance visual output or to catch attention (like error beeps).

In computer games, sound use resembles movie sound effects, and also in some cases aims at conveying information not visible on the screen. It can be both environmental sounds, such as the distant sound of crashing waves when the scenario is an island, or the running of footsteps behind the player, alerting her that she is being followed.

Auditory display

Auditory display is the term for all output sound used in human machine interfaces (Kramer, 1994). 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. An example of data *sonification* is the translation of a mathematical graph: the values of the y-axis are translated into pitch and the x-axis into time resembling a sound wave. That technique is used in The vOICe (2008), which takes the output from a camera, and creates a compound soundscape using time, stereo panning as well as pitch change.

Auditory icons are everyday sounds in interfaces that have an iconic resemblance to the object or action that they represent (Gaver, 1994). A crumbling paper sound when emptying the waste basket on the computer desktop is an example. Closely related to auditory icons, *earcons* are synthesized (musical), and non-figurative auditory cues used to display interface components or events. Earcons have an advantage over auditory icons in that they can be created automatically (Brewster, 1994) and thus are more flexible. However, Ulfvengren, for example, argues that auditory icons are easier to learn (Ulfvengren, 2003) and give the user a direct association if the auditory icon is well designed, and saves the user from the cognitive load of needing to learn and remember the meaning of the earcons.

A *screen reader* and a *text-to-speech* system (TTS) are commonly used by people with blindness or low vision to access written text. The screen reader analyzes the screen content, and the TTS handles the text, and outputs it to the *speech engine*, with a *synthetic voice*. There are different synthetic voices available, and it is usually a matter of preference what voice an individual chooses to use.

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 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 (Gillespie & O'Modhrain, 1995; O'Modhrain & Gillespie, 1997).

Audio-haptic interaction

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 an annual workshop on Haptic Audio Virtual Environments (HAVE), which includes visual display in most contributions. Unfortunately, much of the work is of limited interest when it comes to research on purely non-visual haptic audio display, since most of the work presented includes the visual modality. An annual workshop on Haptic-Audio Interaction Design (HAID) started in 2006 and is more oriented towards the haptics and the audio without the need for visual feedback. Audio-haptic applications that combine the use of audio and digitizer tablet are also a field where users who are blind or have low vision are the target population (Vanderheiden, 1996; Winberg & Hellström, 2003). They do not incorporate force feedback and therefore they fall beyond the scope of this thesis.

Applications making practical use of audio and force-feedback haptics with limited or no visual display for people with visual impairments (especially blind persons) are, for example, those supporting mathematical graphs and charts, games, maps and general access to models and graphics.

Mathematical display

One application uses a Wingman Force Feedback Mouse paired with audio to display geometrical 2D figures to school children (Bussell, 2003). Geometry learning with the aid of haptics with the PHANToM has also been investigated (Rouzier, Hennion, Pérez Segovia, & Chêne, 2004), where the application incorporated the possibility to measure and to compose geometrical drawings. An interactive curve manipulation application was used to create a meaningful mathematics task in a feasibility study on haptic use with the PHANToM (Sjöström, Danielsson, Magnusson, & Rassmus-Gröhn, 2003). At the Glasgow Multimedia Interaction Group, graph designs and how to design intersections between graphs using the PHANToM have been investigated (Yu, Brewster, Ramloll, & Ridel, 2001), as well as the manipulation of different graphs and charts with the Wingman Mouse (Yu, Kangas, & Brewster, 2003).

Audio-haptic games

Games or game-like environments can be used to explore the possibilities of different multimodal designs for interacting with audio-haptic environments. New and exciting computer games are also asked for by the user group. Memory games with haptic objects and sound information have, for example, been used to evaluate the ability to remember the positions of objects spread out in haptic space (Magnusson, Rassmus-Gröhn, Sjöström, & Danielsson, 2002; Magnusson, Danielsson, & Rassmus-Gröhn, 2006; Rassmus-Gröhn, 2006; Sjöström, 1997). Also, blind users have evaluated games that involved exploring a 3D model of rooms and objects in

them using the PHANToM (Szymkiewicz, 2007) and the GRAB device (Wood et al., 2003).

Non-visual image and model representation

Providing simplified access to 2D graphics and 3D models has been requested by several individuals with blindness or low vision. One application area for virtual models and graphics are schools with blind pupils, who rely on specialized material to provide access to the model of a famous building, for example. It is also an area of interest for museums that wish to display their (sometimes very delicate) items to people who cannot see. The possibility to explore and understand 3D-models of complex objects has been reported by De Felice, Renna, Attolico, & Distante (2007), Jansson & Larsson (2002), Magnusson et al. (2002) and Sjöström (2002). Pokluda and Sochor have investigated ways of presenting the users with guided tours of historical buildings (Pokluda & Sochor, 2005). The access to 2D objects (graphics) will be introduced below.

Audio-haptic maps

Other applications for users who are blind or have low vision are virtual environments in the form of maps combining spoken audio (synthetic or natural), non-spoken audio and haptic feedback in 2D or 3D. The maps investigated are of different types and levels of detail. The most detailed attempt was creating a simulator for static and dynamic objects in a virtual traffic environment (Magnusson & Rassmus-Gröhn, 2005). Attempts have been made to convey sea chart information to blind sailors (Simonnet, Vieilledent, Guinard, & Tisseau, 2007). Maps for multi-purpose use with land regions and cities with layers of different complexity and detail have been developed, making it possible for users to choose the data to be displayed (De Felice, Renna, Attolico, & Distante, 2007; Magnusson, Gutierrez, & Rassmus-Gröhn, 2007).

User involvement in design activities

Human-computer interaction (HCI) is a multidisciplinary research area. Stemming from Human-machine interaction and ergonomics, it spawned many branches of methods and traditions. It is surrounded by a grove of rich variation including psychology, computer science, pedagogy, social sciences and design science (Dix, Finlay, Abowd, & Beale, 1993; Gulliksen & Göransson, 2002; Sharp, Rogers, & Preece, 2002). ACM (Association for Computing Machinery) defines HCI as:

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

Nowadays the concept HCI has a somewhat old-fashioned ring to it, and new concepts such as interaction design are used more widely. The use of a new word or concept may be a wish to acquire a concept that is free from the historical ballast of instrumental usability tests and the treatment of the users as secondary.

User-Centered Design

The need to involve users in the design process of interactive systems was pointed out already in 1985 by Gould and Lewis (1985). According to them, three principles should be used:

- Early focus on users and tasks
- Empirical measurements
- Iterative design

These principles have formed the foundation for User-centered design (UCD), although the term itself did not become widely used until 1986, when the book *User-Centered System Design: New Perspectives on Human-Computer Interaction* (Norman & Draper, 1986) was published. Recently, Gulliksen (2002) and Sharp, Rogers and Preece (2002) have added more principles and elaborated on the original ones, putting even more focus on the active involvement of users. In the UserFit handbook (Poulson, Ashby, & Richardson, 1996), developed by the USER consortium in the EU TIDE framework program, UCD is put into practical methods for assistive technology device design.

Early focus on users and tasks as Gould and Lewis (1985) originally saw it stresses the active involvement of the actual end users in the design process and propose that they participate in the design teams. They also describe the need for meeting real users, performing background interviews and discussing designs.

Empirical measurements in the original text meant both objective measurable quantities like learning time, task completion times and other performance measures as well as the test users' thoughts and attitudes about the products they tried.

Iterative design in engineering is a process of prototyping, evaluating, analyzing and refining that is cycled until a "good-enough" product is developed. Iterative design in HCI and more specifically in UCD emphasizes the involvement of users in the evaluation portion, and in some cases it is also divided in different tracks, like conceptual design, interaction design and detailed design (Gulliksen et al., 2002).

Participatory Design

Participatory design (PD) is a concept close to UCD, in that it deals with the involvement of users in the process of product design and development. In short, PD involves actual end users that participate in the design teams. While UCD is an approach to design, PD can be said to be a method to accomplish user-centeredness. While UCD focuses on the involvement of users, it does not specify how this involvement should be achieved. In the original publication, Gould and Lewis (1985) were already suggesting that one way of involving users is to let them participate in the design teams. But other methods, such as ethnography were also suggested.

There is a somewhat different quality to the participatory design concept of "the Scandinavian tradition" (sometimes called cooperative design), and the participatory design practiced in North America. The Scandinavian tradition has its roots in the Scandinavian labor union movement of the early 1970s (Bodker, Ehn, Sjögren, & Sundblad, 2000; Sharp et al., 2002) and the introduction of computer systems in work places. Aside from involving co-design much focus was also put on the involvement of users in the decision about how and whether a new system should be brought into the work process.

Useworthiness

The term *useworthiness* was coined by Håkan Eftring in his PhD thesis (Eftring, 1999). It encompasses the user's high priority needs as well as the usability as defined by Nielsen (1993). At the time, Eftring could not find any definitions of usability that took into account to those needs. This was commented on but not contested by Jonas Löwgren (1999) the same year the thesis was published. Jan Gulliksen later argued against the use of expressions like useworthiness and user experience because he felt that what these terms depict is in fact encompassed by the definition of usability in the ISO standard 9241-11, and the problem is that people use the words as laymen in a "common sense" way. Jan Gulliksen writes:

"ISO 9241-11 defines usability as encompassing useworthiness as well as user experience in that it deals with the user's effectiveness, purposefulness and subjective satisfaction" (Gulliksen, 2008) (author's translation from Swedish)

However, the word *purposefulness* that Gulliksen uses in the article is in fact not used in the ISO standard. According to Abran, Khelifi, & Suryn (2003) the ISO 9241 states that:

"…software is usable when it allows the user to execute his task effectively, efficiently and with satisfaction…"

While it may be possible to understand the word *purposefulness* to contain an element of what the word *useworthiness* depicts, the word *efficiency* is hard to interpret that way. The term *satisfaction* can be argued to contain elements of useworthiness, but in its descriptions, it has more to do with *"how the users feel about the system"* (Abran, Khelifi, & Suryn, 2003; Eftring, 1999). Elements of the user's preconceptions or anticipation about a product or system as Eftring exemplifies in his in-depth user interview, are not encompassed by satisfaction, nor are the user's high priority needs.

Furthermore, there are other definitions of usability. Even in the ISO standard the term has different definitions depending on the section in which the term is described (Abran et al., 2003). Outside of the ISO standard, definitions also vary.

According to Wikipedia, accessed June 18th 2008 (Wikipedia, 2008), usability is:

"…a term used to denote the ease with which people can employ a particular tool or other human-made object in order to achieve a particular goal. Usability can also refer to the methods of measuring usability and the study of the principles behind an object's perceived efficiency or elegance."

Jakob Nielsen (1993) and Ben Schneiderman (1992) use the five following qualities to describe *usability*: *learnability*, *efficiency*, *memorability*, *error handling* and *satisfaction*. Nielsen also puts the usability definition in a larger scope, where terms such as *utility* and *reliability* are not part of *usability*. Löwgren (1993) lists four usability criteria: *relevance*, *efficiency*, *attitude*, and *learnability*. It is indeed hard to see, as Eftring also explains, that any of these terms should in fact encompass the qualities that he seeks to describe.

Useworthiness is still used very sparingly, and when it is, it is sometimes described as having to do with product value (Cockton, 2004). I will, henceforth, without debating ISO standards or usability definitions further, use the word *useworthiness* in the spirit of Håkan Eftring in that it for me pinpoints that it is only the individual user who in the end can decide whether a product is *useworthy* or not. What I also find important, is actually that the word *useworthiness* can be understood in a "common sense" way, as it simplifies the communication with users about the term.

Accessing and creating computer graphics in school

Getting access to 2D graphics and especially computer graphics is still a large problem for school children who are blind or have low vision. Primarily, traditional methods are in use for enabling pupils' access to graphic material: tactile drawings prepared in advance using swell paper, or prepared school material ("picture appendices") to the Braille books used in education. 3D material, which also can be used in education (e.g. models of historical buildings and the like), must be prepared or ordered months in advance, which results in limitations on the flexibility of the curriculum and the lessons. For creating graphics, a type of plastic sheet is used. When it is drawn on (with some pressure) using a ball point pen, the drawn line is raised. It is not possible to erase parts of drawings.
Furthermore, the reading of tactile pictures is a hard skill to master. Normally the teachers will describe the tactile pictures and sometimes help the pupils feel the features in the pictures by guiding their hands and fingers.

Supportive technology for exploring graphics

A touch screen or digitizer tablet with a tactile overlay can be used to enrich the information that a person or pupil can access from a tactile picture, like the NOMAD (Parkes, 1994) and the TTT (Landau & Rosenblum, 2005). When the pupil presses a point on the tablet or screen, speech output will describe the feature or part of the drawing. This enables the pupil to be more independent in exploring tactile paper

drawings. Tactile drawings still need to be prepared and printed, and the different parts of the drawing must be labeled with appropriate information.
The GWP (Handytech, 2008) and similar devices like the NIST device (National Institute of Standards and Technology, 2008) give access to graphics on a computer screen. The GWP has a 24 by 16 array of pins that display a small portion of the screen, while the NIST device has 3600 small pins.

Haptic force-feedback devices have also been investigated for their use in exploring 2D drawings. Early results of attempts to create and use non-visual images has been reported by Roth, Richoz, Petrucci, & Pun (2001), where some degree of automated image recognition was also used. In a feasibility study on haptics, Sjöström et al. (2003) showed that shapes of line drawings were recognized and different features could be referenced to once the users were aware of the contexts.

Supportive technology for creating graphics

There are few tools that enable blind people to create computer graphics. As described in *Drawing and the Blind* (Kennedy, 1993) and *Art Beyond Sight* (Axel & Levent, 2003), there are indeed people who are blind who are interested in drawing by hand. A CAD application has previously been developed that enables users to create drawings with the help of audio and keyboard. This is accomplished by a structured approach of dividing a drawing into small parts and thus enables the user to draw segments of a drawing (Kamel & Roth, 2001; Kamel, 2003).

In 1996, Kurze presented a tactile digital drawing application that combined a digitizer pen with a thermo pen. The thermo part of the pen raised lines on swell paper, and the digitizer recorded the movements to save them digitally. An idea for a voice recognition system for vocal tagging of the drawings was also presented (Kurze, 1996). The greatest drawback of that particular application was that the drawings could not be dynamically edited.

The possibility to use the PHANToM for drawing and exploring drawings has previously been investigated. Two different applications were developed, with a few years in between. The first application ("Paint with your fingers") was created by Niclas Melin in 1995 (Sjöström & Rassmus-Gröhn, 1999), and the target users were children with blindness. This application focused on the possibility to paint colors, and to give them different haptic textures to make it possible to distinguish them from another. The second application took the results from the user trials of the first application, and improved the functionality (Hansson, 2003). The resulting application prototype provided the user with the possibilities to choose colors from a palette and draw with them. Like the previous application, different textures were applied to the colors. Also, a dividing line between drawn segments of different color was added.

During the last couple of years, in parallel with the design and development of the AHEAD application (described below), other drawing applications using the PHANToM or a similar device have been developed. These are referred to in the discussions section.

The Research Persons

A *research person* ("forskningsperson") is defined as *"a living human being whom the research concerns"* (Svensk Författningssamling, 2008).

I have, during my time working at Certec, in total met about 70 persons who have different visual impairments. The common denominator has been that they or people in their family, assistants or friends have believed that they may in some way benefit from using haptic (force-feedback) or audio-haptic technology in learning or information access. Some of the users have participated regularly in evaluations of applications or in discussion groups; others have just tried the audio-haptic systems at a demo session.

Many sighted users have also tried applications formally or informally. Although they do not have any direct relevance to this work, they have helped me see the great diversity in the approaches, the motor skills, and the reliance on vision for guidance that individual users have shown when using force-feedback devices.

Classifications versus individual traits

It is far too easy to refer to potential users as a group having one or more specific characteristics. However, it has become more and more obvious to me, as I have met different people, that specific diagnoses will help little in understanding or predicting how a user will handle a system. In other words, people with blindness and low vision are first and foremost individuals. There are so many variables in the characteristics of people that it usually makes no sense to create subgroups. Therefore, I do not try to classify the users that have participated according to any national or international classifications like the ICF – International Classification of Functioning (WHO, 2008) or the sociologically grounded structure in Grönvik's thesis *Definitions of Disability in Social Sciences: Methodological Perspectives* (Grönvik, 2007). Every single user has an individual set of experiences that affects the results. It is most apparent in the pupil user group (presented in detail below): since the youths differ much in age and maturity, some are still almost children, and others are almost adults.

I have chosen not to write the gender of individual users, because the gender in itself does not add any relevant information. I want to emphasize that results from this small and diverse group cannot be generalized based on subgroups such as gender or degree of visual impairment. However, the gender may be determined anyway in some cases, since I have published a small number of photos in this thesis.

I have also chosen (in the group of pupils) to mention who are blind (and have been from birth) and who have low vision. It has some relevance to the know-how of holding a pen (which is relevant for the holding of the haptic device), and being familiar with symbols, but on the whole, the degree of visual impairment has in our cases not been shown to matter significantly (see also the *Results* section). The contexts, the individual motor skills and the motivation have played a larger role. There have been users with low vision who have had advantages because of being able to see a little, and others who have been hindered by it (e.g. by relying too much on the visual information).

Research Persons in the AHEAD project

In the entire development cycle of the AHEAD prototype application, a total of 46 research persons have participated. Five of them have been school children with blindness and low vision and they play a leading role, since they have been engaged in the continuous evaluation of the prototypes as well as the final evaluations. It is these pupils that are presented in more detail below. The others were:

- Collaborative users in the final evaluation: 3 pupils
- Secondary users: 17 teachers, parents and siblings
- Interviewees: 10 persons (10-66 years) with low vision or blindness
- Formal sound field study users: 11 sighted persons

The school pupil group

For the purpose of the user-centered design process a handful of school children were recruited in spring 2005. An invitation to participate was sent out via a local association for people with visual impairment ("SRF Skåne"), and a health care and visual aids provider ("Syncentralen"), and pupils and families volunteered to participate in the project. They were involved in the project for 2 years. All five pupils (R1-R5) attend regular class, which means that they are integrated in classes with sighted children, using technological aids and in most cases receiving help from an assistant or resource person.

During the project, the school pupil group met at the Design Sciences Department on 7 different occasions, the first one in June 2005 and the last one in June 2007, for iterative evaluation and inspiration. The pupils and the researchers have gotten to know each other quite well, and there has been an air of openness and honesty. All of the pupils have not had the opportunity to attend all the meetings, though, due to other obligations (see Table 1).

Pupil	R1	R2	R3	R4	R5
Age	11	12	12	15	17
Number of reference group meetings attended	4	5	5	5	5

Table 1 Summary of visually impaired pupils and their attendance at group meetings

During spring 2006, there was a break in the regular meetings at the department, and the researchers in the project instead went on field trips to the classrooms of the pupils, documenting the technological aids and observing regular lessons. The parents or siblings of the pupil group members have also participated in the group meetings. All in all there were 3 siblings and 7 parents involved, but at different group meetings. In the following descriptions, the age and school year that they were in at the end of the project (spring 2007) is given. I have chosen not to describe the pupils' diagnoses except for giving information about blindness or low vision. Instead, I describe more thoroughly the kind of technological aids that the pupils are using at school to access

school material. Also, I describe how well the pupils can handle a pen and sometimes their relationship to drawing and drawings.

