Tatiana Evreinova

Alternative Visualization of Textual Information for People with Sensory Impairment

DEPARTMENT OF COMPUTER SCIENCES
UNIVERSITY OF TAMPERE

A-2005-6

TAMPERE 2005

Tatiana Evreinova

Alternative Visualization of Textual Information for People with Sensory Impairment

ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Information Sciences of the
University of Tampere, for public discussion in
the B1100 Auditorium of the University on November 18th, 2005, at 12 noon.

DEPARTMENT OF COMPUTER SCIENCES
UNIVERSITY OF TAMPERE

A-2005-6

TAMPERE 2005

Supervisor: Prof. Roope Raisamo
University of Tampere

Opponent: Prof. Klaus Miesenberger
University of Linz

Reviewers: Prof. Paul Blenkhorn
University of Manchester

Prof. Arthur I. Karshmer
University of South Florida

Electronic dissertation
Acta Electronica Universitatis Tamperensis 478
ISBN 951-44-6443-5
ISSN 1456-954X
http://acta.uta.fi

Department of Computer Sciences
FIN-33014 UNIVERSITY OF TAMPERE
Finland

ISBN 951-44-6430-3
ISSN 1459-6903

Tampereen yliopistopaino Oy
Tampere 2005

Contents

List of publications

This doctoral dissertation is based on the following research papers:

I Challis Ben, Hankinson John, Evreinova Tatiana and Evreinov Grigori. Alternative textured display. In: A. D. N. Edwards, A. Arato and W. L. Zagler (eds.), Computers and Assistive Technology, ICCHP '98: Proceedings of the XV IFIP World Computer Congress, (Vienna & Budapest), Austrian Computer Society, 1998, pp. 37-48. [Challis *et al.*, 1998]

II Evreinova Tatiana, Evreinov Grigori and Raisamo Roope. Color-blinking code and low cost peripheral monitor for people who are deaf or have low vision. *In AMSE Journal, Supplement 2C-2002*, Vol. 63 (4), pp. 129-138. [Evreinova *et al.*, 2002]

III Evreinova Tatiana and Raisamo Roope. A wearable monitor of music notation for visually impaired musicians. *Proceedings of the International Conference for the Work With Display Units (WWDU2002)*, Berchtesgaden - Germany, 2002, pp. 402-404 [Evreinova and Raisamo, 2002].

IV Evreinova Tatiana, Evreinov Grigori and Raisamo Roope. The text entry self-training system with color blinking imaging. *Proceedings of the 7th biannual Conference for the Advancement of Assistive Technology in Europe* (AAATE 2003), IOS Press, The Netherlands, 2003, pp. 989-993. [Evreinova *et al.*, 2003]

V Evreinova Tatiana and Evreinov Grigori. The text input training system through touch screen and color blinking imaging for people with low vision. In: P. Paggio, K. Jokinen and A. Jönsson (eds.): *Proceedings of the 1st Nordic Symposium on Multimodal Communication*, Copenhagen, 2003, pp. 169 – 182. [Evreinova and Evreinov, 2003]

VI Spakov Oleg, Evreinova Tatiana and Evreinov Grigori. Pseudo-graphic typeface: design and evaluation. In: P. Paggio, K. Jokinen and A. Jönsson (eds.): *Proceedings of the 1st Nordic Symposium on Multimodal Communication*, Copenhagen, 2003, pp. 183 – 196. [Spakov *et al.*, 2003]

VII Evreinova Tatiana, and Raisamo Roope. Hearing communication aid based on pseudo-graphic typeface. *Proceedings of the 7th IFHOH World Congress*, Helsinki, Finland, 2004, pp. 137-142 [Evreinova and Raisamo, 2004]

VIII Evreinova Tatiana, Evreinov Grigori and Raisamo Roope. An alternative approach to strengthening tactile memory for sensory disabled people. Paper is accepted for future publication in UAIS (Universal Access in Information Society) journal published by Springer Berlin Heidelberg, 10 pp. [Evreinova *et al.*, 2005]

Acknowledgments

Above all, I would like to express my greatest gratitude to my parents who tirelessly supported and directed me toward the completion of this dissertation.

Next I would like to thank my supervisor, Prof. Roope Raisamo. I am absolutely convinced that this dissertation might not ever be completed if it had not been his delicate and patient way of serving me as a teaching mentor and helping me to proceed through the doctoral program and complete the dissertation with the aid of his useful suggestions and careful reviewing. Starting with my part-time research position in the research project "Tactile User Interfaces" in the summer of 2001, he has provided me with excellent research conditions and assisted me in getting the funded position of graduate student in the UCIT graduate school. This position granted me a peaceful opportunity to complete various research studies resulting in writing the dissertation.

The Department of Computer Sciences at the University of Tampere has excellent conditions for carrying out research and for the completion of more serious work such as M.Sc. theses or Ph.D. dissertation. The head of the department, Prof. Jyrki Nummenmaa, and the head of the graduate school, Prof. Kari-Jouko Räihä, were cooperative in funding my travel expenses. Because of them, I had the excellent opportunity to attend many international conferences and obtain great language, scientific and communicative experiences there.

I thank our department administration, especially Minna Parviainen, Tuula Moisio, and Heli Rikala for helping me with various paper work and organisational tasks.

In addition, I would like to thank Prof. Klaus Miesenberger for being my opponent, and special thanks to my reviewers – Prof. Arthur I. Karshmer and Prof. Paul Blenkhorn for finding some time in their busy schedule, putting effort into reading this dissertation and helping me to make this dissertation as a sound piece of research having smooth and easily readable content by giving very valuable and insightful suggestions.

For funding my research I thank the Academy of Finland, the Graduate School in User-Centered Information Technology (UCIT) and Center for International Mobility CIMO.

Tampere, October 2005,
Tatiana Evreinova.

Abstract

By virtue of lacking visual feedback or access to verbal communication, people with a sensory impairment use alternative means for information imaging that rely on residual senses. For this reason, a wide range of assistive hardware and software came into the market to provide an efficient way of alternative imaging, for instance, of textual information. Nevertheless, nearly one third of these techniques were withdrawn from the market due to lack of use.

Recent innovations offer limited functionality and more often than not, the low accuracy of the produced output hampers the use of assistive aids. Designers should focus not on the technique itself, but on the optimal combination of the intact modalities to provide the disabled user with efficient access to textual information. One of the aims in the adequate use of assistive aids is to shape appropriate modality-specific notions to mediate communication with people having normal abilities. Implementation of the novel assistive techniques may be based on diverse technologies employing speech and speech-like signals, visual and vibro-tactile patterns, which can be used to display unambiguously the semantics of the textual message in a case when the environment has different constraints or the user has inferior perceptive thresholds due to chronic disease. In such cases, the required techniques should provide real-time or close to real time processing and imaging of the textual information so that both ordinary users and people with a sensory impairment would be able to use it autonomously without assistants or interpreters.

The foremost purpose of this dissertation is to consider the latest assistive technologies in order to suggest further improvements. Therefore, the summary provides background for the research papers included and an analytical survey of assistive methods/techniques. The problematic aspects affecting the use of computer help for people having ocular pathology and hearing disorders is the particular subject of our study. The considerations presented are intended for the developers of advanced assistive user interfaces.

The empirical part of the dissertation consists of a collection of the assistive aids which were designed to augment and expand access to the textual information for people with a sensory impairment. The central idea of this dissertation was blending signals of several modalities to reproduce distinct cases of the recognizable spatial-temporal semantic constructions such as vibro-tactile, audio-tactile and color patterns within minimal array of the coding units used for alternative imaging of textual information. Two prototypes of the wearable assistive devices such as BlinkGlasses and TactilePointer and some other software tools were designed to carry out empirical research in these subjects. Eight research papers representing the main contribution of this dissertation are introduced. Careful combination of the empirical research, thorough evaluation and further analysis of the outcomes which the approaches developed resulted in was the main principle for the completion of these empirical studies.

A key question is whether people with a sensory impairment can take advantage of the devices developed and if so, to what extent. How flexible the use of assistive technologies will become and how powerful they are going to be, will depend on the further development of the exploratory strategies directed toward the improvement of the assistive aids.

CR Categories and Subject Descriptors:

H.5.2 Information Systems – Information Interfaces and Presentation – User interfaces: *Evaluation / Methodology, Prototyping, Interaction techniques*

List of Abbreviations

AT	assistive technology
DLS	dynamic lighting sign
IT	information transfer
LED	light emitted diode
OCR	optical character recognition
PC	personal computer
PDA	Personal Digital Assistant
TTE	textured tactile element
TTS	text-to-speech
TVSS	tactile visual substitution system
VRD	Virtual Retinal Display
VTD	Virtual Tactile Display

> *There is much about our daily activity we end up taking it for granted. Reading information in one form or another and using of these novel techniques, which allow communication with anyone, at any time, and from any location are abilities we do not even think about, but they can be indeed arguable to people who can use their sight only partially or cannot use it at all or who cannot even communicate with another person on the opposite side of the same room.*
>
> Kevin Carey
> Director, HumanIT at the School of Education, University of Birmingham

1. INTRODUCTION

Computer technology has significantly advanced for the past decade and continues to evolve rapidly. While technological achievements become nearly inseparable from the user in all aspects of social life, the prevalence of people with a sensory impairment is steadily progressing. Recent statistics show that the amount of disabled people will reach 18% of the world population by 2020. According to perceptive disfunction, there are several categories of disabled people:

- persons who were born with functional limitations or have become handicapped in later life,
- persons who are temporarily impaired due to some accident or trauma, and
- elderly persons whose range of functions is reduced due to age related changes.

By virtue of lacking visual feedback or access to verbal communication, people with ocular and hearing pathology use alternative means for imaging textual information that rely on residual senses. Examples include tactile codes, magnifiers, voice output, Braille displays and embossers, hearing aids, amplification systems and others. For this reason, a wide range of *assistive* hardware and software has come onto the market and should provide efficient access to information and communication environment *for all*.

The Technology-Related Assistance for Individual with Disabilities Act of 1998 (PL 100 - 407) [Disabilities Act, 1998] introduces the first legal definition of assistive devices. An assistive technology (AT) device was defined as: *any item,* *piece of equipment, or product system, modified or customized, that is used to increase, maintain, or improve functional capabilities of individuals with disabilities: valuable tools to promote independence across all areas of daily living.*

Unfortunately, recent innovations offer limited functionality and more often than not, system designers do not take the individual special needs of the end users into consideration [Tabatabaei, 2002]. Cost factor, reduced user performance and limited availability have sometimes made such well-intentioned efforts less than effective and even cumbersome at providing easy use of the devices available on the market [Ballieu, 2000]. Some deaf and visually impaired people have other physical disorders that may also affect the manner in which they communicate. Eventually, perceptive ability may decline. Diabetes could have unfortunate consequences for the aging Braille reader by gravely accelerating the loss of both tactile sensitivity and acuity. Furthermore, visually impaired Braille readers are in a minority as well as the majority of blind people who do not use such a form of access to textual information [Fisher and Petrie, 2002]. This is especially true for those persons who have gone blind in later life. Another problem of deaf people is that a substitution for hearing leads to visual overload and switching attention on visual imaging during gesture or text recognition when the conversion of speech into conventional typefaces is used. It is undesirable in safety-critical situations.

Completed products are often inaccessible due to small but crucial shortcomings and cannot be customized, while they are often referred to "assistive computer technologies" and must follow the original purpose [Gappa and Mermet, 1997]. Bergman and Johnson [1995] define the term *accesibility* as removing barriers which prevent people with disabilities from participating in essential life activities including the use of services, products, and information. They stated that *software that is not accessible to a particular person is not usable by that person*. To increase the accessibility of the currently used products there is a great challenge to provide handicapped people with novel assistive imaging techniques that offer alternative output for intact modality.

Apparently, designers should focus not on the device itself, but on the optimal combination of the intact modalities to provide the disabled user with an efficient way of alternative imaging, for instance, in the case of textual information. Information introduced with an assistive device should enhance and strengthen the acquired knowledge. Designing novel imaging systems and techniques facilitating communication for people with a sensory impairment may be based on diverse technologies including speech and speech-like signals, visual and tactile patterns.

A substantial body of the psychophysical studies on humans being sensorily deprived since youth provide strong experimental evidence for a striking degree of cross-modal plasticity in cortical processing. Shimojo and Shams [2001] suggested that the direction of cross-modal interaction is affected by the structure of the transient/structured stimuli used in a task with the stimuli strongly influencing the multimodal perception, regardless of the modality in which it occurs.

By implementing intermodal transformation, we meet contradictory requirements. First, it is necessary to provide semantic unambiguity and comprehension of the textual information. On the other hand, the duration of the verbal or textual messages displayed in some coded manner should not greatly exceed the duration of the initial message. The most advanced transformation techniques should use the algorithms for time compression. These algorithms should be based on pre-existing knowledge of the user to decrease the requirements for special skills or training and cognitive efforts. Cognitive components, like attention, memory, perception, language comprehension and reasoning, affect the learning skills and can facilitate or inhibit the learning of using a new technique. Therefore, human cognitive abilities must be carefully evaluated when new techniques are in the design stage. It is noteworthy that Software-Human-Hardware-in-the-loop simulation testing is more efficient approach than a usability study of the final product.

The gap in verbal communication between people having normal abilities and handicapped individuals has also to be overcome. A solution has come in the form of the method for textual imaging using several modalities to display unambiguously the content when the environment has different constraints, for instance, noise and distractors, or the user has high/inferior perceptive thresholds due to chronic disease. The required techniques should provide processing and imaging of the textual information for people with a sensory impairment in real time, or close to real time mode. The techniques might be designed in such a way that both ordinary users and disabled people would be able to use them autonomously, without assistants or interpreters.

To improve verbal communication for people who cannot use conventional means we have designed special methods and devices. Empirical studies were carried out to prove which of the new interaction ideas for access to the textual information could really be introduced and utilized by a person in a critical situation of sensory deficit. In order to conduct the empirical research and to structure our observations and hypotheses, we conducted constructive research to implement special prototypes based on new ideas. Thus both constructive and empirical approaches were introduced in this work.

In this dissertation, I present a collection of assistive aids for imaging and subsequent expansion of access to textual information for disabled people. Selected examples and approaches are considered to reproduce the cases of the recognizable modal-specific spatial-temporal patterns and semantic constructions such as color, audio-tactile and vibro-tactile presented within a minimal array of the coding units used for information imaging. I assume that due to mental blending of these modalities we could compensate or substitute blocked information using an alternative way for visualization of the textual information. The basic concepts and interaction techniques implemented have been explained in the research papers which constitute this dissertation.

Paper I explains in detail how to provide a blind computer user with dynamic and/or quasi-static imaging of symbolic information employing the alternative textured tactile element generating a greater number of easily recognizable states of the display surface making use of a minimal number of discrete components.

The technique described in Paper II presents an assistive method and a variant of the compressed light code using visual color patterns displayed through a single two-color light-emitting diode or the blinking spot on the monitor screen. The method enabled reception of 1.5 times higher dynamic perception characteristics of the presented signals than with the help of the monochrome flash and Morse code. According to Guhl [2002], this method could promote deceleration of the degeneration of the visual nerve for people with ocular pathology through an adequate color stimulation of the visual analyzer.

An assistive approach for imaging music notation making use of the wearable peripheral monitor is introduced in Paper III and involving the same idea of diffuse color blinking imaging discussed in Paper II. In this case, imaging of the music tokens was realized with the help of four light emitting diodes, which were coupled with the eyeglasses. We suppose that easily recognizable spatial-temporal composite patterns could be used to display the data described by a long alphabet such as music notation for blind musicians and equation symbols for visually impaired mathematicians.

The techniques introduced in Papers IV and V can help in acquiring typing skills using a conventional keyboard and the color blinking imaging for training of visually impaired persons having residual vision. The proposed methods do accelerate the teaching of visually impaired typists to support conventional text entry, which is available for sighted users.

The method described in Papers VI and VII presents an attempt to facilitate and improve the graphic imaging of textual information. The emphasis in this case study was made on strengthening phonological awareness and logical clarity of the language transfer in subtitling signing within a digital television environment.

In Paper VIII, the assistive aid is a system of non-verbal vibro-tactile communication cues. In contrast to other methods and attempts in the development of vibratory communication cues/languages [Geldard, 1960; Geldard and Sherrick, 1972; Conway 2001], a special game method was introduced based on sequential learning paradigm. The technique for blind manipulating, including mobile devices, is based on gesture recognition and spatial-temporal mapping for imaging vibro-tactile signals. The system of vibro-tactile patterns could be used in an independent manner or to strengthen or facilitate the perception of visual or verbal semantic constructions. The vibro-tactile patterns can be employed like awareness cues for blind, deaf or deaf-blind persons, also in the situation when the vision is occupied or the use of sound signals is impossible. The proposed approach and the tools allow creating a new kind of mobile communication environment for deaf-blind people.