Pupil R1

Pupil R1 was 11 years old and attended fifth grade in spring 2007. The pupil has low vision and used enlargement techniques (CCTV) to view the whiteboard and teacher as well as for enlarging graphics and sometimes text in books. A computer with a Braille display and speech synthesis was used for writing and Braille books and tactile material were used for accessing regular school books. A resource person, A1, helped the pupil. At the time, the pupil had an interest in and was able to draw pictures with pens, and was also able to write with a pencil. The pupil appeared to have no problems using the AHEAD application for drawing. The pupil also used the visual screen picture of the AHEAD application in the final evaluation, and the cursors (visual representation of the PHANToM contact point and the mouse cursor) were adapted for this particular pupil to see.

Pupil R2

Pupil R2 was 12 years old and attended sixth grade in spring 2007. The pupil has low vision and used a computer with a Braille display and speech synthesis to write and read. Braille books and tactile material were used to a large extent. The pupil was able to use enlargement for operating the computer, and used a mouse to choose programs for example. A resource person, A2, who was working alongside the teacher in the class mostly helped pupil R2 to access material, but sometimes taught the other pupils as well. Pupil R2 had documented problems with fine motor skills and was not particularly interested in drawing. The pupil experienced some problems in interacting with the AHEAD application, especially when drawing, and had problems limiting the hand force used to stay in contact with the virtual objects.

Pupil R3

Pupil R3 was 12 years old and attended sixth grade in spring 2007. The pupil has been blind from birth and was using a computer with Braille display and speech synthesis, Braille books and tactile material for accessing school material. In art class the pupil often used wax thread to do 2D art. A resource person, A3, in class was primarily occupied helping the pupil with material access and guiding. In the beginning of the project the pupil did not really understand the meaning of 2D drawings for blind users. The pupil was also inexperienced with a pen. Initially the pupil had problems using the AHEAD application, but during the final evaluations only minor problems were observed.

Pupil R4

Pupil R4 was 15 years old and attended ninth grade in spring 2007. The pupil has low vision and used a computer with Braille display and speech synthesis to write and read. The pupil also used Braille books and tactile material to a large extent (e.g. for accessing the periodic table and picture graphics). A resource person helped the pupil with guiding and accessing school material. The pupil used enlargement on a

computer at home, and when doing so, even in maximum zoom (20), the pupil needed to sit very close to the screen. This pupil showed an interest in computer drawing, and used Paint for it sometimes, although it was very tiresome because of the concentration required and the effort of leaning forward to see the screen. Pupil R4 also had the motor skills to easily use the drawing application. Aside from participating in the AHEAD application design project, this pupil spent a week doing vocational training at the Design Department.

Pupil R5

Pupil R5 attended the second year of high school in spring 2007, at an aesthetical program with music as a specialty. The pupil has been blind since birth and used a stationary computer with Braille display and speech synthesis as well as a Braille display equipped laptop for school use, when lessons were held in other classrooms than the home room. The pupil did not use a pen very well, but in other cases had sufficient motor skills to use the AHEAD application for drawing. This pupil has participated in evaluating haptic applications since 6 years of age while the others in the pupil group were new to the PHANToM and haptic applications.

Teachers, teaching assistants and fellow pupils

The final evaluation was conducted during the spring semester in 2007 with the school pupils described above, 3 fellow pupils (E2, E4 and E5) and teachers and resource persons. The teachers (T1, T2, T4 and T5) and resource persons (A1, A2 and A3) have participated in choosing the appropriate school subject and in fine tuning the material used for the final evaluation (see also Table 2). The teacher for pupil R3 did not participate, the assistant for pupil R4 did not participate, and pupil R5 did not have an assistant at the time for the final evaluation. The collaborators for the pupils in the group work were fellow pupils according to Table 2. For the pupils who worked alone, the collaborating role was at times taken by the assistant, but then with some focus on guiding and teaching (therefore they are not mentioned in the table). The lengths of the lessons for the final evaluation varied between 40 minutes and one and a half hours.

Pupil	R1	R2	R3	R4	R5
Planning	T1, A1	T2, A2	A3	T4	T5
Final test session	A1, T1	A2	A3	T4	T5
Collaborator		E2		E4	E5

Table 2 Overview of persons involved in the final evaluation

Method

The specific methods for each context have been presented in the respective articles. Here, I mainly want to highlight and structure the most important methodical aspects that have been relevant throughout the work. They have, of course, been developed and modified during my PhD studies; both because of new knowledge from research as such and because of my own learning process and increased awareness.

1. An action-oriented approach

My focus is action-oriented: I study the use and context of audio-haptic environments rather than the technology per se and I focus on what the users really are doing. However, the focus on action in the situation and the research person in action does not change the fact that it has been necessary to spend roughly 50% of my PhD studies on technological aspects, research and application development. Nor does it imply that the interviews and the discussions I have carried out have not been important ways to convey results and understand problems and possibilities, as well as an overall context.

2. Built-in methodical aspect: a limited number of research persons

As described in the previous chapter, the total number of research persons is small for the end user group. It is impossible to carry through any random controlled trials for any group of low vision children. This is because each individual has an individual set of experiences which influences their results. This precludes the formation of a relevantly matched control group, and there are also too few in the Swedish population to enable the forming of such groups. As a consequence, one might state that none of the usability studies that I have participated in have been quantitative. However, in the HCI tradition it is not unusual to present behavioral studies based on a smaller number of users and to present results as design recommendations based on statistics. The data in the quantitative studies have been collected by computerized logging or letting participants rate such factors as the difficulty of certain tasks. The studies that are quantitative in nature have engaged both blindfolded sighted users and users with visual impairments.

3. Another built-in methodical aspect: a changing technological basis

The audio-haptic technology and its application areas are constantly developing, and are still in somewhat of a pioneering phase. Therefore, it has to a high degree been affected by the continuously ongoing development of haptic hardware and application programming interfaces (APIs), hindering iterative software development with full control over compatible versions. At the same time, we have made a conscious choice to follow both the commercial hardware and software development, which enabled us to make more complex, reliable and stable applications. Every new project and application has been built upon a better technological framework than the previous, which is an advantage, although the results of the older and the newer projects can thus hardly be compared.

Consequently, my research is concerned with neither pure technological research, nor with pure behavior studies under controlled conditions. I have focused on user contacts and user trials of audio-haptics as soon as it has proven to be sufficiently stable. In fact, it is the latter that is one of the most important results of the AHEAD application evaluation: that it was sufficiently stable to render meaningful user evaluations.

4. Longitudinal versus transversal approaches

A relevant aspect use of technological aids is that the artifact is useworthy (Eftring, 1999) for the individual person in a given situation and also in the long run. To assess a long-term useworthiness, longer learning periods and evaluation periods are required, allowing the artifact to become a ready-to-hand tool (Suchman, 2007). The long-term ready-to-hand aspect is consequently separated from the HCI term *learnability*. This is usually defined as being a subpart of the term *usability* (Dix et al., 1993; Löwgren, 1993; Nielsen, 1993) and correlates to the ability to quickly learn to use a technical artifact and without apparent effort. In context this can be exemplified by being able to walk up to a ticket machine the first time and use it successfully without needing to read lengthy instructions.

But many artifacts force a user to get past a "learning threshold" in order to use it successfully. For us, it has been an advantage to engage users who have overcome the general learning threshold of the haptic device in our evaluations. This has enabled a larger focus on the applications developed and intended use, and less on the particular device and its functioning. Just as Peter Anderberg in his thesis FACE, (Anderberg, 2006), I want to find out what may be achievable when interfaces are optimally adapted and beginners' difficulties are overcome.

An everyday example of the difference between short-sighted learnability measures and long-term ones can be found in the use of the computer mouse. Today we do not dispute the usability of the computer mouse as a technical artifact although it caused many users (among them myself) lots of problems when it was introduced. I have also watched my children learn to use the mouse, gradually understanding the mapping and being able to control their own movements. As for useworthy non-technical artifacts such as the regular alphabet, or the Braille alphabet, most people willingly accept learning efforts if they consider the end effect to be worthwhile. The users are generally more motivated to learn new technology if they can envision the technology to be of future use or pleasure. How much difficulty a user will tolerate, such as the patience needed to learn new technology and the willingness to put up with beginners' problems is described as the *threshold of indignation* by Paul Saffo (1999). The useworthiness of an audio-haptic system will (potentially) be higher for a person who relies on touch and sound for interaction. Also, users who have had time to learn and understand a tool or aid are more easily able to contribute with ideas of use.

A side-effect of the long-term approach is that users and researchers get to know each other quite well. The mere existence of common experiences and a long-term acquaintance enables more straight-forward communication and makes it possible to get to the heart of things quickly.

5. Early focus on activity

Lewis and Gould promote "early focus on tasks" to be an important component of user-centered design (Gould & Lewis, 1985). However, the very word "task" has in the context of "task analysis" and HCI acquired an instrumental ring to it as described by Kaptelinin and Nardi (2006):

"HCI models deals with lower-level interaction limited to 'tasks'. Tasks are typically described in terms of the functionality of a system rather than their meaning for the subject. However, using a system does not normally have its own purpose; its meaning is determined by a larger context of human activity carried out to accomplish things that are important regardless of the technology itself, such as writing a memo to a colleague or keeping in touch with a friend."

Thus, my focus is on activity, but in descriptions I mainly use the word *task*, and that I use synonymously both for general tasks and for more specific tasks when I describe the exercises in the school settings, for example. The early focus on tasks/activities has been less straightforward than the early focus on users from the target group, in part because much of the research and application development has been of an investigating nature, where the tasks have not been given from the beginning. A large part of the research has been to actually try to find out what activities an audio-haptic application can be useful for.

To focus on users and tasks, we have regularly had meetings or evaluation sessions with people of the target user group, from the beginning of the single projects until the very end. Data have also been collected through informal conversation, semi-structured interviews, field visits and observations as well as video and audio recordings of evaluation sessions.

6. Lead users and generative users

From the very beginning of my research, blind users have been especially considered as both generative users and part of the end user community when designing audio-haptic applications. The terms *generative user* is described in Håkan Edeholt's thesis *Design, Innovation and other Paradoxes* (Edeholt, 2004). It is used for persons who are not (necessarily) end users, but users who help the designer generate new ideas. An example of a generative user for a car stereo could be a person who is blind. Not that a blind person would ever drive a car, but that we are in essence all blind when we need to maneuver a car stereo while keeping our eyes on the road. This fulfills one part of the principle: "early focus on users", or rather "constant focus on users". And since almost all projects have had the same target user group, knowledge about this group collected in one project can migrate into the next project, and there be refined and so on.

I consider the difference to be fundamental between user tests involving people with severe visual impairment compared to involving blindfolded, sighted participants. We have engaged sighted users only when there has been a genuine risk of "wearing out" the willing test participants. This has mainly been the case in two

kinds of tests: one focusing on details in the user interface, another on pre-evaluations of immature user interfaces. In both, we anticipated that blindfolded sighted participants can advocate for users with severe visual impairment.

In his book *Democratizing Innovation* Eric von Hippel (2005) defines lead users as:

"…those who face needs that will be general in a marketplace for a majority months or years later."

Von Hippel argues for a democratic innovation in which the actual users share their needs and solve their problems together. Our user involvement has tried to approach that situation by acknowledging that the pupil group members are indeed lead users of audio-haptics, by letting them learn to use haptics, and by inviting them to participate in design decisions and evaluations.

7. Empirical measurements

As earlier stated, my main focus has been on the action – when and where it is. Formal, semi-formal and informal usability tests have been conducted. The informal tests have had less focus on specific tasks; the application has rather been used as a basis for discussion. When relevant, the entire test sessions have been recorded on video (sometimes just audio). These recordings have enabled us to double-check observations or automatic logging when it has been hard to understand or analyze. In some cases, the videos were analyzed more thoroughly (e.g. see article III in this thesis). The evaluated applications have sometimes incorporated possibilities to log the actions of the user (e.g. keyboard commands, sampled mouse movements and sampled PHANToM movements) (Magnusson et al., 2005; Magnusson, Rassmus-Gröhn, & Eftring, 2007; Rassmus-Gröhn, Magnusson, & Eftring, 2006).The position logs have been compared to the haptic material to attempt to evaluate the scanning strategies and see if the user has explored different parts of the models. The logs can also show the parts that the user has spent much time on. We have been using timekeeping to rate the success of solving evaluation task (Magnusson et al., 2002; Rassmus-Gröhn et al., 2006). It is not without its problems, since task solving abilities, motivation, and the thoroughness with which individual users go about solving tasks, differ greatly. Despite this, we found it possible to use timekeeping for some evaluations, especially comparing the same user's success in different tasks or with different interface components.

In some cases, rating scales have been used to calculate a mean result for the difficulty of a task, for example, or the preference for an application, and for a minority of cases, statistics have been presented (Rassmus-Gröhn et al., 2006). In most cases, the qualitative results have been more enlightening than the quantitative, providing information about why a task is difficult or why a user interface design detail is hard to use.

During user evaluations, both formal studies and informal ones, users have been asked to express their thoughts about the interaction aloud. In single-user evaluations they have been encouraged to express whatever crossed their minds when trying to

solve a task or when freely exploring a user interface. In collaboration tasks, this was not specifically encouraged; however, the users' naturally discussed problems and tasks solutions. This approach has also been discussed by Lucy Suchman (2007) as being preferable to the traditional single-user think-aloud technique that can sometimes be considered artificial.

8. Semi-structured interviews

The importance of information transfer between users and developers has been described by von Hippel (2005), who characterizes information as being "sticky", i.e. that it is actually very hard to transfer information from users about users' needs and contexts to the developers. According to Kvale (1996) interviews are:

"…attempts to understand the world from the subjects' point of view, to unfold the meaning of peoples' experiences, to uncover their lived world prior to scientific explanation."

Therefore, we have made sure to have enough time to chat with the participants in connection with the testing. During breaks, we have learned much in terms of background and context information about how our test participants face and overcome problems of everyday life, but also about problems that are still hard to master, and what possibilities the users can see and what ideas the users might have for solving those problems.

The most frequently used planned interview scenario has been the post-test interview. There, questions about the user interface, its goals, its functioning and its efficiency have been put to the test participant. The participants have also been asked to express ideas for improvement or ideas for other applications. The questions have been a mix of open questions where the interviewer has asked follow-up questions to clarify or to pursue an interesting subject further and of closed questions with preferred answers in a rating scale or yes/no-questions. Background interviews have also been conducted that focus on the specific areas of interest that a project has had as its goal (e.g. questions of internet usage, or of school subject preferences and problems) (Rassmus-Gröhn, Magnusson, & Eftring, 2007b).

9. Iterative design

Using an iterative design process has allowed for mutual learning throughout the design process. The researchers have learned from the users and the users have learned from the designers and all of us have learned from the artifacts and the interaction. One result of this is an ongoing change of the requirements set up; another that the user needs and wishes as well as the technological possibilities and limitations can be seen more clearly as time goes by.

Participatory design methods may sometimes be used to make early designs in collaboration with future users. Although this is very interesting and an approach that we believe can be fruitful in many cases, there are several problems posed by the special technology used and the particular user group. Naturally, people with severe visual impairment have problems sketching and making lo-fi prototypes, for example.

The very nature of haptic devices and audio interactions also makes it hard to suggest or implement lo-fi prototypes at all. Furthermore, the novelty of the technology, and the fact that it has not yet reached a consumer market, makes it additionally hard for people to imagine what it might be used for, and how. These problems are especially emphasized in the projects where the target users are children, as they do not have the experience that adults have.

Thus, a recurring method to start the design dialogue with users has been to introduce them to a functioning prototype that is sufficiently advanced to provoke thought and evoke reactions, ideas, rejection or questions. The ideas for the prototypes have emerged from prior discussions with users or background interviews (see above). These prototypes (when received well) have then been refined iteratively and evaluated iteratively.

Application and evaluation

The design and development of audio-haptic applications and the evaluation of application ideas, user interface details and detailed concept applications that I participated in have, in retrospect, been intertwined and not always followed logical steps. It is the sheer multitude of applications and evaluations, and the numerous meetings with people from the end user group that have led to the AHEAD application and its focus on reaching a situated and useworthy end user scenario.

Application selection

At the beginning of the project that led to the AHEAD application an initial round of interviews was performed, aiming at collecting information about what visually impaired people themselves considered to be the most important problems concerning information access in school. Ten visually impaired persons participated in the study, and it was apparent from the answers that the interests and the problems that the participants experienced during their time at school varied greatly. The collection of answers suggested that several application areas could be of interest: access to images, arts and drawing, maps and geographical data, mathematics (including tables, graphs, geometry, and statistics), physics (rigid bodies, electricity, magnetism, waves, quantum mechanics, etc.), chemistry, games and also gymnastics. Generally, persons that had attended a dedicated school for blind persons remembered having problems with math, and those who were attending integrated school classes with sighted classmates expressed as a common denominator that access to the information on the blackboard/whiteboard was a problem.

An important factor for maximizing utility and promoting widespread use was to aim at an application that could be used in several different school subjects and over a range of years. Therefore, development of an all-round application for creating line drawings was initiated. This choice was also discussed with and approved by the pupil user group.

Iterative design-evaluation process

While an open design idea of a line drawing application was the starting point, the features of the drawing application and its functioning in a school situation gradually developed in the design evaluation loop, involving the pupil group of five youths as well as their families and their teachers and resource persons.

In parallel, two larger studies involving sighted users were performed: one concerned the sound field feedback (Rassmus-Gröhn et al., 2006), and one concerned how the pulling force when guiding or returning to a fix point was to be adjusted (Magnusson & Rassmus-Gröhn, 2007). During the two years of iterative work, the pupil group and their families participated in informal and semiformal tests (Rassmus-Gröhn et al., 2007b).

The test activities were comprised of:

- Drawing and feeling lines in negative and positive relief
- Using vertical or horizontal work area
- Changing the relief a using virtual button or keyboard button
- Drawing an image and feeling it
- Drawing specified shapes: a rectangle and an Arabic numeral
- Exploring Arabic numerals
- Exploring two geometric shapes
- Creating a specified drawing and using the shape conversion tools
- Collaborating by marking and text tagging prepared drawings
- Usage of fix points
- Usage of sound field for shape recognition
- Design of auditory icons
- Usage of TTS tagging of objects in the drawing

To increase the mutual understanding of researchers' and teachers' work, the researchers undertook field trips to the classrooms, sitting in and observing a regular lesson. The teachers and resource persons were also interviewed about their work concerning special arrangements, preparations or possible limitations that they experienced due to having a visually impaired pupil in class. Similarly, the teachers visited the researchers and were introduced to the AHEAD application.

Final AHEAD application description

AHEAD runs best on a dual-core or double-processor computer. Either a PHANToM device from Sensable Technologies Inc. or a Falcon device from Novint Technologies Inc. can be used for haptic feedback and control of the application. A mouse may be used in parallel for non-haptic control of the program. Regular headphones or speakers are used for sound feedback.

The application has been developed with the Reachin API (versions 4.0 and 4.1) platform for haptic control, along with FMod Ex 4.04.30 used for non-speech sound control and Microsoft SAPI 5.1 for text-to-speech synthesis (TTS). The virtual environment in the application consists of a virtual sheet of paper in the vertical plane. The application can be used in two different modes: one for editing and one for exploring relief drawings. In explore mode the users can explore text tagged relief drawings. The haptic image is produced as positive or negative relief for the PHANToM user. The drawing is also represented 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 grey. The users can select drawn objects by touching them with the PHANToM pen or hovering over them with the mouse cursor. When selected, the text tag for the line is spoken by the text-to-speech engine. The mouse user can guide the PHANToM user by a pulling force that drags the PHANToM pen tip to the mouse cursor position. Similarly, the PHANToM user can drag the mouse cursor to the PHANToM position.