Chapters 1, 2 and 3 provide background for the papers and an analytical survey of existing assistive methods/techniques. The problematic factors affecting the use of computer help for people with ocular pathology and hearing disorders is the particular subject of this summary. The research papers are introduced in Chapter 4. The suggestions regarding the future directions and development of proposed assistive aids are also given in Chapter 4. Chapter 5 is a summary of the work accomplished.

2. DISPLAY TECHNIQUES FOR BLIND AND VISUALLY IMPAIRED USERS

As noted in the introductory part of the dissertation, with the loss or decrease of any particular sense due to some accident, trauma or age-related changes, perceptive thresholds of intact modalities may become more acute. For instance, the case studies undertaken by Gougoux et al. [2004] demonstrated that blind people are better able to judge the direction of pitch change between sounds than sighted listeners, even when the speed of change was ten times faster than that perceived by the listeners having normal vision. This phenomenon has been observed only in cases when the subjects became blind at an early age. Apparently, the younger the onset of the visual impairment or blindness is, the greater is the chance of developing superior perceptive thresholds of residual modalities and the higher is the degree of cross-modal plasticity in cortical processing which was normal before the disability had occurred. Nevertheless, people who have visual impairment do not acquire extremely heightened senses straight after partial or complete loss of the visual sense.

Handicapped people should learn how to strengthen their residual senses. When acquiring valuable skills, blind or visually impaired users can manipulate their residual senses to gather and process information blocked in another perceptual channel. The challenge for the developers is to exploit the heightened residual senses that blind and visually impaired people have, in order to expand the current technologies and to provide them with an efficient way of imaging textual information. Assistive user interfaces have to be carefully designed and adapted to be easy for disabled people to use and to mediate their communication with people having normal abilities.

Nowadays, many output techniques have been developed to provide blind and visually impaired users with imaging of textual information. Although some of the assistive techniques suggest a fair facility in use, the problems are still unsolved. This occurs due to the fact that typically sighted designers guide the elaboration process of the assistive techniques. When imaging textual information for the blind, it is likely that the overall sketch conceptualization of the textual imaging from the viewpoint of the end-user might be considered as problematic for developers with normal sight. By simply closing their eyes, developers are not able to entirely understand the true severity of this design problem as they rely heavily on visually based preconceptions of the kind of form an interface has to take and visual based culture in a wide sense. It is also inadequate to expect that a blind consumer will learn to use an interface that is primarily more convenient for sighted users.

This chapter provides a state of the art in the recent assistive technologies available to people with ocular pathology and providing them with imaging textual information. At this point, display techniques that employ the sense of touch and hearing as well as techniques which use residual resources of visual perception such as diffuse color vision, will be subjected to analysis. The problematic aspects affecting the use of alternative methods/techniques, are also described.

2.1. Tactile codes

Many blind people still involve sighted persons to read to them on a regular basis as the simplest and most efficient way to access textual material. However, they cannot rely on the other person as a reader assistant when the content of the text is private or confidential.

To substitute for visual access to the printed or written material, blind people, unlike sighted persons, rely heavily on the intact cutaneous sensation produced by skin receptors [Hyper-dictionary Web site]. Psychologists have stated that blind people are rather strongly aware of sensory kinesthesia than comprehending outward information through auditory channel [Heller, 1987].

Embossed coding provides one of the possible ways for imaging textual information for blind people. The earliest attempt to create embossed code was undertaken by a blind Arab professor in the 14th Century. He developed a special way to identify his books and of making notes on them [The National Council for the Blind of Ireland, Web site].

In Britain, tactile codes began to proliferate widely in the early 1830s. Such a tendency resulted from a competition organised by the Society of Arts in the pious hope that blind people would at last be able to read the scriptures [Reading codes for the blind, Web site]. The types invented were mostly produced by sighted people. For this reason, the suggested types were often easier to read by sighted people than by blind people with the use of touch.

In the early 1830s Fry first proposed embossing the Roman type [Lorimer, 1996]. Alston, who was treasurer of the Edinburgh Asylum, had published the system later. He established a press and produced several books using the suggested type [The New York Institute for Special Education, Web site]. Alston type is shown in Figure 1.

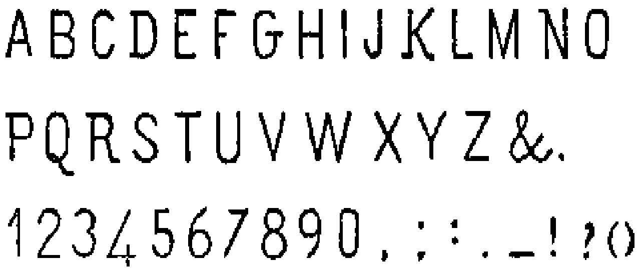
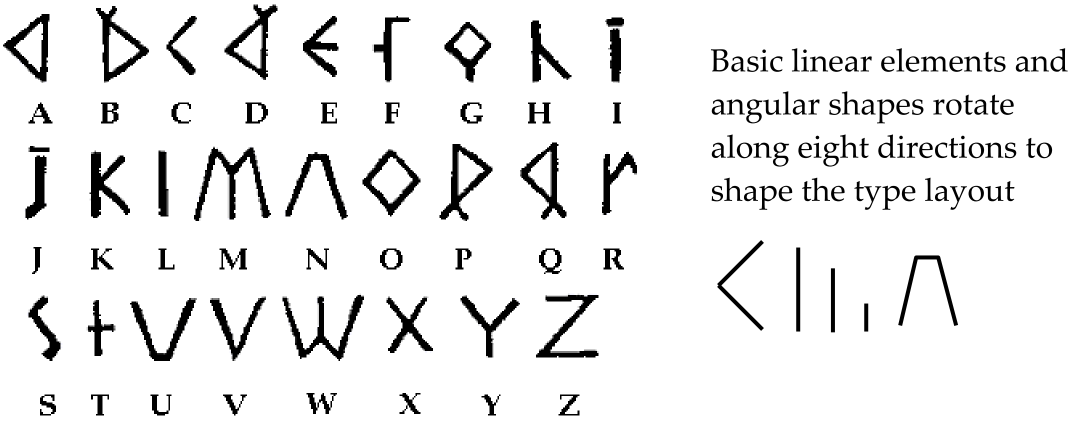


Figure 1. Alston type [The New York Institute for Special Education, Web site].

In 1831 James Gall introduced an angular embossed Roman type [The New York Institute for Special Education, Web site; RNIB, Web site]. In 1834 the first book was produced making use of Gall type. It was the Gospel of St. John [The National Council for the Blind of Ireland, Web site]. Gall type is shown in Figure 2. The alphabet characters differed widely from the rest of the embossed types used in France at that time. The type consists of 26 configurations chosen from the upper and lower cases of the Roman alphabet characters that James Gall considered to be the most suitable to read making use of touch. James Gall shaped symbols, at the same time keeping them similar to the ordinary Roman type to facilitate touch reading. Such alphabet characters as A, B, D, P, and Q became more triangular in shape, O was a diamond and G a smaller diamond standing on a stalk [Lorimer, 1996]. The characters N and U were presented with the help of a pared-down and inverted trapezium. The rest of the alphabet characters remained closer to their original shape.

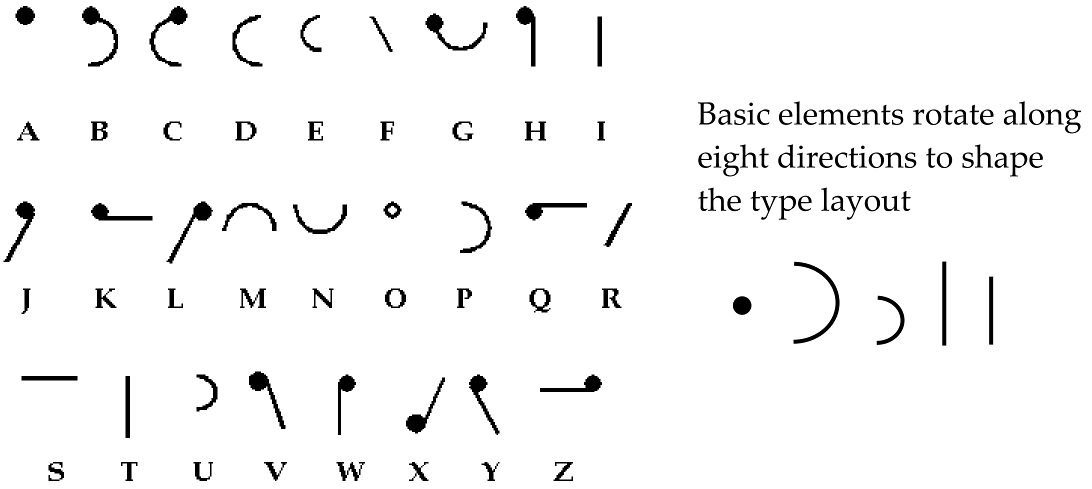
Creating the type, Gall believed that by using well-known basic elements in the construction of the alphabet as for sighted people, blind readers would feel more similar to sighted readers. Simultaneously, knowing the type, the relatives could help them to manage with deciphering the characters [Lorimer, 1996]. However, the suggested type has never been extensively used since the embossed Roman letters were too densely cramped to interpret them easily by touch. Later Gall realized this. Then he made the type more angular, but the more the type differed from the Roman alphabet the less sighted teachers accepted it.



Basic linear elements and angular shapes rotate along eight directions to shape the type layout

Figure 2. Gall type [The New York Institute for Special Education, Web site].

Working on the improvement of the embossed coding for the blind, Lucas introduced in 1838 abbreviated stenographic type [The New York Institute for Special Education, Web site]. The alphabet characters consist of straight lines and curves with or without a dot at one end [Lorimer, 1996]. This starting point also is acting as an anchor of tactile attention. The Lucas type layout is shaped with the help of five basic elements as shown in Figure 3. Paula Lorimer indicated that the straight line with the blob had 16 different positions according to the angle and edge on which the blob occurred. 8 positions for the curved lines were used [Lorimer, 1996]. Both start position and angular accuracy discrimination are extremely important factors with an impact on the recognition of the embossed patterns in a sequence.



Basic elements rotate along eight directions to shape the type layout

Figure 3. Lucas type [The New York Institute for Special Education, Web site].

To fasten the reading process, the alphabet characters were often assigned plural meanings to represent a word. The vowels were also often omitted. For this reason, the interpretation of the context relied heavily on guessing. To give an example[1], the first sentence in St. John's gospel started as:

in t bgini ws t wrd a t w ws w g, a t w ws g

The example sentence can be decoded as:

In the beginning was the word and the word was with God,
and the word was God

As it can be seen from Figure 3, some alphabet characters like T and I, D and E, V and Y had a very similar shape while it is known that these letters can frequently occur in a quite large number of the most commonly used English words. The frequencies of the letters as they appear in 18584 common base words[2] are shown in Table 1.

Table 1. The frequencies of six English letters in the most commonly used English words [`http://www.deafandblind.com/`]

Alphabet character	Number of words	Occurrences, %
D	4186	22.52
E	11991	64.52
I	9364	50.39
T	8929	48.05
V	1531	8.24
Y	2815	15.15

It is obvious that the proposed system required a lot of time for the user to become an expert-level reader of it. In her doctoral dissertation, Pamela Lorimer cites one example of how problematic it was to study the Lucas type when Thomas Lucas opened a school for shorthand pupils. The director of the Deaf, Dumb and Blind School at Bruges, visited the school and reported "One of the pupils, after a year's practice, could only with difficulty read one line which I gave him in St. John's gospel published by Mr. Lucas and succeeded only after making frequent mistakes". The abbreviated nature of the Lucas type had complicated the issue of reading imprint for blind readers even more than the cramped Gall type. For these reasons, tactile stenography has never been widely used.

---

[1] More detailed information about the relative frequencies of the letter occurrences in the English language can be found at a website [http://www.deafandblind.com/].

[2] The example sentences are taken from doctoral dissertation of Paula Lorimer [Lorimer, 1996].

By the time when Louis Braille, a cobbler's son, lost his sight in early childhood after an accident with one of his father's tools, over 20 different systems of tactile types had been developed and the range of them was not limited only to the types discussed above. As a 10-years old, Braille entered the Institute for Blind Youth in Paris and became acquainted with the difficulties the embossed types caused to the blind pupils during the reading process.

In 1821 a retired military man, Captain Charles Barbier proposed the use of the alphabetical code invented in his own to the Institute where Louis Braille was studying at that time. The code consisted of the dots and dashes and primarily should have been used to maintain communication with artillery crews during combat. However, it was never employed by the military personnel [Neimark, 1970]. Barbier's sonography used a 12-dot cell, 2 dots wide and 6 dots high. This was more than a human fingertip could cover. Each dot or combination of the dots within the cell stood for 36 basic phonetic sounds instead of letters. A large customized board, laid out 6 cells across and 6cells down, was used to write the sound symbols [Davidson, 1972].

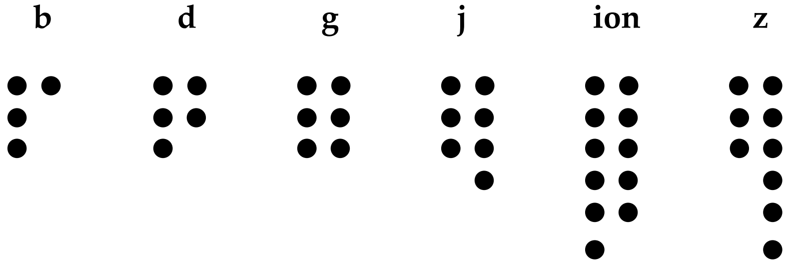


Figure 4. Selected examples of the sound symbols comprising Captain Barbier's original sonographic code [`http://www.brailler.com`].

The Institute rejected to use the code after some few months whereas Louis Braille kept experimenting with it [Neimark, 1970]. He thought of the Barbier's system as an excellent basis for creating the common reading code, which might be used by the blind individuals. However, Braille also understood that in order to become effective and easy enough to read, Barbier's system had to be improved. The code did not include punctuation marks, numbers or musical signs as well as horizontal dashes in addition to the dots. Louis Braille spent nine years developing and refining the system of raised dots which blind people still use to read with their fingertips.

The basic system makes use of six dots which code all the alphabet characters. That is, 64 raised patterns can be composed based on a six-dot cell, including a space sign (empty cell). Now adopted standard for the Braille cell includes the following sizes of the font dimensions: the elevation of the dot is 0.5 mm; the horizontal and vertical blank between the centers of the dots within a cell is 2.5 mm; the blank space between dots in adjacent cells is 3.75 mm horizontally and 5.0 mm vertically (Figure 5). A standard Braille page has a size of 27.94 by 27.94 cm and typically comprises a maximum of 40 to 42 Braille cells per line and of about 25 lines [RNIBa, Web site; RNIBb, Web site].

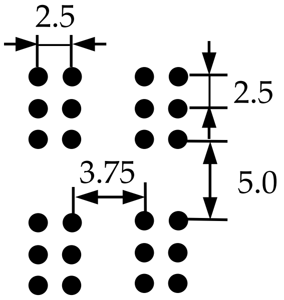


Figure 5. Dimensions of the Braille cell in mm [RNIBa, Web site].

Legge’s studies have shown that these sizes are suitable for paper layout but it is not ideal for tactile recognition, as during the inspection of Braille text the dots/pins may be felt differently depending on both the finger movement direction (horizontal, vertical or inclined) and the individual tactile threshold [Legge et al., 2000].

In the English Braille alphabet, 26 symbols represent the letters of the alphabet and 10 symbols are punctuation marks. The rest of the symbols introduce frequently used digraphs, for instance, OW or ER, and widespread short words such as AND or WITH. Braille type is shown in Figure 6. Reading Braille code can usually be done with use of the index fingers of both hands moving from left to right along each line. The one index finger has to move across the dots up to the moment when the line is finished. The other index finger begins reading the next line. This gives to the Braille reader a sense of paginal continuity.