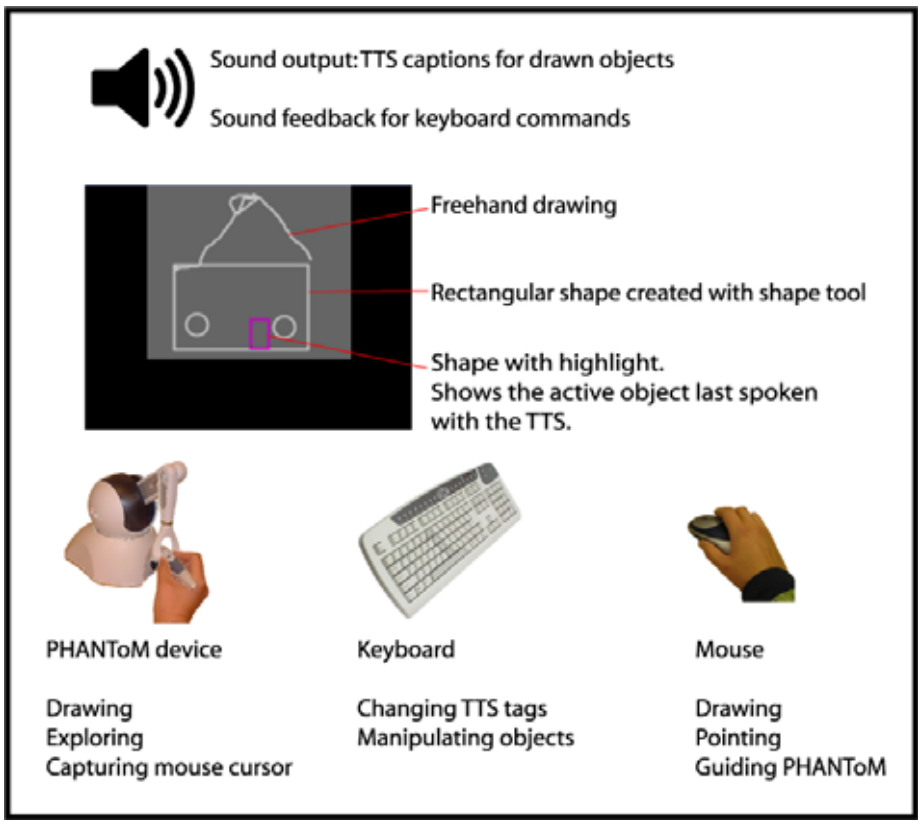

Figure 3 Overview of functionality of AHEAD

In the edit mode the PHANToM user can create and edit drawings while at the same time being able to feel the lines that are previously drawn. Drawing lines is done by pressing the switch when in contact with the paper, while moving the PHANToM pen in the desired shape. The mouse user presses the left mouse button while drawing. Drawn lines or objects can be manipulated in different ways: moving, resizing, copying, pasting and deleting. Additionally, text tags for the lines and shapes can be changed, and shapes can be transformed into straight lines, perfect rectangles or circles. The manipulation tools are fitted with feedback sounds designed to resemble a real world manipulation of similar nature (i.e. auditory icons). For example the copy function sound effect is a camera click. Actions in general have feedback sound, either by auditory icons or by spoken text information. The PHANToM user can place fix points in the environment, and receive help in the form of a pulling force to return to these fix points. Drawings can be saved and loaded with the application, using the applications customized MICOLE file format ".mcl". The format includes the objects and the text captions for them. A ".png" import function is available. The files imported needs to be grayscale and exactly 256*256 pixels.

Final evaluations

Following the iterative loop, the final evaluation of the application was performed in spring 2007. It is not entirely true to say that the iterative design and evaluation ended, for there were some changes made to the application also during the final evaluation, although they were minor. The aim of the final evaluation was to assess the whole chain of activities, from the planning of the school task to the actual lesson in the classroom supported by the AHEAD application, i.e. creation of school material by teachers, resource persons or the pupils themselves as well as accessing that school material without need for special assistance by technical personnel, for example. However, the focus of the design and evaluation of the application was on the pupils' access and manipulation of material and collaboration, and less on making it easy for the teachers to produce material. Therefore, the actual school material was created for the teachers, although they were highly involved in the process of choosing and fine-tuning the material.

Evaluation tasks and material

Three of the visually impaired pupils worked in collaboration with sighted classmates when doing their school tasks (see Figure 3). Two of the pupils were working primarily in single-user mode, but were also instructed by their resource persons. Five sets of school material were created for the subjects: mathematics, geography, navigational training and literature. In all cases except mathematics, the application was used only for exploring ready-made graphics, but in the mathematics case, the drawing functions were used.

Figure 4 Two pupils collaborating while using the AHEAD application making markings on a map of the Skåne region in Sweden

For the geography tasks, simplified maps with text tags were designed to substitute the tactile maps or CCTV enlargement that the pupils usually used as a basis for

learning about the geography of a country or continent. In literature, the task was to stage set a Shakespearean play, and the pupils were therefore presented with simplified drawings of a Shakespearean theater, the Globe. For the navigational training (which was an individual task for the visually impaired pupil in class only), a map over the school yard and its surroundings was prepared and used as a basis for a treasure hunt. In mathematics class, the pupils used the AHEAD application to draw geometrical shapes in a mathematical communication exercise. For more details on the tasks, see Rassmus-Gröhn, Magnusson & Eftring (2007a).

A PHANToM OMNI, a laptop and a pair of headphones was used in all cases except the evaluation in mathematics class, where an extra screen and an extra keyboard were attached to the laptop to provide for the secrecy that was needed for the task (one pupil was not allowed to see what the other was drawing).

Evaluation procedure

A pre-final pilot test was performed at one of the schools three months prior to the four remaining final tests. The pre-final pilot used an earlier prototype of the application with no logging functions, and the final file format for saving files was not implemented at the time. Furthermore, the post-test questionnaire was somewhat differently designed and only the visually impaired pupil was interviewed, while in the later tests collaborating pupils and teachers involved were also interviewed. In two cases, the pupils had a short instruction session before the real lesson. This was particularly important for pupil R4 who was using the application for drawing and was introduced to some test-specific features.

The data collected in the final evaluation included logging (PHANToM position, TTS events and keyboard commands), observations, semi-formal post-test questionnaires and video recordings. In the videos, the pupil who used the PHANToM was the focus for filming, and in all cases the screen was filmed to make it possible to see the movements of the PHANToM proxy and mouse cursor. The hand of the PHANToM user was also filmed at times, in order to se how the pen is used in the pupil's hand, except for the pre-final pilot test with pupil R5. The five videos were analyzed in an iterative fashion and observations were categorized to highlight usability, collaboration and also specifically the interaction of the visually impaired pupil with the PHANToM and AHEAD application, see appended publication III.

Results

The outstretched nature and diversity of my audio-haptic research makes it partly irrelevant to comprehensively summarize the results over the years. For detailed results, I refer to the individual publications, primarily the appended publications. The full method used in the process of designing, developing and evaluating the AHEAD application is in itself a result of my learning process during these years of research. The application and its functioning, the design decisions and the planning and implementation of the evaluations, are results of the ongoing iterative learning and design process including pupils, researchers and teachers. Below, I present results tied to the AHEAD application project.

Groundwork for on-site evaluations

By carrying out the iterative design-evaluation loop and conducting on-site evaluations in classrooms, I show that it is indeed possible to undertake such research in close collaboration with end users. This has put some demand on the technology used for the evaluations.

A. The AHEAD application was sufficiently stable to yield results related to work tasks or activities rather than to usability. It puts the focus on the use of the application and system rather than on the limits of the interface. Overall, of the tagged events in the video analysis less than 0.5 % related to usability problems, and only 2 major bugs/stability problems were found. After the pre-final pilot test, a number of issues were solved to facilitate observations (e.g. logging) and one major bug was corrected after the pre-final pilot test. This indicates that the application prototype had no major design flaws and also was sufficiently stable to promote activity connected to the school work rather than introducing new difficulties.

B. The AHEAD application was sufficiently efficient to be run on a fast laptop; the OMNI was used for haptic interaction, and a pair of headphones for the audio. This was important for two reasons. For the final evaluation as such it was essential that the entire hardware was easily portable to bring to meetings with the teachers for showing changes in the material, disturbing them as little as possible in their ordinary work. The other reason was that the system inflicted minor changes in the work place of the visually impaired school pupils, since their ordinary work places are already full of equipment. In a not too distant future, such a system like the AHEAD system could be installed directly on the pupils' ordinary computer, adding only the PHANToM device (or similar) to the equipment.

C. The AHEAD application system runs on a laptop with a PHANToM OMNI and a pair of headphones for use in basic mode. In the beginning of the haptic interface era, an audio-haptic system with the same capabilities would not only be large due to the need of a powerful stationary computer and a PHANToM with a control box, it would also be hard to afford both for individual persons and schools.

Today, the entire system can be purchased for less than 35 000 SEK, which is less than an ordinary Braille display. If or when an ordinary computer in the price range that can be provided as an aid in school work is sufficiently fast (a matter of years), only a PHANToM OMNI device (or similar) would be needed. The total cost for it would then be about 20 000 SEK.

Individual use and interface issues

Audio-haptics in the form of the AHEAD application has shown to be useful in a school context. It adds functionality that is not present in the technological aids used today, and it is sufficiently flexible to use in several school subjects and for users with different needs and abilities.

D. The AHEAD application was developed with flexible use in mind. The five visually impaired school pupils that participated in the final evaluation used the application in different tasks, in different subjects and in individual group settings.

Pupil	R1	R2	R3	R4	R5
Age	11	12	12	15	17
Subject	Geography	Geography	Navigation	Mathematics	Literature
Residual vision	Used	Not used	None	Not used	None
Collaborator		Pupil E2		Pupil E4	Pupil E5
AHEAD mode	Explore	Explore	Explore	Edit	Explore
Previous PHANToM experience	30 min	30 min	1 h	1 h	> 3 h

Table 3 Overview of the diversity of pupils, school subjects and collaborators

E. The users need to have sufficient motor skill to use the AHEAD application. Motor skill in this aspect and visual impairment may have a correlation, in part because the PHANToM grip is formed like a pen and therefore promotes a pen-like use. Children, especially those who are blind from birth, seldom use a pen at all, and therefore both holding the pen and moving it about can be hard. Having said that, it is not the visual impairment that limits the use of the PHANToM device for the individual person, but the individual's motor skill. On the other hand, when the users are in fact used to pens, it is indeed a good way to explain holding and moving the PHANToM pen as a normal pen for writing or drawing. PHANToM users are not restricted to using a pen grip, however. One of the blind pupils in the final evaluation changed the hand grip of the pen frequently and used it for longer periods of time holding it like a navigational cane. This may or may not have affected the quality of the haptic feedback, but the observations confirm that it was a successful strategy for that particular pupil.

F. Visually impaired children who are on the boundary between needing to use tactile material and enlarging visual material may put much focus on the visual feedback of the system, preventing them from gaining good haptic experience. The same is seen to happen for some fully sighted persons, who, when faced with using the PHANToM for the first time, experience very little haptic feedback, since they focus on the visual feedback. This was seen very clearly especially in the early PHANToM applications, where there was no visual model presented on the screen. The sighted persons who tried the PHANToM and the applications/models for it had problems experiencing anything at all, since the visual input told them that there was nothing there to feel. In that respect, people with visual impairments who tried the system were often at an advantage since they were not fooled by contradictive inputs.

G. There have been no apparent differences in the overall success between the blind pupils and the low vision pupils. The fact that the pupils are of different age and have individual motivation has influenced the success of school task performance much more. Only one noteworthy difference: the pupils who are blind (and have been so from birth) are less familiar with visual symbols than the low vision pupils. This has relevance for the selection of material that can be presented to them but is of no relevance for their handling of the AHEAD application.

H. Almost all of the involved research persons in the user group are interested in having their problem solved regarding access to 2D graphics, and find the AHEAD application to be a good start. 4 out of the 5 pupils in the final evaluations were interested in using the system for future school work, and they were also satisfied with its functioning. Of the 5 pupils, 4 were asked in more detail about their preferences (R1-R4), as well as the teachers (T1, T2 and T4), assistants (A1, A2 and A3) and fellow pupils (E2 and E4) that participated (see Table 4 and 5 below). Some table cells are left empty, due to participants not wanting to or being able to answer every question. This detailed questioning did not take place with the pilot study involving pupils R5, E5 and teacher T5.

Pupil	R1	R2	R3	R4	E2	E4	Average
Rating of own result	4	3	4	4	4	4	3,8
Rating of audio-haptics compared to normal material	5	2	5	4	4	5	4,2
Rating of result compared to normal	4	2	5	3,5	4	5	3,9
Rating of wish to use audio-haptics on more occasions	5	1	5	4	5		4,0

Table 4 Pupils' rating of system and task results

Teacher/assistant	A1	T1	A2	A3	T4	Average
Rating of pupil's task result	4	5	4	4	3	4,0
Rating of audio-haptics compared to normal material	4	5	4	4		4,25
Rating of result compared to normal		3	3	5		3,6
Rating of wish to use audio-haptics on more occasions	4	5	5	5	4	4,6

Table 5 Teachers' rating of system and task results

I. The AHEAD interface uses text-to-speech (TTS) for its main audio feedback, although we anticipated using a larger proportion of non-speech information at the project start. Being able to use text information gives the users (both teachers and pupils) a large flexibility in the information displayed. The visually impaired school pupils are used to listening to texts and generally preferred it to non-speech sounds. The TTS information also gives the user a much larger personal freedom in altering the sound information that is displayed. Adapting and fine-tuning non-speech sound is much more complicated for non-professionals.

J. Auditory icons are successfully used in the AHEAD application for illustrating interface events that are user triggered (erase, copy, move and paste functions for drawn objects as well as shape conversions). It was furthermore seen to heighten the experience of the interface. Also, the users seemed to more clearly understand that something was really happening when it was illustrated by a sound, and they also seemed to enjoy the particular sounds.

K. The planned function of the AHEAD application's sound field was primarily to help the user to understand and remember drawn shapes. However, the particular sound field implemented seemed to be of no value. The sound in itself was very individually received. One of the pupils found it highly annoying, although accepted it as resembling the sound used for target shooting for blind users, whereas another pupil enjoyed it and used it more as an instrument and played with it for several minutes. Anyhow, the difference in sound character when drawing or exploring was seen to add contextual information. Especially for one of the pupils this was seen to be a great help, since that pupil had had problems releasing the button for ending a line when drawing.

L. Users were active while working and in some cases adopted strategies to attempt to overcome imperfections. As an example, the text-to-speech (TTS) tags are automatically played whenever the user touches a new object or has been away from the object a certain distance. Receiving only TTS feedback can sometimes be insufficient, since the TTS voices are far from perfect and sometimes pronounce words strangely. Also, when working with foreign words such as the names of capitals in South America, tags should be possible to spell out with the TTS or perhaps also

by adding Braille display. One of the pupils was observed using a strategy to make the TTS repeat its text tag for objects, by leaving them with the PHANToM proxy and then quickly returning to the same place over and over again to try to understand what the TTS was saying.

Context

Testing a prototype of an audio-haptic application in a school environment while attempting to come as close as possible to the intended final use can have benefits. The context is given and the activity focus is easier to accomplish. It will also bring out how different actors (pupils and teachers for example) can have different focus.

M. The use of the AHEAD application in a school subject put the information conveyed by the application in a natural context. In geography class, for example, information was limited to geographic information (in the specific cases: maps). This helped overcome a problem that has been inherent in earlier evaluations with non-visual audio-haptics, where users sometimes explored drawings without being aware of the context, which made it more difficult to understand the drawings.

N. The teachers were involved in the task selection and design process. The tasks had to emerge from the teachers to be at all successfully carried out at the evaluation lessons, and were therefore very much chosen based on the teachers' view of the problems that the pupils had. Also, the teachers seem to put relatively more focus on the pupils receiving information rather than creating drawings by themselves. This is seen in the overweight of exploring tasks (where the material experienced by the pupil was static) over dynamic editing tasks. Only one out of five pupils used the editing features of the application in the final evaluation.

Collaboration

The final evaluation indicated that the collaborative features of the AHEAD prototype were important. However, further investigations concerning how to provide the visually impaired pupils with additional information and support to enable them to take greater initiative in collaborative work are needed.

O. The collaborative function was seen to be very important, in that it was possible to share information between sighted pupils and visually impaired pupils. In regular geometry class, the visually impaired pupils work with tactile maps and short Braille tags which prevents effective collaboration between visually impaired pupils and sighted pupils. Having a common set of information to discuss in geometry class is especially important since geometry tasks often seem to be carried out in collaboration.

P. The guiding function and the pulling force that the guiding applied on the PHANToM user's proxy seemed to work reasonably well, but the design of that particular feature can be investigated further. Some pupils did not like to be guided at

all, since it made them loose their reference points. Also, the guiding strategy seems to matter. In the cases where the guiding person brought the mouse cursor sufficiently close to the PHANToM proxy before beginning to guide, guiding was more successful. Perhaps also a more adapted guiding force can help the guiding user to perform good guiding behavior.

Participation and starting points for design

I have described how different users (teachers and pupils, for example) have been involved in the design process. The novel technology puts extra demand on the participants envisioning the future use.

Q. Generating ideas for possible tasks connected to school subjects was initially very difficult for the teachers. They understood neither the full potential of the AHEAD application nor the limitations of it. Therefore, demonstrators illustrating possible use for school were implemented and shown to the teachers. The demonstrator materials consisted of a map with different details, a geometrical figure and a diagram. It has indeed been an interesting problem that potential end users cannot see the possible use scenarios until actually faced with a scenario that is sufficiently close to their own experience. Even given the scenarios, the teachers seldom ventured outside the given ideas, and when they did, the application area was quite close to the examples. One teacher, for example, did not want to use geographical maps, but rather maps of the school surroundings to enable the pupil to learn independent navigation. Another teacher adapted a geometry task to fit the audio-haptic system.

R. The starting point of the design effort makes a difference. In actively choosing to start in the haptic interface domain (and then adding vision and sound), we have let the haptic interaction take precedence over the others. Had we started in the audio domain, the interface would have been differently designed, perhaps with more audio solutions.

Discussion

In this discussion I start with some methodical issues, thereafter, I venture to the practicalities of drawing applications for non-visual use, finishing off with looking ahead at the future of audio-haptics and the AHEAD drawing application testament.

Hi-fi versus lo-fi prototyping

The very first attempts with haptics already made it obvious that end users do not have the slightest chance to contribute ideas to applications unless they literally get a firsthand experience of a system or tool. This is especially relevant when the technology is novel and a real niche for practical use has not yet been formed or when the technology is to be used in a new context.