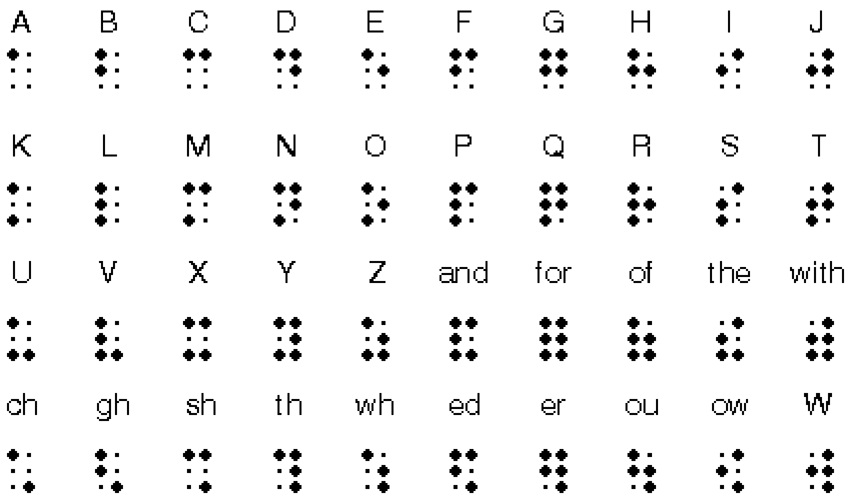


Figure 6. Braille type [Suan Hsi Yong's homepage].

The legibility of Braille characters and the reading speed as well as the accuracy with which blind readers distinguish Braille characters one from another by touch, or recall them from their memory, are crucially interlinked. The number of dots and their position in the Braille cell do affect the linguistic and cognitive processes involved in the reading of Braille imprint.

Challman [1978] measured the legibility threshold values and recognition time for each of the Braille characters by means of the tachistotactometer. Appendices I and II demonstrate the measurement results for alphabet characters, digraphs and trigraphs in Braille code accordingly. Nolan and Kederis stated that the legibility of Braille type is inverse to the tactile threshold. In addition, Nolan and Kederis indicated that patterns with dots in the lowest third of the cell such as U, V, X, Y and Z tended to be relatively illegible compared to patterns with smaller numbers of dots such as A, B, C and K and patterns with dots in the upper third of the cell, for instance, D, F, G and M [Nolan and Kederis, 1969].

Excluding the two-dot configurations, it was found that Braille characters, which have a greater space at the bottom and/or the right required 22% more time to be recognized in comparison to the lower characters ("X" was confused with "M", "ING" with "U"), which required 55% more time to distinguish them from others [Lorimer, 1996]. When reading dotted patterns one by one, the Braille reader cannot look ahead. Foulke argued, for instance, that the sentence "***In his cap…***" could become either "***In his capable hands***" or alternatively considered as "***In his capacity as …***" as well [Foulke, 1991]. This fact significantly affects the reading rate for the Braille code.

With age, some people lose their vision and hearing. Therefore, blindness and deafness are age-coupled perceptive dysfunctions. Braille imaging is equally appropriate for use by both blind and deaf-blind persons. While, it should be also noted that Braille readers are still in a minority as well as the majority of blind people who are not using such a form of access to textual information [Fisher and Petrie, 2002]. Recent statistics show that the number of the blind people making use of Braille is on average 0.02% of the world population [Tabatabaei, 2002]. This is especially true for those who have gone blind in later life. Furthermore, diabetes could have unfortunate consequences for the aging Braille reader by gravely accelerating the loss of both tactile sensitivity and acuity. Finally, the embossed imaging of the paper sheets makes the cost for producing Braille expensive. One A4 sized sheet of embossed paper costs approximately 1 USD [VirTouch Ltd, Web site]. The cost of a Braille display is in the price range of 3500 USD to 15000 USD, depending on number of characters displayed and technology [AFB, Web site; RNIB, Web site].

However, deaf people who have gone blind in later life can also use dynamic articulate representation such as the Tadoma method. Apart from static tactile alphabetic representation such as Braille code, the Tadoma method has to involve vocalization, which includes facial artifacts (skin micro-movements), in a dynamic manner. The Tadoma method employs cutaneous sense to perceive micro-movements of the skin and mechanical vibrations which accompany vocalization or speech reproduction (through a subwoofer). The receiver puts a hand on the face of the speaker, covering the mouth and neck [Tan et al., 1997]. Still, only the use of a subwoofer to amplify and produce the low frequencies of the speech is not enough to approach the same recognition rate as during the face-hand direct contact. However, the reading speed for Braille code is significantly lower than the reading speed when using the Tadoma method. By comparison, maximal average reading speed for the Braille code approximates to 100 words per minute [Foulke, 1991; Challman, 1978] whereas an experienced user of the Tadoma method can achieve a listening rate relatively near to the normal level of speech perception, which is on average about 250 to 300 words per minute [Tan et al., 1989]. Tan also argued that experienced users were able to understand about 40% of the isolated words, and about 80% of whole sentences [Tan et al., 1989]. Although Tadoma can be a fairly accurate method of speech recognition, the problematic aspects to provide a remote communication medium for people with a sensory impairment are still under investigation.

In 1843 William Moon, who became blind in his youth, developed another tactile type, which seemed to be recognized and perceived more easily than the dots-patterned Braille method. Moon simplified the capital letters mostly taken from the standard Roman alphabet and embossed them on heavy paper [Lorimer, 1996; The National Council for the Blind in Ireland, Web site]. The Moon alphabet consists of 27 symbols using the lines and curves at different angles to represent letters, numbers and punctuation marks. 8 letters of the alphabet remained unaltered from the Roman alphabet, some parts of 11 characters have been left out, 2 characters were slightly modified and 5 characters as well as punctuation marks have an original shape. Moon type is shown in Figure 7. To read the symbols the hand has to move from left to right across the page, down to the next line, and then back across the page from right to left [Lorimer, 1996].

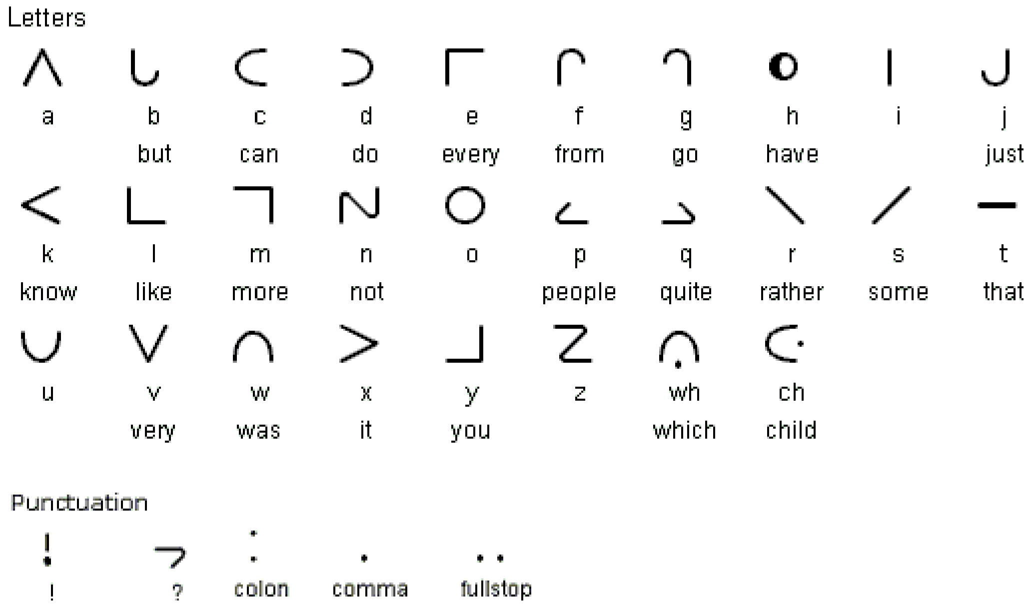


Figure 7. Moon type [Omniglot Web site].

It is noteworthy that in 2002 David Goldberg, Roy Want and Mark Weiser (Xerox Corp. Palo Alto, CA) were granted USA Patent 6,366,697 on "*Rotationally desensitized unistroke handwriting recognition*" with marked reference to the Moon-Type alphabet. Unistrokes is a stylized single-stroke alphabet which can be written with a stylus onto hand-held computers. 22 out of 26 alphabet characters of the Unistroke handwriting use the same 6 basic elements proposed by William Moon (Figure 8).

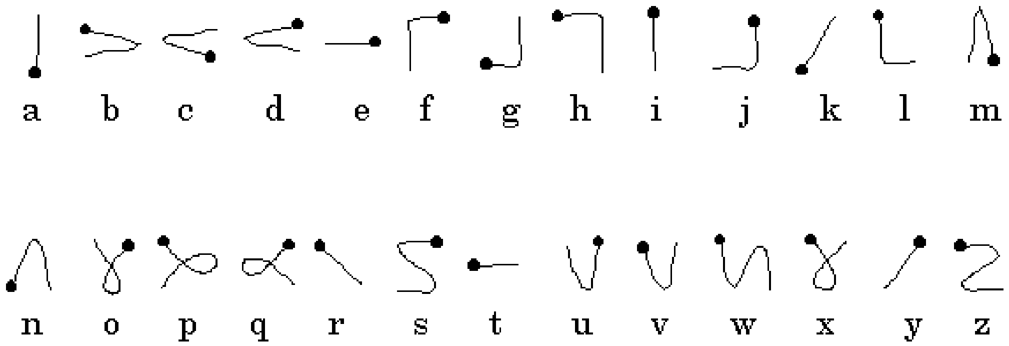


Figure 8. Unistroke alphabet [MacKenzie and Soukoreff, 2002].

Moon type has benefits over Braille in the sense that the proposed system is easier to learn since line-based alphabet letters can be better distinguished by touch and more easily enlarged or reduced than dots. Moreover, such symbols may enhance the legibility of each letter [Gill, 1985; Kelley and Gale, 1998]. In turn, type similarity to the typical print makes blind people able to learn the Moon alphabet in a relatively short time (about 2 days). However, in printouts it is frequently necessary to break words at the end of lines to save space and to allow equal spacing between words. The use of Moon is also hampered by the lack of appropriate writing machines [McCall, 1997; Watkins, 1987] and therefore only a very limited range of literature in Moon typeface is available.

In 1989, Tobin and Hill evaluated a mechanical "Moonwriter" which was intended to facilitate the teaching of blind Moon readers to write texts using the Moon type. Tobin assumed that Moon is not a system merely tactually simpler than Braille for older people who become blind; it may also be *a feasible alternative for some less able and multiply handicapped younger learners because of its smaller number of contractions* [cited on Middleton, 1988].

More recently, the Royal Institute of the Blind (UK) had published a case study in which the availability of the dotted Moon code has been investigated as a production method for children using such a tactile mode on a regular basis [RNIB, case study, Web site]. The software used in the research project combined a standard Braille embosser and Duxbury Braille translation software to produce dotted Moon making use of the embossed patterns of a five-by-five matrix of closely aligned dots. The embossed characters are approximately equivalent to a 28 pt font in size. All participants were able to decode dotted Moon characters and employed dotted Moon for educational goals. As mentioned by the authors, opinions varied about how easily dotted Moon was read, 36% of tested subjects stated that the sample characters were too small to easily distinguish them by touch. Subjects were also asked to indicate which characters in the Moon alphabet were unacceptable or unclear for them to read. The results obtained from the case study carried out in the Royal Institute of the Blind (UK) are shown in Appendix III. As can be seen from this study, major difficulties were observed when the subjects were recognizing characters such as A, K, V and X. Alphabet characters H and O also seemed to be problematic to read whereas the letters N and Z were more easily distinguished by touch than other symbols.

The use of intact cutaneous sense is a very subtle process and, a priori, it does strongly differ from the use of the visual channel. When cutaneous sense is involved, the printed or written material has to be tactually observed to construct a rough mental model of the paginal space. That is, the reader could glimpse the overall reading space at once and after that inspect the material in detail. The range for tactile sensation of the embossed textual patterns is rather small due to overlapping of the sensory fields. Only one embossed pattern at a time can be felt. Heller argued that when the vision of the edges and contours is blocked, a shape could be recognized on the basis of the haptic cues [Heller, 1987]. The reading process may be slowed down if the embossed character is very narrow and small, and vice versa. In other words, visual processing takes place concerning the entire visual area of the typeface. Not only is exceptional contour of the character perceived and analyzed like an array of local spectral maximums, but also diverse possible segments and zones might be detected due to spectral heterogeneity and texture gradient before the final decision is made (Figure 9). Being tactilely observed, the typeface has to provide an abundant number of the features which can really be detected in order to decrease the ambiguousness of visual pieces presented.

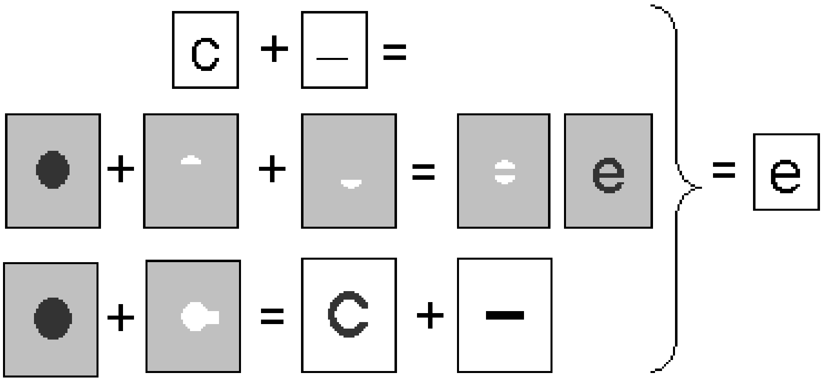


Figure 9. Probable image segmentation, detection and evaluation of graphic primitives at visual observation of the symbol "e".

However, tactile display technology has many constraints to correspond to these requirements. The fact that the attempts to use the early designed embossed codes resulted in failure seems to be predictable. On the one hand, all the embossed characters appear visually simple, but it was hard to recognize them by touch. This comes from the primary complexity of the visual base and median employed by Roman type. In particular, Pamela Lorimer argued that a capital "A" has a simple outline but the internal crossbar is difficult to sense; "M" and "W" are even more difficult because of the number of down strokes. She also pointed out that a lower "e" has a difficult curve to sense and the gap at the right may not be recognized so that the letter may be misread as an "o" [Lorimer, 1996]. Cramped configurations of the Alston and Gall types caused discomfort for the blind readers and were unpleasant to feel, though sighted readers would manage with these types fairly well. The abbreviated nature of the Lucas type led to cognitive overload of the blind reader and broken perceptual transfer of the information presented on the embossed page. The main reason for the greater success of William Moon's code originates from the fact that the shapes of the alphabet characters are significantly simplified in comparison to the shapes of the alphabet characters in previous tactile codes. The elevation height of early British embossed booklets was significantly smaller than the elevation height of modern sheets with the dotted Braille and Moon. The height issue dramatically affected the tangibility of the embossed texture and consequently the learning process for beginners.

The majority of blind people still use embossed communication as their main form for getting access to written and printed material without the assistance of sighted persons. Therefore, every time when inventing a new code or aiming to improve an existing one, sighted developers must take into account the potential of the blind people, who are experienced users of the embossed letters. The density, shape, size and spacing between the characters as well as the elevation of the relief should be carefully considered.

2.2. Tactile output techniques

Textual imaging is a kind of processed and structured surface. Herewith, according to specific rules determined by the linguistic, orthographic or semantic features of the paginal layout, textured elements or textons can be grouped into semantic sequences that may be perceived and interpreted irrespective of physical qualities of the used material whether it is stone, wood, metal or paper.

If modal-specific stimuli are being used, the notion of "tactile sense" can be described as local or diffuse contrast sensitivity to the pressure (in different directions), heat and cold [Youngblut et al., 1996]. Modal non-specific stimuli give rise to local or diffuse sensations such as touch, itch, tickling, pressure, vibration, tingle, pinch, sharp or burning pain. Diffuse tactile sense provides blind and visually impaired users with the qualitative properties of the object surface being touchable. Silvia Perera argued that the soft subcutaneous tissue underneath the contact areas of the fingertips has the highest spatial resolution in the somatosensory system [Perera, 2002]. However, these areas do attenuate small amplitude vibrations before they reach the receptors beneath the skin.

Similarly to audio and visual processing, touch has a strong integration with motor activity. The afferent flow of tactile receptors is rarely interpreted or recognized as a unimodal perceptive message. Touch inspection requires mechanical interaction with the inspected object and proprioceptive signals generated during the movement are needed for interpretation of the tactile pattern. Specialization of tactile receptors and sensory fields does extend the dynamic range of perceptive parameters and leads to the interaction and integration of sensory flows. Therefore, it seems highly possible that the physiological characteristics of the tactile analyzer are not low, but the use of inadequate stimuli leads to inefficient action on a receptive surface and to a lack of exploration of the local sense of the image.