Therefore, we have used functioning prototypes (see also *Method* section) that at least have a limited set of functions working when the users are first acquainted with a prototype. Technology-as-language, i.e. using artifacts as cultural probes (Gaver, Dunne, & Pacenti, 1999), is also described in a rehabilitation engineering context by Björn Breidegard (2006). It is especially important when designing for people with cognitive impairment and children. For people who cannot rely on paper prototypes or mock-ups, such as people who are blind or have low vision, the prototypes also need to be running with at least a limited set of functions to work as a base for discussion. This contradicts the open-ended mindset that is said to be needed to form a ground for innovative design, which implies that a lo-fi prototype method (such as using a paper prototype) is preferred to make it easier to rule out ideas or technological solutions (Rettig, 1994). However, faced with the opposite, a wrong guess expressed in technology is better than no guess at all. It puts extra demands on the developer/designer, though. The developer/designer needs to adopt an attitude that encourages the participating research persons to express any ideas or criticism, and refrain from being protective of the designed technology or even idea. It could be fruitful to adopt a mind-set that the early prototypes are more like sketches.

Also after firsthand experience of the system or tool, some users will be unable to contribute ideas unless they are faced with use scenarios that are sufficiently close to their own experiences to trigger their imagination. This was seen to happen to the teachers involved in the process of evaluating the AHEAD application. They were invited to try the system but were unable to see the possible use for them in their respective contexts, until they were presented with the examples that were designed for them by making educated guesses of possible scenarios. The same has been observed and reported in *Design side by side* (Jönsson et al., 2006) and *Just give us the tools* (Bauth, Svensk, & Jönsson, 1995). This is a kind of "chicken-or-egg" dilemma in the design of new technology and its introduction into new areas. As also presented in the Results section, the teachers were not really able to come up with novel ideas that were far from the scenarios that I had built. From this, I conclude that the teachers would actually need to use the application independently and design their own material before being able to see its potential and being able to adapt it for their own purposes in the classroom.

Situated experience and action

Another aspect emerged later: not only the enthusiasm and the needs of the end users play an important role for the development of the audio-haptics, so does their lifelong background knowledge from other fields as well as their wishes and dreams, revealed by the actual situation. As Paul Dourish writes in his article *Implications for Design* (Dourish, 2006):

"…'users'… [are] actors who collectively create the circumstances, contexts, and consequences of technology use"

This is also discussed by further in *Where the Action Is* (Dourish, 2001) and by Lucy Suchman (2007) as well as by Bodil Jönsson et al. (2004). They emphasize the action in the context and the situation. It can also be described as being loosely connected to activity theory in the context of interaction design as described by Kaptelinin and Nardi (2006). In particular, Hedvall describes activity theory connected to rehabilitation engineering (Hedvall, 2008) where issues such as the "lived perspective" and the "situatedness" of accessibility are in focus. The relation to activity theory also highlights high-level motivation in action which connects back to the concept of *useworthiness* (Eftring, 1999) (see also *Background* section). Additionally, Winberg recently described the context of the social setting in interaction, focusing on the collaborative situations that occur (Winberg, 2008).

It has been important that we face the users (here: the school pupils) where they are, in their normal surroundings, doing their work (almost) as usual. However, looking back and recollecting the iterative design-evaluation loop, this goal has really only been fulfilled in the final evaluation and to some extent in the field trips to the classrooms when we observed a regular lesson. Perhaps it would have been fruitful to establish an even closer contact earlier, to gather more detailed information and knowledge about the needs, wishes and dreams of the pupils. As an example, pupil R4 spent a week's vocational training at the Department of Design Sciences which is my work place. This occurred after the AHEAD project had ended and was an important source of information about situated non-visual computer access that I will carry with me into further research. It also gave me more input on the possibilities to creatively use enlargement in parallel with audio-haptics for drawing. However, getting back to the methodological question of the limited number of research persons, too close and frequent contacts might also be putting too much additional stress on the pupils.

Exemplar and inspiration rather than guidelines

I also want to comment on the nature of the results that I present. It is tempting to reformulate some of the results into recommendations or guidelines. However, given the small number of users, I would rather let the AHEAD development and evaluation process be an exemplar (Chalmers, 1999) and an inspiration of the strong involvement of users and the situated approach that has been used. A guideline is defined by the Merriam-Webster dictionary as (Merriam-Webster, 2008):

"an indication or outline of policy or conduct"

The Business dictionary online defines it (Business Dictionary, 2008):

"[A] recommended practice that allows some discretion or leeway in its interpretation, implementation, or use"

These statements could perhaps justify the transformation of my results into guidelines; however, I will again stress the entire context and the process, which would be lost if they would be divided into subparts.

Validity and reliability in methodological choices

As Peter Kroes elaborates in his article *Design methodology and the nature of technical artifacts* (Kroes, 2002), there are no clear verifications that a "good" method leads to a "good" resulting artifact. This absence of one-to-one verifications has its consequences.

I cannot honestly say that I am sure that the technological outcome of the AHEAD project would have been very different from the actual final prototype application, had we used other methods for eliciting information for building the system and concept. However, I am quite certain that the knowledge that has come out of the project is richer than it would have been had the user contacts been fewer and not so longitudinal. This knowledge, even if it may not have affected the result of the AHEAD application design greatly, will most certainly have an impact on upcoming projects.

Therefore, in a broader perspective, making potential users into actors in the design process is necessary. This is much more important when the users have special knowledge that is hard to transfer to designers (von Hippel, 2005).

Non-visual drawing applications – a recollection

During the time of the development of the AHEAD application, a couple of other non-visual drawing applications were developed. One, created by Crossan et al. is evaluated primarily as a tool for teaching handwriting to blind pupils (Crossan & Brewster, 2008; Plimmer, Crossan, Brewster, & Blagojevic, 2008). The application can be used in collaborative mode, where a teacher can guide the trajectory of the pupil's pen. Thus, that application focuses on the guiding and the learning of shaping letters correctly. Another application created by Gutierrez et al. is primarily for single-user drawing, and it features tools for zooming and different modes of exploration, e.g. free exploration, guided exploration or constrained exploration (Gutierrez, 2008). T. Watanabe et al. have also recently presented a compound technology solution using a tactile display device, a 3D digitizer and a tablet PC to enable blind pupils to draw and feel their drawings (Watanabe, Kobayashi, Ono, & YokoYama, 2006), and to access general graphic material. This system has been evaluated in school with a Kanji (Chinese characters) learning system and tactile games, as well as in geography and history lessons.

These application developments and the AHEAD drawing application, show a positive trend towards using digital solutions for non-visual drawing. Paired with the access of affordable and stable haptic equipment this can be pave the way for introducing the audio-haptic technology in schools, for example, turning blind and low vision children into lead users in this field.

Limitations and weaknesses

There are some issues related to a sincere wish to have done better in the design and development of audio-haptic applications, and especially the AHEAD application.

Level of user involvement

I have already briefly discussed the problem of user involvement in relation to the small number of end users in the target group, and the risk of putting to much work load on the end user group. However, faced with such a problem, perhaps other methods of user involvement should have been examined, like involving sighted youths in an earlier stage, or involving the resource persons earlier in the process as experts on school pupils with visual impairments.

Also, the degree to which the pupils were allowed and able to contribute to the design is a weak point. Perhaps, with the level of involvement that was the case, and the fact that we dealt with school children, it would have been difficult to apply another approach. Design practices for also letting young end users and users with visual impairments participate more in the process would be an interesting research approach; however, in practice, it fell outside the scope of the AHEAD application project.

Synthetic speech vs. non-speech sound

We anticipated using a larger proportion of non-speech information in the AHEAD application than was used in the final evaluation. Although the sound field and the auditory icons were also implemented in the final version of the application, text-to-speech (TTS) was primarily used. In part, this was connected to the use cases, where four out of five pupils only used the explore mode, and thus had no use for the auditory icons. Also, the sound field, when used together with the TTS, would interfere with the understanding of the TTS tags.

The formal test on the sound field also indicated that its design was not sufficiently investigated to render a desired goal of usability. While the test indicated that a change in design might provide additional shape information as was the goal with the original design, insufficient interest was shown by the pupil group to justify further design efforts in changing the sound field within the particular project. Instead, the possibility to use text-to-speech information was seen as being much more important in that it combined a large flexibility in the information displayed, the ability to adapt the texts to personal preferences, and the familiarity with the medium. Nevertheless, the useworthiness of the AHEAD application would perhaps have benefited from further investigations in design of the sound field, or by changing the approach of the design of the non-speech sound entirely. This could be

accomplished by, for example, an attempt to create earcons for drawn shapes based on the pitch, pan and time mapping used for the sound field.

Adaption for secondary users

The iterative design of the AHEAD application involved mainly the pupils in the early stages. There has been an outspoken focus to attempt to solve the pupils' problems first, and then take the teachers' wishes into account. This has, in practice, meant that the secondary users, the teachers, have not been able to evaluate the application as thoroughly as was intended. It would then have been necessary to take an equal longitudinal approach to the teachers' involvement, and thus allow them a longer learning period for using the application. Perhaps that could have been possible, but it is a balance between taking up too much of the teachers' time and involving them enough to contribute to the process.

Initially, the goal was also to enable the teachers to at least prepare some of the school material with the AHEAD application on their own. As it turned out, the main focus was to finish the application to be as stable and reliable as possible. Due to the (previously mentioned) difficulty for the teachers to envision the use of the application, the functionality related to secondary use (i.e. for teachers to create material) was also down-prioritized.

Conclusions

The aim of this thesis as stated in the Introduction is divided into 5 parts.

1st aim: To show that the audio-haptic technology adds functionality and meaning, because the currently used technological aids cannot provide the dynamic information access that the audio-haptics can.

The AHEAD application as such perhaps cannot advocate for audio-haptics to be useworthy in the long run. However, in this special context, a basic drawing application like AHEAD already adds functionality that is lacking in current technological aids. Also, the pupils and their teachers expressed a great interest in using the AHEAD application for further school work as shown in the *Results* section. That the application is computer based also enhances motivation, and in the context of the situation for pupils with visual impairments in Swedish schools, the possibility to acquire such systems is not that far-fetched.

2nd aim: To show that it is possible to undertake on-site user testing of audio-haptic applications in a school environment together with children with blindness, their sighted peers and their teachers.

I have, based on the investigations and the development process of the AHEAD application, shown that it is possible to take an audio-haptic prototype and evaluate it in a classroom during a busy lesson. This was accomplished by involving not only the pupils with visual impairments in the development process but also on gaining approval for the technology and its possible use by involving teachers.

3rd aim: To describe an activity based user-centered iterative process in the development of a prototype of a non-visual drawing application for collaborative use in school (the AHEAD application).

In this thesis and two of the appended articles, the process of design and development of the AHEAD application has been described in detail. Focus has been on the design considerations and the evaluation of the functioning prototypes rather than the technical aspects as such. I am not interested in diminishing the technical work – it is indeed a large part – but the relatively high percentage of evaluations and usability based investigations are the core of my work. By describing the process of development and evaluation, I have also shown that it is possible to deeply involve end users even when they cannot participate in designing by, for example, working with lo-fi prototypes.

4th aim: To emphasize the need of applying a context based, activity based and situated approach to design of artifacts for assistive use.

While the context and the high-level activity is important for everybody using artifacts for different purposes, the individual, the situation, the anticipated activity and the context for people with some form of additional impairment will add to the complexity of the problem to be solved. Therefore, all background aspects that can be brought into the design process will add to the experience of the designer and hopefully affect the outcome.

5th aim: To exemplify the possibilities to carry out collaborative work between pupils with blindness or low vision and their sighted class mates, also when material is based on graphics.

The AHEAD application was on 3 different occasions used by pupils in collaboration, one for learning maps, one for stage setting a theatre play and one for learning geometry. There is more to discuss concerning, for example, the power distribution between pupils, and who takes the initiative in solving tasks. A tool like this might even help to put focus on such inequalities in school group work.

Thoughts and ideas for the future

The complexity of haptics and the slow rate of progress towards more inexpensive hardware have unfortunately had a negative impact on the dissemination of haptic technology and of the possible application areas. Recently (in 2007), a consumer 3D force-feedback device, the Novint Falcon, reached the market, and in spring 2008, a number of games were created or adapted to make use of the Falcon device. However, we have already seen earlier attempts at haptic consumer devices that did not meet the expectations of either consumers or companies (e.g. the Wingman Force-Feedback Mouse). Keeping that in mind, haptic interaction awaits the "killer application" that will bring it into widespread use.

Still, we may very well be on the verge of a change in the interaction with computers. As the increasing use of accelerometers and vibrators (like Nintendo Wii for example) and also the use of small mobile devices indicate, perhaps we are on the brink of a turning point when we will come to rely less on traditional keyboards and mice for computer interaction. Audio-haptics may well play a role in this changed interaction, but to what extent I am reluctant to guess.

Digital maps for mobile and low vision use

For my own part, I will now enter a four-year project (HaptiMap, 2008) concerning interaction and information perceptualization with mobile devices for the purpose of navigation. The word *perceptualization* should be understood in a broad sense, including audio and haptics as well as visual graphics. To this project I bring the experiences from my thesis research, to take on the challenges that I see in the new project.

Long-term user involvement

In the four years of the project, end users will be involved throughout the whole process. My experience with the pupil user group and the AHEAD application design and development process will guide me as I participate in the work concerning user involvement.

Interaction on small screens

The HaptiMap project focus is on mobile devices and in a sense all people become "visually impaired" when running applications and retrieving information on the small screen of a mobile phone for example. It is comparable to running enlargement applications on a computer screen for low vision users. My long-term experience with persons having visual impairments will help form a base for creating the first prototypes.

Non-visual mobile interaction

GPS navigators for cars are designed to display auditory information in order to enable a person to drive a car and at the same time follow a directions conveyed by the GPS voice. Similarly, a person riding a bicycle or walking while using a GPS may

need a way to receive information without looking at a screen. Nor may it be preferable to receive spoken audio information when on foot or riding a bicycle, which can leave room for creating interaction based on haptics (and perhaps non-speech sounds). My experience with audio-haptics will yield input in the design phase, and I look forward to applying my knowledge to mobile devices.

Accessible planning tools

Navigation also has to do with the planning of a trip. Nowadays, digital maps like Google Maps are in widespread use in the preparation of a trip. These maps are as yet not accessible for persons who are blind or have low vision. Part of the project will be dedicated to making such maps more accessible, which lies very close to my experiences with the AHEAD application, as well as from earlier projects like the traffic environment project (Magnusson et al., 2005).

Transferring design practices for accessibility into corporate processes

One subpart of the HaptiMap project deals with transfer of accessibility issues into the planning and design of products in corporate business. My focus on context and process paired with my long-term experience of accessibility issues (especially but not limited to people with visual impairment) will provide input to that work.

Further AHEAD

Concerning the drawing application AHEAD, there are plans to make it available to a larger audience. We hope to accomplish this by continuing the work in close contact with teachers and school pupils, by taking the following actions:

1. Making updates and finalization of the software, including facilitating the process of creating material for the teachers
2. Obtaining three entire systems for the AHEAD application that can be used as pilot equipment on a long-term basis in schools
3. Supporting the teachers and pupils in creating material
4. Creating demonstrators or exemplary material in collaboration with teachers and making them publicly available

By these actions we hope to assess whether the AHEAD application is useworthy in a long-term perspective when the teachers and the pupils have the full initiative to use the system, and are able to do so whenever they see the need for it.

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Svensk sammanfattning

Förr var barn med synskador ofta tvugna att gå i specialskolor långt hemifrån. Idag går elever med synskador i en vanlig klass på sin hemort. De använder i stor utsträckning datorer i undervisningen. Datorerna omvandlar text till syntetiskt tal eller till punktskrift. Svårare blir det när det kommer till bilder - då är det reliefbilder på papper som gäller. Detta kan påverka flexibiliteten i undervisningen, eftersom det kan vara svårt för en lärare att spontant skapa en reliefbild till en elev som svar på en fråga som någon har ställt. Dessutom är det svårt för seende elever och synskadade elever att göra grupparbete med bildmaterial tillsammans.

Under en period av två år har vi tagit fram ett datorbaserat ritprogram (AHEAD), som gör det möjligt både att göra en ritning och att känna av ritningar och höra beskrivningar av detaljer i dem. För att kunna rita och känna använder vi haptik, ett sätt att med motorer skapa en motkraft som överförs till användarens hand. Den haptiska apparaten vi har använt, *the PHANToM*, har relativt hög precision och stark motkraft, vilket ger en tydlig känselupplevelse (se bild 1).

Bild 1 *The PHANToM* används för att styra ritprogrammet

Med ritprogrammet kan eleverna rita linjer och olika former, ändra på storlekar, radera och flytta ritade figurer. Det kan liknas vid en förenklad variant av t ex Paint i Windows men utan möjligheten att färglägga. Eleven håller i det penn-liknande handtaget på *the PHANToM*, och när en linje ritas på skärmen, skapas också en graverad linje som är kännbar. Ritprogrammet kan användas av två personer samtidigt, genom att en person använder *the PHANToM* och en annan person använder en vanlig datormus. Förutom känsel-information kan man också få beskrivningar av detaljerna i bilden. Beskrivningarna läses upp av datorn med hjälp av syntetiskt tal. Dessutom finns det ljudeffekter till olika funktioner för att den som använder programmet ska kunna förstå vad som händer trots att de inte kan se det.

Man kan till exempel kopiera en figur och klistra in den på ritningen. Kopieringen illustreras av ett kameraklick och när man klistrar in hörs ett ljud som låter som om man använder en stämpel.

Fem elever på olika skolor har medverkat i projektet. Under tiden utvecklingen pågått har de provat ritprogrammet vid flera tillfällen och diskuterat hur programmet skulle kunna fungera. Tillsammans med eleverna, deras lärare och klasskamrater gjorde vi också en slutlig utvärdering. Lärarna valde ut ett ämne och tillsammans med dem utformade vi en riktig skoluppgift som baserade sig på användning av ritprogrammet. Sedan genomfördes den uppgiften under en riktig lektion (bild 2).

Bild 2 Två elever abetar med en geometriuppgift, där den ena eleven beskriver en figur i detalj och den andra eleven ska rita figuren utifrån beskrivningen

De viktigaste resultatet av arbetet är att alla eleverna lyckades med sina uppgifter under lektionen. Alla utom en ville gärna arbeta med ritprogrammet även i framtiden. Det visar att programmet kan göra nytta i undervisningen och att det fyller ett faktiskt behov genom att det går att använda i en realistisk samarbetsuppgift i skolan. Dessutom kan man se att det är möjligt och önskvärt att göra utvärdering tillsammans med elever och lärare i en verklig situation. I den kommer det fram andra problem och möjligheter än vad som syns vid en traditionell utvärdering i ett laboratorium.

Selection and summary of publications

While all the publications mentioned in the *Introduction* section are relevant in the context of non-visual audio-haptic application design, four publications have been chosen to be appended to this thesis. The selection of the publications on which this thesis is based was made to narrow down so as to be as relevant to the process of designing and developing the AHEAD application as possible. The publications are contributions to peer-reviewed conferences where the competition and quality of the review process is high, and where the research results quickly reach a large audience.

I. User Evaluations of a Virtual Haptic-Audio Line Drawing Prototype
Authors: Kirsten Rassmus-Gröhn, Charlotte Magnusson, Håkan Eftring
Presented at: Workshop on Haptic and Audio Interaction Design, August 31-September 1, 2006, University of Glasgow, UK

This workshop publication presents the initial steps of the AHEAD application in the design-evaluation loop. Three qualitative evaluations focused on recognizing drawn shapes and creating drawings and were conducted with a reference group of 5 visually impaired children. Additionally, one formal pilot test involving 11 adult sighted users investigated the use of a combination of haptic and sound field feedback. The sound field was a pitch and stereo panning analogy with the pitch varying from low at the bottom of the drawing to high at the top. In the formal test the relief type (positive and negative) was also varied.