The diversity of tactile output techniques is conditioned by the physical parameters of the signals (stimuli) and by the display components. Interaction styles used when sensory impaired user employs tactile output techniques provide recognition of the display surface through active dynamic contact (inspection) exceptionally. The tactile objects can be presented as a quasi-static modulation of the surface structure or the dynamic impact onto the skin: pressure, pulse, vibration, or lateral skin stretch. To transmit the attribute information to the disabled user, different kinds of stimuli can be used varied in number and duration depending on the imaging tactics used.

Tactile output techniques are implemented making use of electromagnetic, piezoelectric, thermoelectric, hydraulic or pneumatic actuators. The maximum force output, torque, friction, power consumption and bandwidth are considered as the crucial parameters in designing transducers and actuators. A comparison of the specific features of the several actuation modes used in tactile output techniques for acquiring tactile stimulation is presented in Appendix IV. There is a concept to drive the elements of the tactile display by wires made out of the shape memory alloys heated by the current. However, the dynamic characteristics of such elements are inferior in comparison to those electromagnetic or piezoelectric actuators have. While a thermoelectric transducer has significant benefits in the generation of the high tensile force output giving a rise to a clear sense and having great enough power to mass ratio, the frequency of changing pin[3] position for actively cooled shape memory alloys does not exceed 10 Hz [Jungmann and Schlaak, 2002]. We believe that such an approach is inadequate for the synthesis of fast-variable patterns of textured images. Tactile displays with electromagnetic transducers have an accurate adjustment of the temporal parameters, but the forces yielded are too low to provide the user with sufficient primary feedback while touching the textured surface. Electro-mechanical tactile displays with piezoelectric actuators or driven pneumatically provide stable parameters for a surface structure modulation but not the parameters of the tactile patterns applied directly to the user's skin. This is determined by the complex interactions between actuator that shapes the physical stimuli, skin and spatial-temporary affinity in which modal-specific stimuli are located. This type of display techniques is not intended to measure the finger pressure or a touch surface to adapt the tactile stimulus or pattern produced concerning the individual sensitivity of the user.

The embodiments of tactile displays are designed primarily to produce Braille characters that are of a textual nature. As a rule, display dimensions are determined by the possible number and sizes of standard Braille symbols displaying from 40 up to 80 cells within one line and up to 25 lines per screen. If the active area of the tactile tablet is 20 × 15 inches then it is possible to display one printed page in the usual format of high-resolution screens with a width to height ratio of 4/3 [Fricke, 1991].

The tactile pins of a tablet are set so that they correspond to the points of a rectangular raster. Distances between neighboring pins vary between 1/10 inch and 1/30 inch, depending on both the functional assignment of the tablet and any redundancy allowed by a chosen technology. While the finger moves in different directions with diverse angles concerning the pins, the lines can be felt as uninterrupted or fragmented, consisting of separate points. The user needs to distinguish between a functionally important tactile object and an observed effect due to a low-resolution display. Therefore, 1/30 inch is considered to be more preferable distance between pixels for a spatial interpolation and effective

---

[3] A pin is a smallest discrete element of the tactile image [Kay, 1984].

information imaging. Still, a mechanical approach to designing touch-based output techniques implies simulation of the “unnatural” textured surface. As a result, a blind or visually impaired user does experience difficulty in recognizing specific details or/and surface properties such as directivity and angularity, and consequently the integrity of the textual information presented is rather broken.

Meanwhile, recent technology is not bounded only by the production of the Braille tablets and related hardware such as laptops augmented with Braille interface, Braille embossers (5 pages of Braille per minute – 11.5×11 inches) and Braille note takers.

In the early seventies, Bliss and co-workers of Telesensory Incorporation created a vibrotactile output technique called Optacon. To transmit scanned input, Optacon employs an array which consists of 144 vibrotactile piezoelectric metal pins placed into a special matrix having a square of 13 mm by 28 mm and including 24 rows with 6 pins in each row and vibrating with fixed frequency of 230 Hz [Youngblut et al., 1996; Tabatabaei, 2002; Snyder, 1994]. The Optacon is connected to a small camera which allows the transformation of scanned characters into vibratory patterns and their representation on the pad. To read vibratory patterns, a blind person relocates the Optacon camera along the line with the aid of the right hand whereas the flat surface of the index finger of the left hand has to be placed straight over the vibrotactile array (Figure 10, on the left). As the camera moves across the letter, the image is reproduced on the vibrotactile array [Snyder, 1994]. Several studies have shown that blindfolded subjects detected the greatest amount of vibrotactile patterns making intense use of the left hand [National Federation of the Blind, Web site].

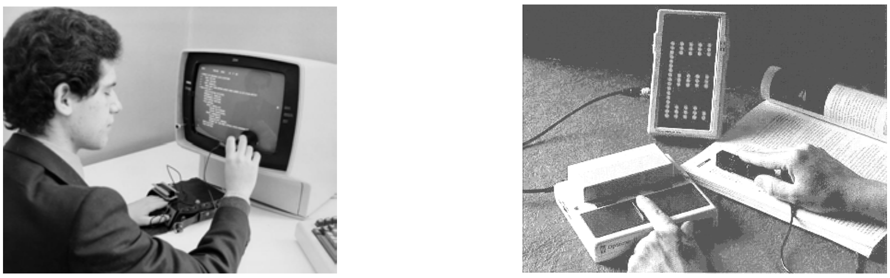


Figure 10. Vibrotactile output techniques – Optacon I and II [ASPHI, Web site; Telesensory Corporation, Web site].

In the early eighties, TeleSensory Incorporation realized a second version of Optacon which had a vibrotactile array combining 20 rows with 5 pins in each row to send textual output from the Optacon handheld scanner which could convert different fonts including Braille sheets into a series of vibrating pins that would simulate printed letters (Figure 10, on the right). Optacon technique exploits the fact that at any moment blind or visually impaired users can only feel a small region of a tactile display regardless of its overall size. Making use of this device, the user manipulates with an "electronic eye" over the pieces of the tactile output pattern with one hand whilst a small but variable part of the whole pattern is presented to one finger of the other hand. It was supposed that the technique could be equally suitable for interaction with text and graphics. Nevertheless, this way is unnatural as sliding of the fingertip and mechanical contact with inspected surface brings much more information needed for a mental reconstruction of the tactile image.

Moreover, Optacon technique does not benefit over the touch-based techniques augmented with Braille interface due to great cognitive load while imaging textual information in a dynamic manner. This way requires a significant concentration of attention and leads to a loss of semantic sense of the text presented. As a result, the effectiveness of the user's navigation is reduced; the time taken in forming the whole percept increases and consequently the reading speed with the use of Optacon is very low and averages to 20–30 wpm.

To achieve reasonable reading speed i.e., nearly 80 wpm, the blind user has to spend a long time in training [National Federation of the Blind, Web site]. The one-row Braille interface can provide the user with an integral cell-like pattern without chaotic sliding from one textual fragment to another and thus to retain the unique meaning of the information imaging. The cost factor, the price of the Optacon device was around 4,000 USD, hindered its use [Snyder, 1994].

Craig Chanter and Ian Summers of the Biomedical Physics Group at Exeter University designed a special fingertip stimulator array to simulate tactile sensations on the fingertips. The top piece and underside of the piezoelectrically driven array are shown in the Figure 11. The spatial resolution required for stimuli is determined by the density of touch receptors in the skin - around 1 mm^2 on the fingertip [Summers et al., 2001]. For this reason, The Exeter fingertip stimulator array has been designed with 100 pins arranged on a 1 cm × 1 cm square matrix, which covers the fingertip.

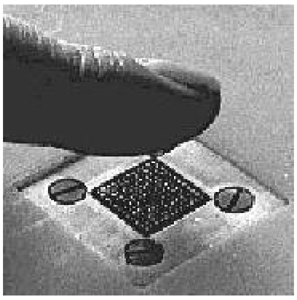


Figure 11. Top view of Exeter tactile array [Summers et al., 2001].

In comparison to Optacon which allows the production of only stimuli at a preset frequency of about 230 Hz, the frequency range of the stimuli of the Exeter array varied widely from 25 up to 400 Hz. The device was able to generate a large number of spatial and temporal vibro-tactile patterns, as diverse skin receptors could sequentially or simultaneously be activated due to the difference in their frequency response [Perera, 2002].