The results of the formal study indicate a subjective preference as well as a shorter examination time for negative relief over positive relief for the interpretation of simple shapes such as 2D geometrical figures. However, the presence of the position sound field with a pitch and stereo panning analogy was not shown to affect task completion times or subjective success ratings by the participating users.

II. Iterative Design of an Audio-Haptic Drawing Application
Authors: Kirsten Rassmus-Gröhn, Charlotte Magnusson, Håkan Eftring
Presented at: CHI 2007 Work In Progress, 28 April - 3 May, 2007 San Jose, California, USA

In brief, this publication presents the design process right up to before the final evaluations of the audio-haptic drawing program AHEAD. The application was developed in close collaboration with a user group of five blind/low vision school children. Sighted persons have participated in some non-visual evaluations. The paper gives a broad overview of the application functionality. It also shows how investigations of user interaction techniques and basic research on navigation strategies and drawing behavior and tools were carried out. Among the evaluations were studies on the use of sound fields, on relief design and on work area orientation. In particular, the use of the shape creation tools, a pilot study on collaboration and a pulling force design experiment are presented.

The results show that the kind of shape conversions chosen (a user draws a circle, and then converts it into a perfect one) work for the pupils, and that they enjoyed the audio feedback of the tools. In the pilot study with collaborative use and the possibility to add tags to drawn shapes it was also obvious that the new features were very important for the useworthiness of the application. The pulling force was given its final adjustment based on this formal test.

The paper concludes by pointing out that the design process used has provided an increased understanding of how to design a working haptic-audio drawing application to be used by blind and sighted school children in collaboration. It also describes the final aim of the application: aiding school work in different subjects and shows how work would commence with creating tasks relevant for a school setting.

III. AHEAD – Audio-Haptic Drawing Editor and Explorer for Education (edited version)

Original authors: Kirsten Rassmus-Gröhn, Charlotte Magnusson, Håkan Eftring
Originally presented at: HAVE 2007 – IEEE International Workshop on Haptic Audio Visual Environments and their Applications, Ottawa, Ontario, Canada, October 12-14, 2007

This publication reports on the pre-final and final evaluation of the AHEAD application primarily for the purpose of assessing its practical use in the context of school work and in a collaborative situation. The evaluation was carried out in five different schools and in different school subjects. Three of the visually impaired pupils in the pupil group worked in collaboration with sighted classmates doing their school tasks. Two of the pupils were working primarily in single-user mode, but were also instructed by their resource persons. Five sets of school material were created for the subjects: mathematics, geography, navigational training and literature. In all cases except mathematics, the application was used only for exploring ready-made graphics, but in the mathematics case, the drawing functions were used.

In the original article, presented at the above mentioned workshop, preliminary results were presented. Later, an indepth video analysis and a full post-test-interview analysis were carried out. For the purpose of showing the entire result, the original article was edited and the complete analysis was presented.

The results of these tests showed that programs like the AHEAD application could be a useful complement to the materials already used by visually impaired children at school. All pupils succeeded in performing their assigned school tasks with the aid of the AHEAD application. All the teachers involved, and four out of five pupils stated that they would be happy to use the AHEAD application for more school work.

IV. Navigation and Recognition in Complex Haptic Virtual Environments – Reports from an Extensive Study with Blind Users

Authors: Charlotte Magnusson, Kirsten Rassmus-Gröhn, Calle Sjöström, Henrik Danielsson
Presented at: Eurohaptics 2002, July 8-10, 2002, Edinburgh, UK

The article reports the major results from an extensive study with 23 participating blind or low vision users from Italy and Sweden. The users were presented with models in three dimensions of different complexity: geometrical shapes, VRML objects in different shapes (a grand piano, a satellite, a guitar and a pot), mathematical surfaces and a traffic environment. The geometrical shapes and the VRML objects evaluations were focused on the ability to recognize shapes, while the traffic environment was a dynamical model which was also used for navigation. The mathematical surface application was used by a limited number of participating research persons who had expressed an interest in and some understanding of 3D mathematics. This application was used in a collaborative setting with the test leader and the user exploring and discussing mathematical surfaces together.

The outcomes of these tests show that the users were able to handle quite complex objects and environments. It was also shown that realistic virtual environments appeared easier to handle than more abstract ones. This highlights the importance of context, and thus the usefulness of other input channels beside the purely haptic one. Another important factor observed was the individual haptic scanning strategies used by the research persons, and the importance of accurate haptic models was pointed out.

I

User evaluations of a virtual haptic-audio line drawing prototype

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Abstract. A virtual haptic-audio drawing program prototype designed for visually impaired children has been gradually developed in a design-evaluation loop involving users in four stages. Three qualitative evaluations focused on recognizing drawn shapes and creating drawings have been conducted together with a reference group of 5 visually impaired children. Additionally, one formal pilot test involving 11 adult sighted users investigated the use of a combination of haptic and sound field feedback. In the latter test the relief type (positive and negative) was also varied. Results indicate a subjective preference as well as a shorter examination time for negative relief over positive relief for the interpretation of simple shapes such as 2D geometrical figures. The presence of the position sound field with a pitch and stereo panning analogy was not shown to affect task completion times.

1. Introduction

The present paper describes preliminary tests with a prototype of a virtual haptic-audio drawing application for low vision and non-vision users. The purpose of this application is to allow visually impaired users to create and access graphical images. The application is and will be developed in close collaboration with a user reference group of five blind/low vision school children. The objective of the prototype is twofold. During the early development stages, it is used as a research vehicle to investigate user interaction techniques and do basic research on navigation strategies and helping tools. Later, the prototype will be tailor-made for use in schoolwork and the final application should be possible to use in different school subjects.

Getting access to 2D graphics is still a large problem for users that are severely visually impaired. Using a haptic display in combination with audio feedback is one way to enable access. There are many issues to address, e.g. how to provide an overview, to what extent users are able to interpret a combination of lines or line segments into a complex image, how to design the lines to get appropriate haptic feedback, what hardware to use etc. General guidelines to create and develop haptic applications and models are collected in [1]. Applications making practical use of non-spoken audio and force-feedback haptics for visually impaired people are e.g.

applications supporting mathematical display [2], [3] & [4], games [5-7] and audio-haptic maps [5;8].

There are few tools that enable blind people to create computer graphics. As described in [9] and [10], there are indeed people who are blind who have an interest in hand drawing. In [11], a CAD application is presented that enables users to create drawings with the help of audio and keyboard. This is accomplished by a structured approach of dividing a drawing into small parts and to enable the user to draw small segments of a drawing. In [12], a study on a haptic drawing and painting program is presented, and that work can be seen as a pre-study to the work in this article.

2. Interface and equipment

The presented prototype makes it possible to make black & white relief drawings and tries to incorporate improvements suggested by [12]. The Reachin 4 beta software is used to control the haptic device, which can be either a PHANToM OMNI or a PHANToM Premium. The sound control is based on the FMod API.
The application consists of a room with a virtual paper sheet, which a user can draw a relief on. The virtual paper is inscribed in a limiting box. When the PHANToM pen is in touch with the virtual paper the user can draw on it while pressing the PHANToM switch. The haptic image is produced as 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 grey.
At the time of the test the haptically touchable relief was updated every time the user released the switch on the pen. It was at the time a problem to let the user feel the exact line that was drawn, since it caused instability in the PHANToM.

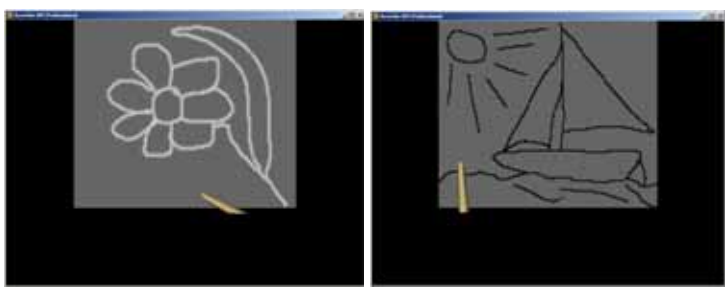

Fig 1. Screenshots of the drawing program in negative relief to the left and in positive relief to the right

However, this problem has been fixed (May 2005) partly by including GDI+ software and it is now possible to feel the line drawn (except the last segment).
To enhance the user's perception of localization a sound field was added. When the cursor moves in the virtual room, the pitch of a position tone is changed, brighter upwards, and mellower downwards. 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 (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. Also, to differentiate the walls of the limiting box from the virtual paper a contact sound is played when the user hits a wall with the PHANToM pen

Drawings can be saved in png format, and a png import function has also been implemented. 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 also be used e.g. to smooth out relief lines.

3. User evaluations

The application has been gradually developed since 2005. It has been continuously evaluated by a reference group of 5 school 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.
In March 2006, the application was tested in a formal pilot test with 11 sighted adults (aged 25 – 72). The users made the test without visual feedback from the screen.

3.1 Qualitative evaluations with reference group with children

The reference group has (to date) used the drawing program at 3 different group meetings. Not all of the reference group participants have been present at every meeting. Design work has been iterative and the users have been presented with new features and changes in the prototypes at every meeting. All three evaluations have been qualitative. The first two evaluations were of an informal nature, with few and loosely formulated test tasks. Instead 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 evaluation also incorporated some formal test tasks. During these tests, drawing has been tested with and without audio feedback, with positive and negative relief and with program interaction governed by virtual haptic buttons and keyboard commands. We have used the PHANToM Omni and Premium models for our tests. The tasks tested are summarized below:

- Draw and feel lines in negative and positive relief (haptics).
- Use vertical or horizontal work area.
- Change the relief using virtual button or keyboard button (haptics).
- Draw and feel an image (haptics + audio).
- Draw a specified shape – a rectangle and an Arabic number (haptics + audio).
- Explore and recognize Arabic numbers (haptics + audio).
- Explore and recognize two simple geometric shapes (haptics + audio)

3.2 Formal pilot study with sighted adults

A formal pilot user test was conducted on the latest prototype version with complete sound field mapping to pitch and pan, vertical drawing paper, limiting box and png

file save, whose features are described in more detail above (section 2). The PHANToM Premium was used for this test, and a pair of headphones was used when sound field feedback was available. The users were presented with different recognition tasks and were asked to describe or reproduce the experienced relief drawings in different ways either using the drawing program itself, pencil and paper or verbal description (table 1). Four different test cases (see table 2 and 3) were designed to overcome the learning effect bias in the test. The users were also asked to rate the difficulty of the recognition tasks on a scale from 1 to 5, where 1 means least difficult, and 5 means most difficult.
In total, there were 16 test tasks regarding recognition and reproduction of 2D geometric figures in outline and abstract or mathematical curves with one or two parts (fig 3). The complex tasks were symbols from road signs either in positive or negative relief (fig 4). For each task the time to examine figures was measured. When the user considered himself/herself ready with the examination the time was stopped and the user was free to use as much time as he/she needed to reproduce the task figures. For the road sign recognition, the user was also asked to point out the test task road signs among a collection of road signs with similar features.

Table 1. Reproduction methods for test tasks

Task 1 geometry	Task 2 curves	Task 3 geometry	Task 4 curves	Task 5 road signs	Task 6 road signs
Verbal descr.	Drawing-program	Verbal descr.	Drawing-program	Pencil & paper	Pencil & paper

Table 2. Test cases for formal pilot test, sound field variations.

Test case	Task 1 2D geometry	Task 2 curves	Task 3 2D geometry	Task 4 curves	Task 5 road signs	Task 6 road signs
1, 2	No sound	No sound	Sound	Sound	No sound	Sound
3,4	Sound	Sound	No sound	No sound	Sound	No sound

Table 3. Test cases for formal pilot test, variations in relief type. For each task there were 4 subtasks (for complex tasks 2) with varying relief type.

Test case	Subtask X.1	Subtask X.2	Subtask X.3	Subtask X.4
1, 3	Positive	Negative	Positive	Negative
2,4	Negative	Positive	Negative	Positive

Fig 2. Sample recognition task material for outline tasks. Two geometrical figures and two curves, one open and one closed.

Fig 3. Sample recognition task material for area tasks, Swedish road sign symbols.

4. Results

4.1 Results from qualitative evaluations

All users seem to enjoy the program, and have found it easy both to draw and feel the lines. For line following negative relief seems to be preferred, although one user expressed a liking for positive relief. In general both types of relief seem to be wanted. Our first test was done using the PHANToM Omni model, while later tests due to practical reasons were done using a PHANToM Premium. This caused problems since the Premium pen is less easy to hold (particularly for blind children who are not as used to holding a pen as sighted children are). Furthermore the tiny switch on the Premium was harder to manipulate than the buttons on the Omni – particularly for children with more problems with their fine motor skills. Both vertical and horizontal work areas have been tested. The horizontal work area puts less strain on the arm, and allows for external physical constraints (e.g. the table) to stop the user from pushing through the haptic surface too much. The vertical work area on the other hand seems to generate more distinct haptic feedback – uses express that shape differences may be easier to feel with this orientation.

There was no clear preference for keyboard buttons over virtual buttons. The advantage of the keyboard is that it can be accessed without moving the PHANToM, but our users have to remember a lot of keyboard commands already, and thus keyboard use may lead to an unwanted increase of the memory workload.

For the tests with both haptics and audio, all three test users were able to use the application as intended, and the different task results for the users seem to match personal differences in fine motor skills and the ability to remember images. Two of the three users could draw a square and a number, two could recognize the Arabic numbers and all three could recognize the simple geometric shapes

(circle/triangle/square). During the test session some general observations were also made. It seemed as if some of the 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 big problems releasing the switch to feel the painting. The sounds, however artificial, did not disturb the users very much, although one musically trained user found them disturbing. That same user also indicated the similarity of the sound with the aiming sound used for target shooting for blind users. Another user expressed great enjoyment with the sound and spent quite much time playing with it.

4.2 Results from formal pilot study

The formal test took approximately one hour to complete. 10 out of 11 test persons were able to complete the test, although a few test tasks had to be cancelled due to time restraints. One out of the 11 users had an elbow injury leading to less controlled fine motor movements, which first caused overheating in the PHANToM motors, and then caused the user to break the test due to pain.

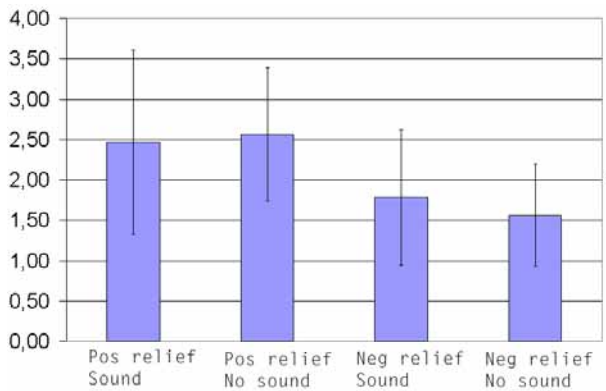

Fig 4. Mean estimated difficulty of geometry recognition tasks on a scale from 1 (least difficult) to 5 (most difficult).

In general, the geometry recognition tasks were found to be the easiest. The time to complete the examination of the figures was shorter than the time to examine curves and road signs, and there can also be found indications that negative relief is to be preferred over positive relief, both subjectively (figure 5) and by time measure (figure 6). However, there appears to be no significant difference between the presence and the absence of the sound field.

Since the task did not incorporate any reproduction of the geometrical figures by drawing, there is no information on how users perceived the figures in exact detail. However, 3 out of 10 users described the pentagon (se figure 3) as being “a house side” or “a square with a triangle on top”. One user mistook the octagon (8 sides) for a heptagon (7 sides), another user for a nonagon (9 sides). Two users also mistook the hexagon for a pentagon.

Further, in the curve recognition tasks, there appears to be no major difference between the different conditions neither concerning subjective measures or time measures (figure 7).

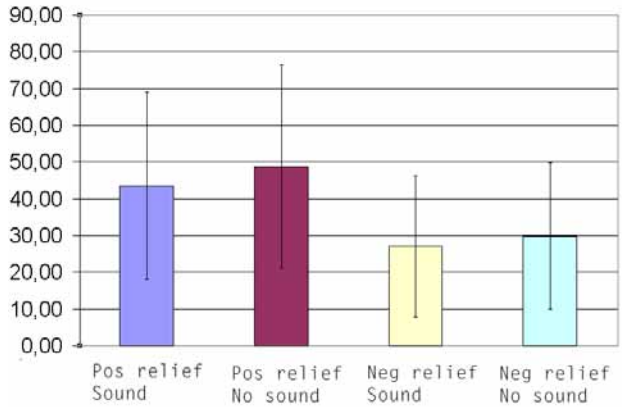

Fig 5. Mean measured time in seconds spent on geometry recognition tasks.

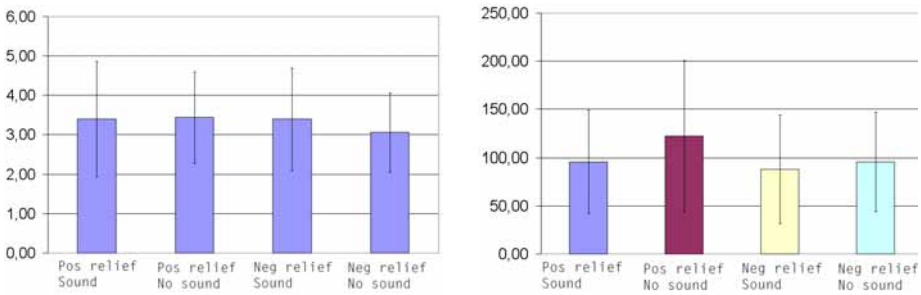

Fig 6. Left: Mean estimated difficulty of curve recognition tasks on a scale from 1 (least difficult) to 5 (most difficult). Right: Mean measured time in seconds spent on curve recognition tasks.

Table 4. Number of correctly drawn curves by user number.

User	Nr of correct curves	Total nr of curves
1	7	7
2	7	8
3	6	8
4	7	7
5	2	8
6	3	8
7	5	8
8	6	7
9	5	7
10	6	8

As can be seen in table 4 a majority (8) of the ten test users drew more than half of the figures reasonably correct. The most common type of major error is that part of the figure is missing. This occurs particularly when the figure contains separate parts or when there is an intersection inside the figure. But also in the case of a single line, this may occur when the figure contains sharp direction changes such as the curve illustrated in figure 8.

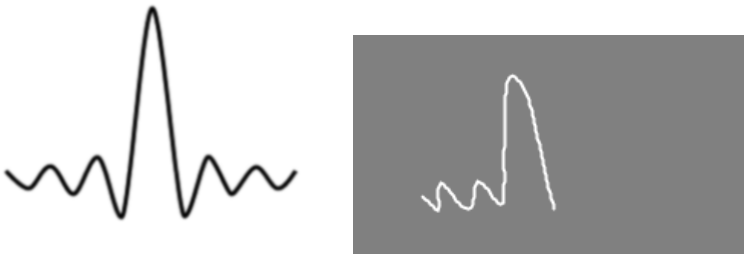

Fig 7. Curve recognition task: the original curve and one example of the curve drawn by a user.

For this type of figure several users missed the part of the figure before or after the big "bump" in the middle. The drawings also illustrate the need for better feedback during drawing, since minor mistakes such 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 even more difficult; the mean rating was 4 on the 1 to 5 difficulty scale. However, despite the obvious problems the users had to examine and to reproduce most of the signs with pencil and paper, the users still pointed out the correct road sign on average 3 out of 4 times when presented with a chart of 24 different road signs.

It is hard to extract any information about benefits of choosing either one of negative or positive relief. Since it was a whole area that was embossed (positive or negative) the scanning of the area was difficult in either mode. Nevertheless, some observations were made that indicate that negative embossment is easier to scan because it more clearly constrains the user to an area.

5. Discussion

The formal pilot study shows that there is a tendency towards the preference for negative relief when it comes to following lines for the simpler line based drawing (e.g. geometrical figures). Also the time measurements indicate that negative relief is easier to use. This approach is also used by e.g. Yu et al. in [13]. It seems that this effect is less obvious in recognition of more complex line drawings. The study in [14] also shows that individual preferences for relief vary.

The examination time results for the positive relief rely much on the strategy adopted by the user. If a user follows the inside of a closed figure, recognition tends to be found easier and object examination times shorter. This effect is furthermore

indicated by the complete failure of one user to follow the open curve in figure 8 in positive relief.

The error made by 3 of the users, who mistook the pentagon with sloped sides for a figure with straight vertical lines is also exemplified by Riedel and Burton in [15]. The sound field present did not give users any help in determining the slope either, since the stereo panning of the sound has too low resolution.

The sound information was shown not to affect the examination times and recognition accuracy. Pakkanen and Raisamo [16] have previously shown that exact recognition of geometrical objects using a combination of vibro-tactile feedback and audio is hard. Some users also expressed annoyance with the sound, whereas some users enjoyed it despite its artificial sound. 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 result. 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.

All user tests showed that the application could be used also to create own line drawings in either positive or negative relief. However, since it (at the time of the test) was not possible for the user to feel the exact line that he/she was drawing, there was no easy way to connect the end point with the start point or start segment of the same line to produce closed curves.

6. Conclusions

- Both positive and negative relief is possible to feel and to work with.
- Negative relief is preferred when working with simple line shapes.
- There are indications that negative relief shortens examination times.
- Drawing lines with a haptic drawing tool is not too easy, but not too difficult either.
- Both vertical and horizontal virtual paper will work in the short run – but what about ergonomics?
- Simple shapes can be recognized when they are kept in a specific context.
- The sound feedback can be used to get information about the program mode.
- Sound feedback did not seem to have a positive effect on task completion times.
- The PHANToM Premium is hard to use especially for blind users who also don't handle an ordinary pencil very easily.

7. Acknowledgements

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II

Iterative Design of an Audio-haptic Drawing Application

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Abstract

This paper presents the ongoing design and evaluation of an audio-haptic drawing program that allows visually impaired users to create and access graphical images. The application is developed in close collaboration with a user reference group of five blind/low vision school children. The objective of the application is twofold. It is used as a research vehicle to investigate user interaction techniques and do basic research on navigation strategies and help tools, including e.g. sound fields, shape creation tools and beacons with pulling forces in the context of drawing. In the progress of the development, the preferred features have been implemented as standard tools in the application. The final aim of the application in its current form is to aid school work in different subjects, and part of the application development is also to create tasks relevant in a school setting.

Keywords

Haptic, auditory, force-feedback, blind, low vision, iterative design, interface, drawing

ACM Classification Keywords

H5.1 [Information interfaces and presentation (e.g., HCI)]: Multimedia Information Systems.
H5.2 [Information interfaces and presentation (e.g., HCI)]: User Interfaces -- Auditory (non-speech) feedback, Haptic I/O, User-centered design
H.5.3 [Information interfaces and presentation (e.g., HCI)]: Group and Organization Interfaces – Computer Supported Cooperative Work

Introduction

Getting access to 2D graphics is still a large problem for users that are severely visually impaired. Using a haptic display in combination with audio feedback is one way to enable access. General guidelines to create and develop haptic applications and models are collected in [1]. Applications making practical use of non-spoken audio

and force-feedback haptics for visually impaired people are e.g. applications supporting mathematical display [2], [3] & [4], games [5-7] and audio-haptic maps [5;8]. As described in [9] and [10], there are indeed people who are blind who have an interest in hand drawing. In [11], a CAD application is presented that enables users to create drawings with the help of audio and keyboard. In [12], a study on a haptic drawing and painting program is presented.

Iterative design process

User-centered design is a design philosophy that focuses on the end users needs and wishes for a products functionality [13]. This is motivated by that fact that it is very hard for designers to foresee the needs and wishes of others, and is especially important when the end users are people with impairments.

In the current work our target group involves children with visual impairments. This presents special problems since the number of available users is quite limited (making the group both small and diverse) but also since theses users are children which, among other things, makes it hard to do more extensive or "dull" tests.

To deal with these problems we have used an adapted user centered approach. User involvement has been achieved through a reference group where we have had discussions and performed qualitative and explorative tests. This process has been complemented by more formal tests of basic functionality by a larger group of sighted users. This way we avoid subjecting the limited group of end users to too many tests and also avoid putting them in front of uncomfortably dysfunctional applications, by performing tests to evaluate basic functionalities with blindfolded sighted users. The above described approach was based on the assumption that for more basic functionalities we expect reasonably similar results for blind and blindfolded sighted participants. It should be noted that for more complex tasks and realistic situations this is not generally true, and in these cases we will always need to involve the real end users.

Initial user requirements

At the start of the project we performed an initial round of interviews with 10 blind persons (ages ranging from 10 to 66). The answers suggested several application areas that could be of interest: images, arts & drawing, maps and geographical data, mathematics (including tables, graphs, geometry, and statistics), physics (rigid bodies, electricity, magnetism, waves, quantum mechanics etc), chemistry, games & gymnastics and following what happens on the blackboard.

Since we were targeting an application that could be made useful over a range of years and that was available through a stationary computer we decided to start working on a simple drawing program which could cover some basic aspects of most of the application areas above (except games and gymnastics). This choice was also discussed with and approved by our reference group.

Current status of application

The Reachin 4.1 API software has been used to develop the haptic part of the application, along with FMod Ex 4.04.30 for non-speech sound and Microsoft SAPI

5.1 for speech synthesis. A PHANToM device is used for haptic feedback and control, and a mouse can be used for non-haptic control of the program.

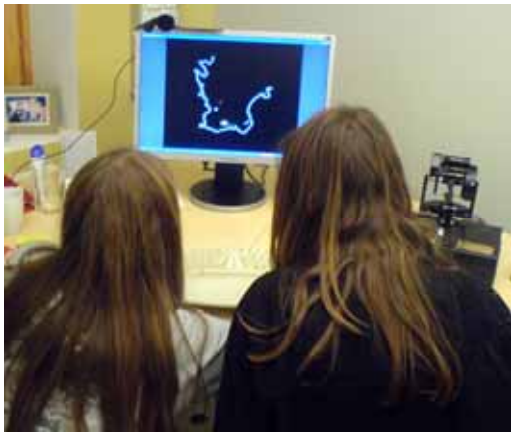

Figure 1 Two pupils collaborating in using the drawing application.

The virtual environment consists of a virtual sheet of paper. The PHANToM user draws by pressing the switch when in contact with the paper. The mouse user draws while pressing the left mouse button. The haptic image is produced as positive or negative relief. The drawing is presented 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 grey. The PHANToM user can feel the lines while drawing. Each line is attached with a number and text tag which is spoken by the application each time a user selects an object by touching it with the PHANToM pen or hovering over it with the mouse cursor. Objects can be manipulated in the different ways; moving, resizing, copying, pasting and deleting. Additionally, text tags for the shapes can be changed, and shapes can be transformed into straight lines, rectangles or circles. The manipulation tools are fitted with feedback sounds designed to resemble a real world manipulation of similar nature. E.g. the copy function sound effect is a camera click.

The mouse user can guide the PHANToM user by a pulling force that drags the PHANToM pen tip to the mouse cursor position. It is also possible to place beacons at specific points in the environment. The user can later return to these beacons by activating a pulling force.

There is the possibility to turn on a sound field to aid localization. When in contact with the virtual drawing paper the volume is louder, and when the user is drawing the tone is changed to a saw-tooth wave. Vertical position is mapped to the pitch of the tone, while horizontal position is mapped to the pan of the sound source.

A png import and export function is available. The files imported must be grayscale and 256*256 pixels.

User evaluations

The application has been tested at five different occasions by a reference group of five school children, aged 10 to 16. Two of the participants are blind from birth, and

three participants have various forms of low vision. All of them read Braille and are integrated in normal schools in southern Sweden. Two separate studies with sighted participants have also been conducted. The first investigated the usability of the sound field feedback and the relief preference. 11 adults (aged 25 – 72) participated. The second was to test force beacons and force design. 14 participants aged 10-73 performed this test.

Qualitative evaluations with reference group

The reference group has visited the lab and used the drawing program at informal meetings, followed by discussion. During the first three occasions, drawing was tested with and without audio feedback, with positive and negative relief and with program interaction by virtual haptic buttons and keyboard commands.

At the fourth meeting, the shape drawing tools were used. All three users were first introduced to the tools and how to use them and then guided to complete a specific task – drawing a house.

The fifth meeting introduced the collaborative version of the application. The accompanying persons used the mouse and the visually impaired pupils used the PHANToM. Aside from some general experimentation with the application, the users were asked to solve 2 tasks of school work nature. Both tasks were focused on exploring, marking and text-tagging in prepared drawings (one on finding right angles in a figure, and the other on marking points of interest in a map).

Formal pilot studies with sighted persons

The first formal pilot study included image recognition tasks, and to find out how different images, sound/no sound and positive/negative relief influenced the recognition performance. A pair of headphones was used when sound field feedback was available.

The second test concerned the design of the dragging forces used to return to specific points in a drawing (so called beacons). Although beacons have been tested before [14] the actual design of the force has not been systematically investigated. We tested six different types of radial dependencies: two roughly constant forces (constant, tanh(r)), two forces that increased towards the target (1/r, 1/sqrt(r)) and two forces that decreased towards the target (r, sqrt(r)). Forces that did not tend to zero at small distances had a short linear part for very small distances. This linear part was attached so that the force function was continuous throughout the whole space. The PHANToM Premium was used for both tests.

Results

In [15], detailed results on the first three qualitative evaluations and the first formal test are described. Here we present the results for the drawing tool test and the collaborative test involving the reference group, and the beacon test with sighted participants.

Drawing tool test

All users completed the test with no apparent problems other than remembering commands. The tools worked as expected, and the users managed to draw houses (figure 2) but it was commented on the problem to find the corner of the house and connect the roof to it. All participants also appreciated the audio feedback for the manipulation tools. They found the application noticeably more interesting than in previous meetings. At the particular test session, no tools for the creating of straight lines was implemented, but it was asked for and therefore realized shortly afterwards. More tools were also asked for, e.g. tools for making triangles or stars.

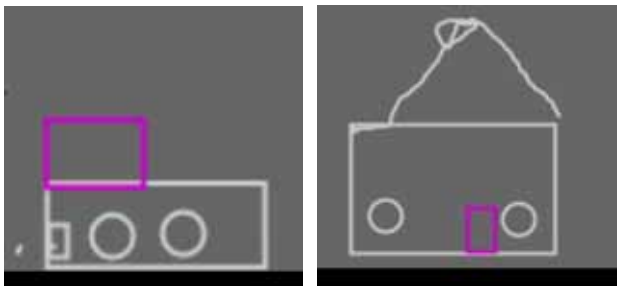

Figure 2 House drawings from the two participants in the user trials. The houses on the right looks as intended from the instructions given. The colored rectangles in the drawings indicate the object currently selected.

Collaborative test

The results of the fifth test with the collaborative environment were very diverse, although all pairs of users can be said to have succeeded in solving the tasks at hand. In most pairs, the visually impaired user was the one that marked out the points on the map and the angles in the figure. However, there is the issue of speed – it is simply much faster to obtain an overview of the scene visually compared to using the PHANToM. Thus, the sighted participant guided the other user in all pairs – sometimes verbally, and sometimes with the dragging force. Especially one user, who, despite continuous test sessions with the PHANToM had not learned to use it efficiently, was guided with the force by a parent. This actually made the child understand better how to move with the PHANToM in order to get good feedback. In the pairs with children and parents together (3 of the pairs), the sighted parent was the one who lead the work and prompted the child to do things. One pair was a child (12 yrs) and a friend of the same age, and in this case the lead was not so clearly taken by the sighted pupil.

Results from formal beacon experiment

For the type of tasks studied, users preferred forces that did not interfere too much with exploration. Also, depending on the task, some short distance snap-to-point behavior was seen to be useful. The favorite force dependencies were constant, tanh(r) and 1/sqrt(r). The 1/r was thought to be too weak far away and too strong at close distance while the opposite was true for the linear force (too strong far away and too

weak at short distances). An interesting observation is that the beacon force can be quite strong towards the end of a movement compared to what is tolerated initially.

Conclusion

The design process used has provided us with an increased understanding of how to design a working haptic-audio drawing application to be used by blind and sighted school children in collaboration. This application will be tested in schools with tasks of school-work nature during the spring of 2007.

Acknowledgements

We are especially grateful for the participation of the reference group with children and accompanying persons. We also like to thank Steve Wall and Johan Kildal for discussions concerning the beacon design as well as all our test users. This work is funded by the EU/ IST eInclusion projects MICOLE (IST-2003-511592 STP) and ENACTIVE (IST-2002-002114).

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III

AHEAD - Audio-Haptic Drawing Editor And explorer for education – edited version

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This section is an edited and extended version of the original workshop publication [1], adapted to the thesis in that the initial problem domain and the presentation of the interface are not repeated here. The video post-test analysis was not presented in the original publication.

Abstract

Using the AHEAD drawing application, which makes it possible to draw and feel virtual relief drawings with the aid of a haptic device, 8 school pupils, 2 assisting resource persons and 4 teachers have been evaluating school tasks concerning the access and production of graphical material. The tests have been situated in the schools, and been performed during a busy lesson (4 out of 5). Prior to the final evaluation session at school individual tasks based on the AHEAD functionality have been created in collaboration with researchers and the pupil's teachers and resource persons.

Short description of learning tasks

Three of the visually impaired pupils worked in collaboration with sighted classmates doing their school tasks. Two of the pupils were working primarily in single-user mode, but were also instructed by their resource persons. Five sets of school material were created for the subjects: mathematics, geography, navigational training and literature. In all cases except mathematics, the application was used only for exploring ready-made graphics, but in the mathematics case, the drawing functions were used.

Learning tasks for pupil R1

The learning task chosen was to learn to interpret maps and learn about the geography of Russia. The task for all pupils in the class was to draw a simplified map of the country, featuring the most important parts such as mountains, rivers and major cities.

The test setup consisted of a PHANToM OMNI, a laptop running the program and acting as screen and keyboard for the pupil. The AHEAD application was loaded with a customized map of the European part of Russia (see figure1). The pupil used this map as a substitute for looking in the map book through the CCTV, which is the way the pupil usually performs the task, inducing problems such as glare and

problems with overview. The pupil had a tactile map of the outlines of European Russia to make a simplified map from, using markers and crayons to draw and write on the paper map.

Figure 1 Map of the European part of Russia. All borders, cities (circles), the river Volga and the major lakes have text captions spoken by the TTS

Learning tasks for pupils R2 and E2

The learning task chosen was to learn to interpret maps and learn about the geography of South America. The task in the lesson for all pupils was to make a simplified map by hand of the continent, with major mountain ranges, lakes, countries and capitals.

R2 was working together with a sighted classmate E2, collaborating on the task using the AHEAD application. The classmate would make markings on a tactile map, while the visually impaired pupil was exploring the map (see figure 2) and telling his class mate what to write down.

Figure 2 Map of South America. All borders, capitals (circles) and the surrounding ocean borders have text captions than are spoken by the TTS

Learning tasks for pupil R3

As the test task a kind of treasure hunt was implemented to promote navigational training and increasing the pupil's navigational skill. Detailed maps of a path from the school to the local bakery were prepared and the pupil was to explore every map

step by step. When the first map (see figure 3) was explored and the treasure on that map was found and the pupil felt confident enough to remember the route, the pupil was supposed to travel by foot unaided by the assistant to the treasure in the real environment. The teaching assistant followed and was allowed to give verbal hints referring to the map, but the assistant was instructed not to help in other ways (by leading the pupil for example). After the pupil succeeded with finding the first treasure, the other 2 maps were explored.

Figure 3 Map of the school yard. All permanent ground obstacles were modeled and the details described by the text captions spoken by the TTS

Learning tasks for pupils R4 and E4

The learning task in the particular lesson was to practice using geometrical mathematical language, i.e. words like “rectangle”, “sphere”, “angle” and “diagonal” to describe a composite geometry figure to a fellow pupil. The test setup consisted of a laptop running the program and acting as screen and keyboard for the sighted pupil E4 who also was using a mouse for input. The visually impaired pupil had a separate keyboard attached to the same computer, a screen, headphones and the PHANToM OMNI. Half of each screen was blinded by a piece of cardboard to prevent the pupils from seeing the drawing the other person made.

Figure 4 The left picture shows the empty grid for the mathematic task. The right picture shows a picture from the test (with the grid removed for better clarity)

The AHEAD application was loaded with a file with a subtle grid in positive relief, and a middle line with the spoken caption "Stop, middle line" (see figure 4). The pupils were supposed to use one part of the virtual paper/screen each to draw on and the middle line was not to be crossed until the last phase of the task. There were three parts to the task; first, one pupil would design a composite figure in the drawing application (without showing it to the other pupil); second, the same pupil would describe the figure to the other pupil who would try to draw a copy based on the description; third, the pupils would together compare the copy to the original figure.

Learning tasks for pupils R5 and E5 (Pre-final pilot test)

The learning task was to, on the basis of an image of a traditional Shakespearean theatre (i.e. The Globe); place the actors on different parts of the stage and balcony etc. in every scene of a Shakespeare play which they had read in advance. The image was marked with the different parts of the theatre – e.g. formal stage and balcony.

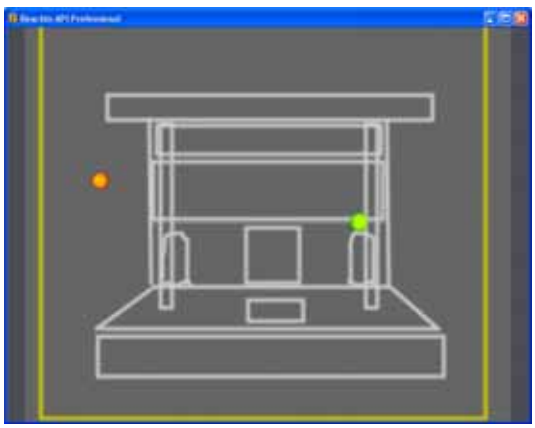

Figure 5 A simplified drawing of a Shakespearean theatre. The major parts such as pillars, main stage, balcony, trap door, valves etc. were marked with captions.

The AHEAD application was used to load prepared drawings of the Globe Theater (example in figure 5). There were 4 different files with stage information to choose from. The pair of pupils could choose freely between the files, using the one that suited them the most. Pressing a shortcut on the keyboard would start a standard Windows file load dialog that was supported by JAWS to enable text-to-speech outside the AHEAD application.

Video post-analysis procedure

The videos have been recorded on either digital tape or on a hard disk camera. At every test, the pupil who used the PHANToM has been the focus for filming, and in all cases the screen has been filmed to make it possible to see the movements of the PHANToM proxy and mouse cursor. The hand of the PHANToM user has also been filmed at times, in order to se how the pen is used in the pupil's hand, except for the pre-final pilot test with pupil R5.

The five videos have been analyzed in an iterative fashion. First, the videos were looked through, and any immediate observations or thoughts were written down. The observations were preliminarily organized in different categories to highlight usability, collaboration and also specifically the interaction of the visually impaired pupil with the PHANToM and AHEAD application. Then, the videos were examined again, using a video annotation tool, ELAN 3.4.0. The videos were tagged with descriptions of the work flow, tied to the categories found.

Figure 6 A pupil using the AHEAD application in geometry class

During the process of tagging and examining the videos in detail, the categories were revised somewhat, and the final categories were:

A. Collaborative learning and guiding with the AHEAD application as an actor or reference
B. Pupil's own navigation and exploration with the AHEAD application
C. Usability problems and possibilities of the AHEAD application
D. Ergonomics of the PHANToM OMNI as used in the tests
E. Miscellaneous observations

Video and log analysis results

The results of the observations made in the classrooms, as well as the re-observations made during video analysis, show that the AHEAD application has been used successfully in all five occasions. Furthermore, all the teachers and four out of the five visually impaired pupils were enthusiastic about the system and would like to continue using such a system for education, if it were made available.
Pupils R1-R3 and R5 used the application in the explore mode to access ready-made 2D drawings using them as a reference for discussion and for learning about

geographical maps or detail maps. Pupil R4 primarily used the edit mode for creating (mathematical) drawings.
Overall, the tagged events in the tests related less than 1% to usability problems (not counting the miscellaneous tags), and only 2 major bugs and stability problems were found. After the pre-final pilot test, a number of issues were solved to facilitate observations (e.g. logging) and one major bug was corrected after the first final test (see also table 1). This indicates that the application prototype had no major design flaws and also was sufficiently stable that it could promote activity connected to the school work rather than introducing new difficulties. Another reason for the final evaluation to run smoothly was that all the pupils were sufficiently introduced to the handling of the PHANToM device and in part also that they had made early pilot tasks with an AHEAD prototype with nearly the same functionality. This enabled the pupils' to use the system as a tool for a school task and not needing to learn to use the tool first. All pupils were working actively with their tasks after a maximum of 9 minutes of introduction.

Pupil	R1	R2	R3	R4	R5
Length of test lesson (minutes)	40	40	60	40	80
Filmed length of interaction (minutes)	37	31	26	40	66
Training time (minutes)	0	0	2	9	0
"A" tags: Collaboration	43	26	39	26	43
"B" tags: Navigation	27	20	37	62	23
"C" tags: Usability	0	3	1	5	6
"D" tags: Ergonomics	0	24	9	0	9

Table 1 Summary of observations by tags, together with the total time spent on lessons and interaction.

The balance of "A" and "B" tagged events show in part the kind of task that each pupil has been working on, but also to which extent the pupil has had need for guiding and help. In the case with pupil R4 the overweight of "B" tags has to do with the relatively long periods of active drawing tasks during the lesson, when pupil R4 was actively drawing and using the application as a drawing tool. Pupil R5 however, had more collaborative discussion with the material in the AHEAD application as a reference (stage setting a theatre play). Looking more closely at the data, one can also see that pupil R5 is most frequently guided with the dragging function (mouse user drags PHANToM). This illustrates that very different use scenarios can be supported by the AHEAD application, with a varying degree of guiding and help, from virtually no help at all to frequent guiding.

Of the visually impaired pupils who were working in explore mode, three (R1-R3) explored their material actively, constantly moving the PHANToM pen about and listening to the text tags attached to the different features of the drawings. Pupil R5, who used the material more as a reference and not necessarily was required to understand the complete drawing, was less active and was guided more frequently.

Problems that arose connected to the explorations were:

- Difficulties to hear what the TTS said
- Moving around too fast to hear the complete TTS tags
- Feeling insecure if there was no sound feedback in e.g. empty areas
- Having trouble following lines
- Falling through the virtual paper

Some of the problems were overcome by guiding, either from a collaborating pupil or an assistant or researcher. In one specific case, a pupil was clearly seen to use a strategy by withdrawing from an object and then returning to it again to repeat the TTS message over and over again when it was hard to hear or understand. This seemed to come quite natural for that particular pupil, although the difficulty in understanding the TTS can also be seen as a design flaw that should be fixed with an alternative user interface behavior, and by using a different TTS voice.

The exploration behaviors by the different pupils are largely connected to the different tasks and settings and are therefore neither easily nor meaningfully compared. The geography tasks, for example, do not explicitly encourage pupils to go about working with any specific strategy. Pupil R2 was seen "jumping around" with the PHANToM pen in the map rather than trying to follow paths. Pupil R3, who had a map over the school yard to learn to navigate in, more clearly followed paths and returned to known reference points in the drawing. However, the assistant for pupil R3 also more clearly guided the pupil verbally by explaining details and encouraging the pupil to return to the specific places. Pupil R2 was instead working with a class mate most of the time and received no help to gain a systematic strategy. To illustrate the different exploration behaviors, the collected PHANToM positions samples in the log file can be compared to the original drawings (figure 7).

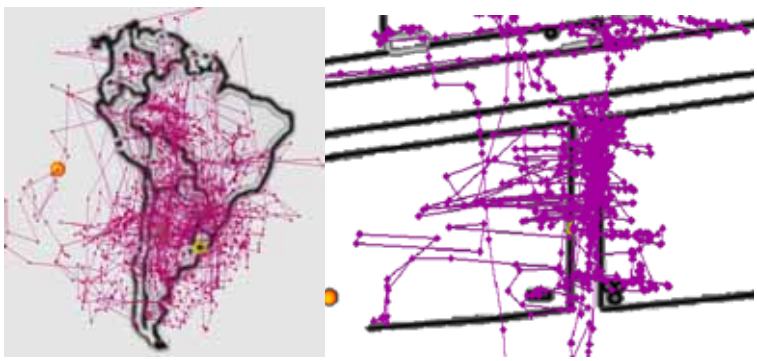

Figure 7 Position logs for pupils R2 (left) and R3 (right). Pupil R3 is orally guided to find paths and uses small movements and therefore spends more time on the desired objects, whereas pupil R2 makes large sweeping movements. Note however that the dots are samples of positions and the paths in between dots are interpolations

The interesting result is that either exploration strategy is successful. And once the pupils have learned to use the system, efficiency is gained through learning even better strategies for exploration and navigation in the virtual drawings. Also worth to note is that although the interface is not nearly perfect, it is sufficiently stable and users are active while working and can adopt strategies to overcome imperfections.

Detailed case result descriptions

Pupil R1 (European Russia map).
This pupil used PHANToM, audio and screen to interact with the map. The cursor on the screen was enlarged to enable this pupil to be able to see it. The pupil used the map as planned as a reference for drawing a map by hand with major features on. The pupil was especially pleased to be informed about the population of the major cities, as this feature is not given in tactile maps and is hard to understand in an enlarged paper map. The pupil was well able to handle the application with the map, and rated it higher when asked to compare it with the normal way of working with maps.

A problem was that the geographical names were displayed in TTS only, making it hard for the pupil to understand the names and their spelling. The teaching assistant asked the pupil to look for the correct spelling for some of the names in the drawn map book, drawing some attention from the task at hand and forcing the pupil to work with 3 media at the same time. The teaching assistant tried not to intervene, and the guiding function of the application was never used. The pupil needed much help to find and understand the tactile map on paper. The overall workflow of the pupil could be described in 3 steps: first, the pupil explored the map in the AHEAD application, then the pupil got help by the assistant to find the same location on the paper tactile map, and then the pupil wrote (with a pen) the name of geographical place on the paper map.

Pupil R2 (South America map)
The pupil collaborated with a fellow pupil. The visually impaired pupil used the PHANToM to explore the map, and the sighted pupil looked at the map, and made markings on a tactile map and wrote the country and capital names on a sheet of paper. The markings were small stickers with Braille numbers, and it was actually hard for the pupil to handle them, which forced the visually impaired pupil to wait.

The visually impaired pupil had quite large problems with the handling of the PHANToM. The force the user exerted to press against the virtual map was too hard, and the PHANToM OMNI device could not resist it, which can be seen in the log file. Although the pupil pressed very hard and at times penetrated the virtual surface with 2 cm the TTS information and the relative positioning of the pupils own hand conveyed the needed information in most cases. The pupil could tell the collaborator about the position in relation to the other countries or oceans, e.g. “Chile is to the left (west) of Brazil but to the right (east) of the Pacific Ocean”. At X times, the collaborating pupil guided the pupil by dragging force or with oral information.

The major countries and their capitals were found fairly easy, however, smaller countries (i.e. French Guyana, Surinam and Guyana) were too small to handle, and the teaching assistant insisted on asking the pupil to find them. At the end of the

lesson, the visually impaired pupil got really tired and annoyed with the system, and sat sideways on the chair, while still working with it.

Pupil R3 (School yard map)

There were 3 maps leading step by step to the last goal (the local bakery). The pupil started with the map that showed the first part of the path with a known school entrance and known features outside the entrance. The teaching assistant guided the pupil orally to different features in the map – both previously known places and other places not known to the pupil before. The pupil also explored the map freely, discussing with the teaching assistant and commenting on the features that were encountered. The pupil was told to search in the map for a spot with a treasure. When the treasure spot was found, the pupil and teaching assistant went through the best way to travel to the treasure. The path was then repeated until the pupil felt secure to find it in the real environment. Handling the PHANToM and the map environment seemed to be easy for the pupil, who used fairly small, controlled movements in the search for different features. This approach, however, made it harder to travel open spaces in the map.

The pupil then had to go to find the real treasure. The real distance from the entrance door was about 30 m. The teaching assistant was allowed to accompany the pupil and also give hints referring to the map. The treasure was found after hints and some discussion, but the pupil was about to go the wrong way while following an edge. The pupil also had to navigate on the way back to the school entrance.

Back in the classroom were the application was placed, the pupil worked on the next two maps in direct succession, since the time was about to run out. The teaching assistant also attempted to use the guiding function with the mouse dragging the PHANToM, but this disturbed the pupil's feeling of control and direction and the pupil asked not to be guided by force but rather by oral description. On the way to the end target (the bakery) the pupil was helped and hinted in order to feel that the task was accomplished.

The pupil found the map and orientation tasks relevant and inspiring. When walking in the real world, the pupil said "I can hear Ingrid in my head" ("Ingrid" was the TTS voice used). Also, the pupil made comparisons to ordinary tactile drawings that had been used previously to learn to navigate around the school yard, and thought the AHEAD system to be much better. It is interesting to note that this was so despite the fact that a tactile map can be brought along and be explored with many fingers.

The test session was clearly tiresome for the pupil. In the post-test interview, the pupil was asked: "Was it easier working with the system in the beginning of the session or towards the end?". The pupil answered that it was easier to work with the system in the beginning since the pupil was more alert then.

While working with the map, the pupil was observed using a strategy to make the TTS repeat its text tag for objects, by leaving them with the PHANToM proxy and then quickly returning to the same place.

The teaching assistant's role was to verbally guide and encourage the pupil to explore the map, and also to break down the task into smaller subtasks when needed.

The pupil needed much verbal guidance, and the teaching assistant did also fill in the context for the pupil. This supports and strengthens the usefulness of the AHEAD application as a learning tool.

Pupil R4 (Geometrical drawings)

The pupils both managed to use the application for the intended task, and the video shows that the pupils enjoyed themselves and communicated well around the task. They took turns designing and making original drawings and copying a drawing, in total 6 times. Looking at the resulting images (figure 8) it can be seen that the pupils have succeeded with the task - both have managed to understand the instructions and show this understanding by drawing a reasonable replica of the original (the drawings are not perfect, but they catch the essence of the design).

By analyzing the logged position information and watching the video it is apparent that the visually impaired user can orient in the workspace, and understands its size and the lines drawn in it. Only once the user fell through the virtual paper, but this did not pose any problems at all, since the user could repair from it quickly.

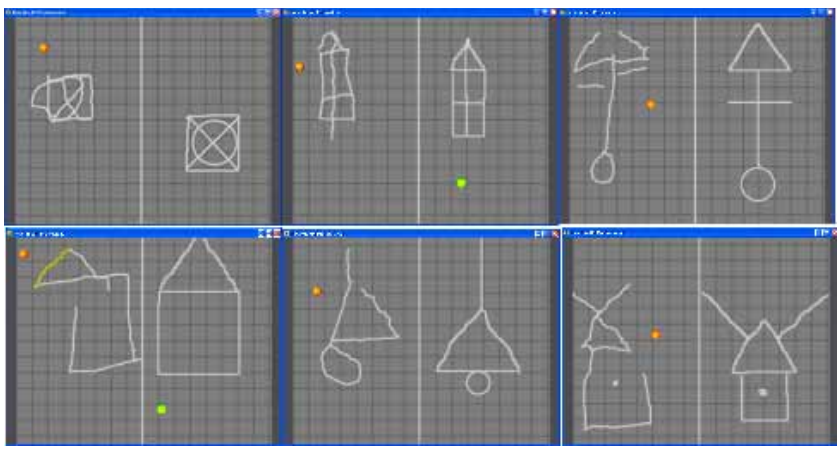

Figure 8 The pairs of drawings generated. In the top row, the mouse user (to the right) designed the original, while in the bottom row it was the PHANToM user that did this. The time order in these images are task 1,3 and 5 in the top row and 2,4 and 6 in the bottom row.

At the beginning of the lesson, the user had a strategy to make a figure (i.e. a rectangle), and then directly check it by feeling it. This can be seen in the logs and the video. It is also apparent that the user is well aware of the positions of the objects drawn. E.g. in the fourth drawing (designed by pupil R4), the circle under the triangle is positioned at the left lower corner of the triangle. This is the way that it was intended, according to the video observations. At the end of the lesson, the pupil did not check the drawn figures as thoroughly after drawing them. E.g. when drawing the house in the 4th figure above, in the second attempt (the first was erased) the user first drew the rectangle, and then checked just the top line and then went on to draw the roof directly. Whether this is because the user felt confident that the figures "stuck" on the paper, or the user just is less interested in making them perfect is hard to say. However, it seems the pupil is more relaxed to the task or the system at least.

Interesting to note is that the conversion tools for making perfect rectangles, circles and lines were rarely used. The sighted pupil occasionally used the moving function and made 5 shape conversions, but the visually impaired user did not. The outspoken goal for the task was not either to make nice drawings, but to communicate clearly about mathematical objects.

The grid that was intended to make it possible for the users to make drawings with specified sizes was possible to use but prohibited some drawing movements. Since the grid had to be possible to feel, it was made with a raised relief since it should not interfere with the users own drawn lines in negative relief. When making diagonal lines and curved lines, the grid was a disturbance and prohibited a flowing draw-motion, which made figures look uneven. Also, when a line was drawn, the grid disappeared in the groove of the line, which made it hard to measure distances in drawn lines. E.g. when R4 in drawing no 5 (top row, right), was asked to draw a "horizontal line, 2 squares down", the user was unable to feel the grid, and instead identified the top of the line, and moved slightly outside the line to the left and traced two squares down and drew the line from there. This can be seen in the drawing also, if one looks closely, since the horizontal line on the side is not attached to the vertical line at all. The same strategy was used on the right side, but there R4 had problems identifying the grid lines correctly, and therefore the right line is one square above the left line.

Another progress over time can be seen on behalf of the strategy used by the visually impaired user R4. In the beginning of the lesson, R4 lets the sighted user E4 explain the whole figure that E4 has designed. Then R4 starts to draw and asks for clarifications when needed. E4 on the other hand, begins to draw immediately when R4 starts an explanation. In the end of the lesson however, R4 also starts to draw immediately when E4 starts to explain.

One problem that did occur was that the user on one occasion accidentally erased the wrong line – something which shows that more feedback is needed for the erasing function. The test leader accidentally informed the pupil that it had occurred; otherwise, it would have been interesting to see how the pupil would recover from a mistake like that. After completing the drawing, the pupils were allowed to check each other's drawings. The sighted pupil lifted the cardboard to look at the visually impaired pupils' drawing, and the visually impaired pupil was allowed to feel the sighted pupils drawing. The visually impaired pupil did not actively explore the drawing, but was guided around by the sighted pupil, feeling the gestures of the drawing. Whether this was a misunderstanding of the functioning of the application or just a way of making the exploration easier for pupil R4 is not clear.

Discussion and conclusions

In general the results of this tests show that programs like the AHEAD application could be a useful complement to the materials already used by visually impaired children at school. Despite the single point haptic interaction provided by the PHANToM, pupils found that the AHEAD application provided good overview of the displayed 2D graphics, and two pupils in particular commented that this was

actually better than the raised line images normally used (despite the fact that these can be explored by all fingers simultaneously).

The fact that the environment allowed for both a mouse user and a PHANToM user to have access to a common workspace was seen to be important, and to increase the usefulness of the application. The guiding function where the mouse user guided the PHANToM worked well when the mouse user used a guiding motion to lead the PHANToM user to a target or show a shape. The result of the guiding depended on how the mouse user used it – and the test results indicate that one should advice the mouse user on how to use the guiding efficiently. Still, it is important to note that some users may not like being guided (these results agree with the observations made in collaborative haptic environments with multiple PHANToMs [2]).

Also, the usability problems observed suggests that a Braille display should be connected to the system and that the user should be able to change the orientation of the virtual paper.

Further Work

The described evaluations are aimed at foreseeing use scenarios in school in a not too distant future. There are still challenges, aside from the problem of expensive hardware and software. The next step will be to investigate if and how a teacher or teaching assistant will be able to use the AHEAD software in school, preparing the material and using it without technical help.

Acknowledgements

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IV

Navigation and recognition in complex haptic virtual environments – reports from an extensive study with blind users

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Abstract

The following article reports result from an extensive study with 25 blind users from Italy and Sweden performed during the summer 2001. The tasks reported here test recognition of geometrical objects, recognition of VRML objects, mathematical surfaces and navigation in a traffic environment. The outcome of these tests show that blind users are able to handle also quite complex objects and environments, and that realistic virtual environments in some cases appear easier to handle than more abstract test environments. This highlights the importance of context, and thus the usefulness of other input channels beside the purely haptic one. Another factor observed to be important is haptic scanning strategy. Tentative results for age, gender and blindness from birth are presented, and the importance of accurate haptic models is pointed out.

1. Introduction

Haptic applications hold great promise for blind persons. Using a haptic device it may be possible to make VR, pictures and graphs accessible also for blind persons. To be able to develop useful applications for the blind, however, it is important to gather more information about the ability of blind users to interact with different haptic virtual environments. Thus, during the summer of 2001 an extensive user test study using the PHANToM haptic device and including 25 blind users was performed. The tests described below are subset of the full study.

2. Test persons

The 25 test persons had ages ranging from 12 to 85 (mean = 39, median=37, standard deviation =19.4). 16 persons were male and 9 were female. Figure 1 shows the age and gender distribution of the test persons. 14 of the test persons were Italian and 11 were Swedish.

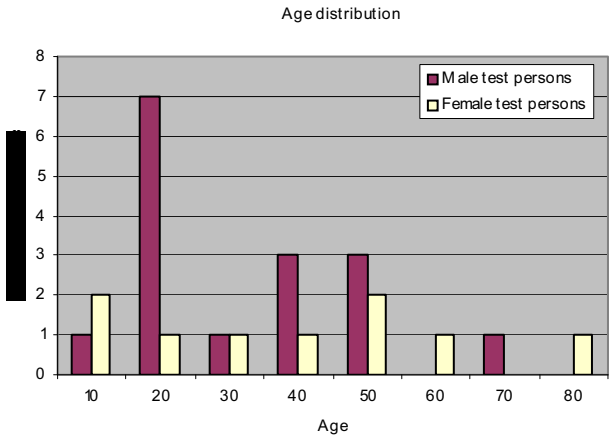

Figure 1 Chart showing age and gender distribution of test persons. The numbers on the X-axis should be interpreted as an age range (10 is the range from 10 to 20).

Only one of these persons (born in 1916, blind at the age of 64) had severe difficulties with the haptic environment. This person appeared to find both the concept of virtual reality and a haptic environment in general difficult to understand. Also, the person seemed to use both hands to a greater extent than the other test persons when exploring the real world. It was interesting to note that the haptic illusion appeared to disappear as soon as this person tried to feel the object with the other hand (the hand not occupied by the haptic device). Despite this, the person could complete a few tests, and might have done better with more training [1].

3. Research questions

The purpose of this part of the study was to obtain a better understanding of how blind persons can understand and interact with more complex and realistic virtual environments. With this in mind, the tests were designed to investigate the questions: Can a blind person understand haptic models of real objects? Can a blind user understand a more complex/realistic haptic virtual environment? Can a blind person navigate in this kind of environment? How disturbing is the VRML approximation perceived to be?

4. Test descriptions and results

Prior to the tests that were conducted, all test persons underwent a pre-test phase, where they had the possibility to get acquainted with the PHANToM device and the concept of virtual haptics. The idea behind the pre-tests was to try to minimize first-time user problems.
The tests that were made are of mixed nature, but the focus has in general been on making qualitative observations although quantitative data was also gathered during the tests.

For most applications, a series of tests with different challenge levels was conducted. Ideally, all users were supposed to succeed with the first test in the series, while the later tests were of a higher challenge level.
About half of the test persons used a pen tool to operate the PHANToM, while the others used a modified thimble with a strap that makes it easier to adjust it to different finger sizes. Furthermore, all surfaces in all tests include friction as this has been shown to make surfaces easier to follow [2].

4.1. Geometrical objects test

The user should, after navigating in a constrained virtual environment (VE) containing geometrical objects, build a copy of the VE with real geometrical objects. The tests included both a VE with only a single object, and a VE with three objects placed in a 3x3 grid (the grid test). The user had access to number of physical representations of different geometrical objects (a cylinder, a cube, a half cylinder, rectangular parallelepipeds etc). The user was instructed to feel the virtual model, and then to build a copy of the VE with the physical models (see figure 2).

Out of 25 users 20 identified the single geometrical object correctly (80%). This is in line with the results reported in [3]. All users correctly identified the general shape, but errors were made when judging the exact proportions of rectangular parallelepiped objects.

The grid test was significantly more difficult, and although 20 users out of 23 picked the right number of objects, and 18 out of 23 placed them in the right squares only 9 out of 23 (39%) managed to present the correct solution. Looking at the errors we see that 5 persons had the right number of objects in the right places, but did not pick the right 3D shape, although the objects selected were judged correctly in 2 of the 3 dimensions. Furthermore 3 users misjudged the proportions of one object, but otherwise solved the task correctly.

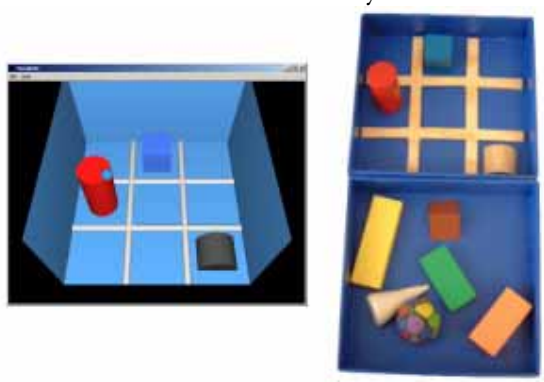

Figure 2 The 3x3 grid environment. To the left, a screen dump of the VE, to the right the physical models to build the copy with.

Looking at different groups of test persons we see that 8 of the 14 errors (57%) are made by persons younger than 30 years old. 11 users below 30 did this test, and we see that 72% of those failed (42% of the older users failed). 9 of the 14 errors (64%) are made by persons who are blind from birth. 13 users blind from birth did this test,

and thus 69% of these failed on the overall level (50% for those not blind from birth). 7 of the 8 women (88% of the women who did this task) made errors and 7 of the 15 men (47% of the men). The use of thimble or pen does not appear to have had any influence on the overall success rate.

4.2. VRML test

The user should feel different VRML objects, and discuss their physical properties with the test leader. The first test was a recognition test where the user was asked to identify the VRML object (a vase) and the difference of surface friction on the outside and inside of the vase (figure 3). It should be noted that the answer to the recognition test was considered correct also if the user answered with a shape that was similar to a vase (e.g. basket, fish bowl etc.).

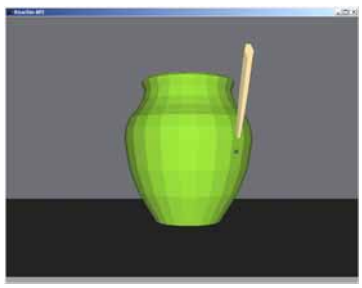

Figure 3 VRML model screen dump; a vase.

In the two following tests the users were told what the VRML objects represented (a grand piano with a stool and a satellite, see figure 4) and were instructed to describe the object and to locate different parts of it.

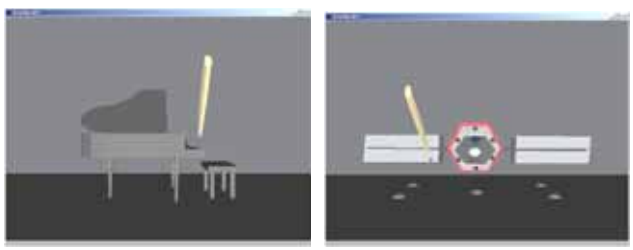

Figure 4 VRML model screen dumps; a grand piano with stool and a satellite.

Additionally, four users were also asked to describe and identify a VRML model of a guitar and a sword in the form of a recognition test (figure 5).

19 out of 24 users could identify the vase (79%). 20 of 24 identified and described both the grand piano and the stool (83%). 22 of 23 could find the parts of the satellite (96%). Of the 4 users asked to identify the guitar 3 succeeded despite some imperfections in the guitar model. Of the 4 users asked to identify the sword 3 could locate and explore it, but none of them identified it as a sword. The fact that the models were made up of flat triangles was not found very disturbing (1.6 on the average on a scale from 1 to 5).

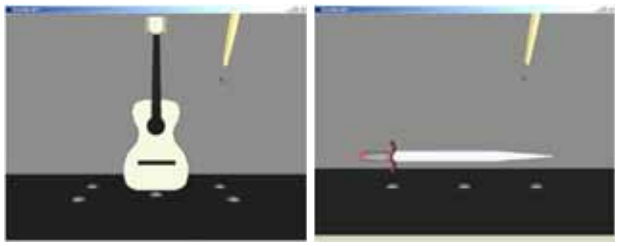

Figure 5 VRML model screen dumps; a guitar and a sword.

4.3. Mathematical surfaces

A general curve display program was tested (figure 6). This program makes it possible to submit an equation corresponding to a mathematical surface and get a haptic rendering of it. This haptic rendering is made up of small triangles just like a VRML model. During the test the users were asked to feel and describe different 3D surfaces. This test was performed by 7 users and all of them could feel and describe the surfaces. Only one of the 7 who did this test was a woman (the test was only made with users who had a particular interest and knowledge in mathematics). The challenge was judged as 1.5 on the average. Just as in the VRML case the fact that the objects were made out of triangles were not considered very disturbing (1.2 on the average on a scale from 1 to 5).

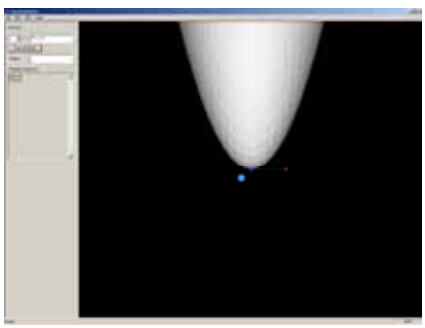

Figure 6 Screen dump of curve display program; z=x*x+y*y surface.

4.4. Traffic environment test

The VE consisted of 6 houses (2 rows, 3 columns) with roads in between. The roads, sidewalks and houses had different surface properties. The first task was to explore and describe the environment. Then, the user was asked to find a way from the leftmost house (house A) in the front to the rightmost house (house B) in the back (see figure 7). The user was asked to find the shortest route between the two houses while staying as much as possible on the sidewalks (flying was not allowed). The houses A and B each emitted a sound (non-speech) when pressed to confirm to the user that it was the right house. As a third test, dynamic objects (cars) were added to the environment and the user was again asked to go from house A to house B without being run over. Four users also tested a simple "move the world" function on this

world. The four users could move the contents of the world using the up (move back), down (move front), left, right keys on the keyboard.

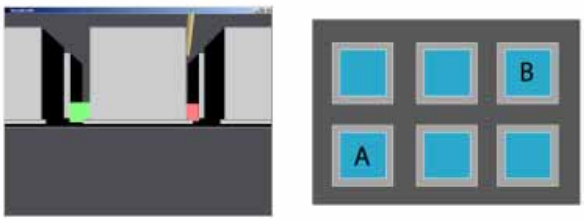

Figure 7 Screen dump and birds eye view of traffic environment.

21 users of 21 could identify houses, pavements and roads. 17 of 21 (81%) completed the house-to-house exercise successfully. All 4 persons that tested the move the world function could handle it after some initial confusion.

5. Discussion

5.1 Geometrical objects test

The fact that proportions may be difficult to judge accurately has been discussed in [4]. In the test 4.1 this was shown to hold also for proportions in different directions on the same object. At the same time the test confirms the observation in [3] that blind persons are able to identify simple shapes using the PHANToM despite the fact that a one-point interaction is very different from their natural mode of exploring objects. The test also confirms the observation made in [4] that the use of a thimble or a pen for the interaction does not influence the results in this kind of tasks.

The difficulty of the grid test (with 3 geometrical objects in a 3x3 grid, described in 4.1) was actually something of a surprise. Even if the difficulty to judge proportions accurately is disregarded (raising the success rate to 12 out of 23) this result was somewhat unexpected. A closer analysis of the kind of errors performed indicate that the majority of the errors were due to inefficient and/or incomplete haptic scanning. The users would not explore the object fully in all three dimensions, but would limit his/her exploration to two dimensions (usually by following the floor). As the haptic scanning strategy is something that can be learned, the results may be expected to improve with training [1]. It is an interesting question how one best should guide the users towards an efficient exploration technique – some users appear to have an efficient way of scanning almost from the start, while others need more training (and may be expected to benefit from guidance – possibly from an agent advising the user with respect to the scanning technique used).

18 persons out of 23 (78%) had the right number of objects at the right places which indicates that inefficient and/or incomplete haptic scanning has less effect on tasks that include locating positions only. However, users that did not succeed with this task were often seen to follow the outline of the grid square and would therefore entirely miss the object placed in the interior of the square.

There appears to be a higher error frequency among the users below 30 on this test, and furthermore a substantial difference in performance between men and women was noted. Whether this reflects real differences or whether this is due to the limited statistics available is still an open question. It is however possible that this difference may be connected to the ability to do mental rotations (an overview of cognitive sex differences can be found in [5]) as the haptic objects and the real objects sometimes were rotated with respect to each other. More tests are needed to verify this point. Factors which may influence the results are:

- training - this was the first test in the series
- motivation – several of the users did not appear as motivated during these tests as they did later
- stress – the users knew we were timing the exercise, and thus some tried to complete as quickly as possible even though we told them not to bother about the time

5.2 VRML tests

This test showed that the users could identify and understand also fairly complex objects. It also shows that the users are not particularly bothered by the VRML approximation.

In view of the poor results on the grid test this result again was somewhat surprising even though the tests are not strictly comparable. Apparently complexity does not necessarily imply difficult – a well known but complex object may be more readily understood than a simpler but unfamiliar object. A complex object may actually contain more hints that can help the user in the identification and exploration. The previous experiences and understandings of the user thus come into the picture. This may be both helpful and hindering. It was apparently helpful for the users who managed to find the thin support rod, which holds up the lid of the grand piano. It was probably also helpful for the one user, who had a grand piano himself, and who could comment on the size of the stool in front of the grand piano (the stool is too large in comparison with the piano). And it was probably helpful in general for all users when it concerned both the vase and the grand piano. In contrast, the user who had imagined the piano with the keyboard facing him was initially hindered by his preconception, and it took much longer for him to understand the object.

Another observation made during the test was the importance of haptically accurate models. Already before the tests the problem with holes (i.e. the user could "fall through" the object at certain points) was noted. Already for a seeing user this kind of error often has great consequences for the haptical illusion, and models with obvious holes were not included in the tests (this problem is discussed already in [6]). Despite our efforts to select good models, the models we had access to were made for seeing persons and thus invisible parts were often carelessly modeled. The vase had a funny ridge on the inside, the grand piano had no strings and neither the piano nor the stool was well modeled underneath. These inaccuracies were in most cases not serious enough to hinder the identification tasks. The one exception was the sword used in the four-user test, which was elliptical (not sharp). This had the effect that

none of the three users who could find and describe the object could identify it as a sword. The hole on the guitar from the same test was not really a hole, one could not explore the inside of the guitar, and furthermore it was possible to get stuck unpleasantly under the strings. Despite this three out of the four users who tried this model identified it as a guitar. Thus some inaccuracies may be tolerated, but it is clear that key features of an object have to be correctly modeled (a sword should be sharp for example).

In this test the users did not have access to additional sound information, helping agents, guided tours etc. The only help accessible was bumps on the floor, which served as reference points [7]. These bumps were used to some extent in the four person tests (particularly the sword), but were otherwise ignored to a large extent. That the blind users still could handle complex objects such as the grand piano and the satellite (the screen dump of the satellite looks somewhat simple in figure 4, but it contains a lot of detail) so well is very encouraging. With haptically accurate VRML models and additional help we feel that it is reasonable to expect users to be able to handle significantly more complex environments.

5.3 Mathematical surfaces

Seven persons tested a general haptic curve/surface display program. All of them could feel and describe the surfaces. Just as for the VRML case they were not particularly disturbed by the fact that the surfaces were made up of small triangles. This strengthens the case for VRML type models in this kind of applications, as long as the models are haptically accurate as discussed above.

At the same time this test illustrates the problem of testing this kind of more advanced mathematics programs. The testing of a general curve/surface display program requires some level of mathematical knowledge, and the number of test users thus becomes quite restricted. A way around this obstacle is to create specific tasks that allow testing of program properties without requiring a high level of formal mathematical knowledge. In another test in the same test series, the users had to solve tasks relating to a model eco system, and although the mathematics involved was fairly advanced it was possible to solve the problems also with limited mathematical knowledge (the tasks were to verbally describe a 2D curve, to point out maxima and minima and to solve a simple optimising problem). This problem setting made it possible to perform the tests also with our youngest two test users who were 12 years old. To find good tasks for more general 3D surface properties remains an open challenge.

5.4 Traffic environment test

The street environment did not present any particular problem to our test persons. This environment was generally enjoyable. Even though the navigational task did contain some difficulty (81% success) it got a low challenge rate. This kind of environment could readily be extended to training, games and map applications.
It should be noted that the rendering of the moving cars actually could be said to be haptically accurate. As the PHANToM is a one point haptic device, the shape of a car

hitting you is unimportant. A moving box works fine. It is also important to note that this environment with several moving objects would be fairly confusing if it were presented without the information that it represents a traffic environment.

To further enhance this kind of environment, realistic 3D sound should be added to make it possible to hear the direction the cars are coming from. Also, test users asked for pedestrian crossings with sound.

To allow users to explore larger worlds some kind of zooming or moving operations are necessary (preferably several). Four persons tested a simple move function, and the results were encouraging. After some initial confusion (the move function was quite crude, and it was possible to end up inside the houses) the users appeared to find a working strategy: they would put the finger close to a surface and then move the surface away. That already this crude moving function could be made useful makes it reasonable to assume that more elaborate moving functions will make it possible in the future for blind persons to get haptic access to worlds considerably larger than the small PHANToM working space.

6. Conclusion

The outcome of these tests show that blind users are able to handle and understand also quite complex objects and environments, and that realistic virtual environments in some cases appear easier to handle than more abstract test environments. Thus context is seen to influence results significantly also in haptic surroundings. The result of a line drawing test performed within the same test series furthermore supports this conclusion. In this test the success rate raises from 33% to 83% once the user knows that the unknown line drawing represents an elephant. The importance of context is a fact, which again [8], [9] highlights the importance of additional input such as sound in a complex haptic VE [9]. Another factor observed to be important is haptic scanning strategy (cf. exploration path in [10]). An indication that proportions in different directions can be difficult to judge accurately is furthermore obtained, as well as an indication that age and gender may influence test results in this kind of tests. Surprisingly enough the influence of blindness from birth appears less significant. It is possible however, that the age indication actually is connected to blindness from birth as many of the test users younger than 30 actually also are blind from birth. But the exact influence of these two factors, or the combination of them, cannot be separated in this test.

The evidence from the tests when it concerns shape recognition versus orientation/navigation is somewhat conflicting. The test results support the conclusion that navigational tasks also in quite complex virtual haptic surroundings can be handled by blind users. The evidence when it comes to shape identification is somewhat conflicting, the geometrical objects appear hard while the VRML models appear easier (as long as expected key features of the object are present). This may to some extent just reflect the test setup, and further tests to resolve this issue should be performed.

It has been shown that for the objects included in this test, the blind users are not greatly disturbed by the VRML approximation. What does disturb the illusion

however is if the model is not haptically accurate. Holes, unmodeled or poorly modeled parts makes it more difficult to understand objects, and if the imperfections are bad enough it may actually make it impossible for a user to obtain an understanding of an object.

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Persons who have visual impairments are still excluded from accessing certain types of information that are accessible to the general public. For accessing graphics, and especially digital graphics, no standardized technology is in widespread use. In school education, preprinted material with relief pictures complicates teamwork in collaborative settings, making it harder for pupils with visual impairments to work together with their sighted peers and to make it possible to acquire a shared understanding of school material.

The emergence of haptic hardware and the possibility to create interfaces for non-visual audio-haptic interaction has opened a door to the access of digital graphics and 3D models. Still, the price of high-precision haptic devices is a hindrance. So is the lack of useworthy applications. In relation to the design of audio-haptic interfaces for use in school, this thesis has the following aims:

- To show that the audio-haptic technology adds functionality and meaning
- To show that it is possible to undertake on-site user testing of audio-haptic applications in a school environment
- To describe an activity based user-centered iterative process in the development of a prototype of a non-visual drawing application for collaborative use in school
- To emphasize the need of applying a context based, activity based and situated approach to design of artifacts for assistive use
- To exemplify the possibilities to carry out collaborative work between pupils with blindness or low vision and their sighted classmates, even when material is based on graphics

The results demonstrate the value of working close to pupils and teachers and of evaluating new applications and technology in real situations and contexts. Long-term studies also make it possible to focus more on process than on single usability studies.

This thesis can also be found on:
www.certec.lth.se/doc/ucdofnonvisualaudiohaptics

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User-Centered Design of Non-Visual Audio-Haptics