In the late sixties, Bach-y-Rita [Bach-y-Rita et al., 1969] developed a tactile visual substitution system which converted a video image into a vibro-tactile pattern. To produce vibratory stimuli, the tactile array was composed of 20 by 20 vibrators, which could be placed on the thorax, abdomen or back of the blind user. The prototype of the tactile visual substitution system (TVSS) was tested with 100 blind people. These studies have shown that both congenitally blind and subjects who have gone blind in later life were able to strengthen their spatial cognition of the surroundings and started to discriminate foreshortening, vanishing points and other features after the use of TVSS device in two days. However, the attempt to exploit this device on a regular basis was not fortunate enough due to the lack of proposed video-tactile mapping (perception/cognition problems) and technology.

Bach-y-Rita and other researchers suggested the use of another body part to employ sensory substitution and to diminish unit size at a maximum. A display unit was mounted on the tongue making use of several sensory neurons to transmit visual signals in the brain. A wearable (battery-powered) part of the tongue display unit and a way of the use of this device are shown in Figure 12. The tongue display unit consisted of an array provided with 144 electrodes having an area of 12 rows × 12 columns. The wearable unit has a camera, which transmits electrical signals to the array. Thus, the user could feel a tingling sensation in some of the tongue fields [Bach-y-Rita and Kaczmarek, 1969].

Electro-tactile transducers have significant benefits in power consumption (less than 10–40 μW is required per stimulus, giving rise to a clear sensation on the tongue as the interaction surface) and an accurate adjustment of temporal parameters. However, current regulation is a very complex process that requires fast adaptive circuits which can follow the contact impedance between an electrode surface and the skin. When matrix technique is being used the area of contact is about 1–2.5 mm^2 per pin-pixel. A high impedance of the skin (about 10–50 $\times 10^3$ Ohms$\times$cm^{-2} for dry skin) requires applying high voltage (50–200 V) to provide the needed sensation when a diameter of electrodes is about 1 cm^2 and the source of the current provides pulses of a single polarity (polarization changes perception thresholds). When the area of electrodes is decreased, skin impedance increases and the needed voltage could be more than 400 V.

According to Bach-y-Rita's observations, 50 hours of practice was required to get the feel of the unit and learn how to interpret the received stimuli [Bach-y-Rita and Kaczmarek, 1969]. Further, the researchers plan to mount the electrode array on the roof of the mouth and study human sensations to presented complex patterns.

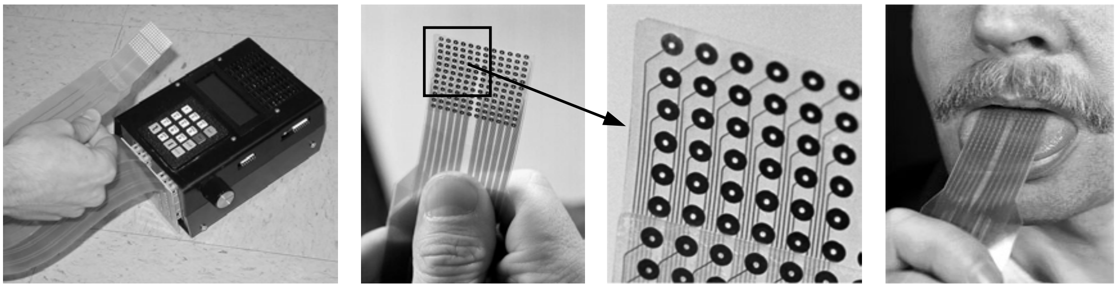


Figure 12. Tongue placed electro-tactile display: wearable unit, tongue array and a way of using device [Bach-y-Rita and Kaczmarek, 1969].

In the case of interaction with a touchpad there are many different possibilities for delivering a tactile (vibratory) sensation to the skin surface (palm or finger) with high efficiency. Thus, a number of devices have been implemented so that people who are blind or have low vision could freely move the hand along a virtual plane and inspect the surface to gain access to textual or/and graphical information.

To give an example, the electronic vision group at the University of Heidelberg implemented a virtual tactile display (VTD) which has a small operative active area consisting of 48 tactile pixel elements that can be moved by the user across a large surface having a square 164 mm x 159 mm and providing access to approximately 4000 virtual pin-pixels [Maucher et al., 2001].

VTD output technique is shown in Figure 13. A user can get either textual or graphical information in the form of tactile sensation through her/his fingertips.

Virtual tactile technique was tested with blind and blindfolded sighted subjects in order to measure the recognition degree of the presented tactile patterns [Maucher et al., 2001]. Individual movements during tactile pattern perception were recorded and analyzed to detect possible similar trends and strategies in recognition of the patterns. The study showed that blind subjects required half the time for pattern recognition and moved over the tactile pad twice as fast as the sighted persons. However, in a sense this way seems to be unnatural as a sliding of the fingertip and a direct mechanical contact with inspected surface is needed to enlarge kinesthetic feedback with directional tactile signals. This information and synchronization of perceptive flows are needed for a mental reconstruction of the tactile image.

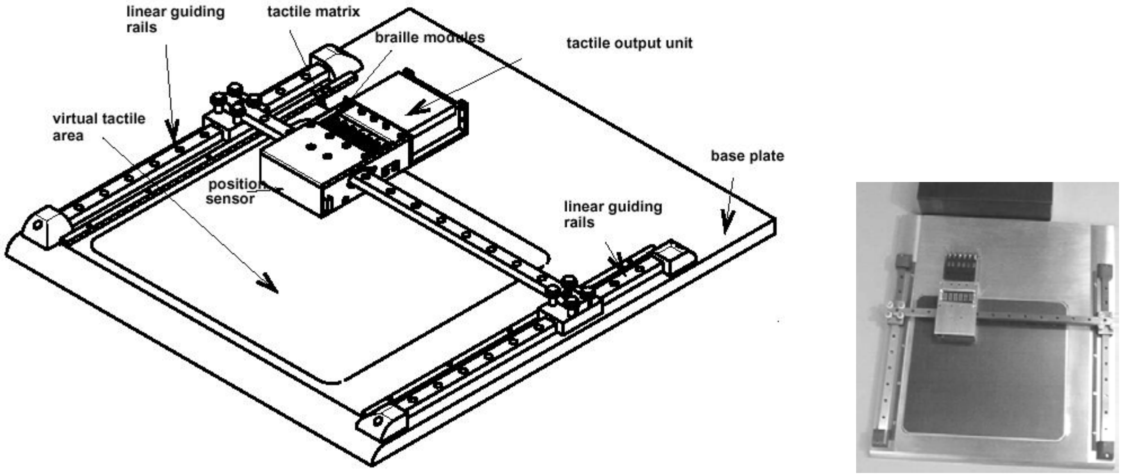


Figure 13. VTD output technique and its mechanical components. [Maucher et al., 2001].

There is a clear trend that various mobile terminals will widely address tactile interaction. However, the possible number of actuators used to simulate different tactile sensations is very restricted in mobile devices due to their size, weight and power consumption. Some interaction features create obstacles in producing stable tactile sensations with sufficient spatial-temporal resolution of the signals and patterns. The authors propose using small actuators such as a piezoceramic bending motor [Fukumoto and Sugimura, 2001; Poupyrev et al., 2002] or shaking motor [Nashel and Razzaque, 2003] attached to a touch panel or mounted on a PDA. Fingertip interaction with touchscreen has a limited contact area and should provide very low friction. This hampers vibration transition. In this case, the blind or visually impaired user could perceive only minor components of the vibration being produced.

Notwithstanding the crucial growth of batch production of devices equipped with vibro-tactile output, human cutaneous sense is still being misused. Most of designed tactile output techniques are considered to be unsuitable for further use by blind people. Alternative touch-based presentation is lacking of potential users due to their principal distinctive difference from the visual counterparts. When the flat surface is being inspected with the cutaneous sense, it cannot be used as a substitute for portrayed visual space. Cutaneous sense can provide the blind user with relatively narrow information bandwidth ~28dB [Shimoga, 1993]. In contrast, the vision allows a user to quickly get the feel of the general paginal layout. Lederman and Campbell [1983] argued that the exceptionally slow, sequential nature of tactile perception does require strong cognitive activation of the touch sense and *physically active exploration* to discover relationships between pieces of a tactile pattern. During such exploratory behavior, the motor component plays an important role in integrating perceptual information and extract the features of the surface (tactile pattern) that is being inspected by touch. Such body parts as fingertips, hands, wrists, arms, shoulders, and torso adjust reader position as s/he slides over the texture. Even millimetric variations in the elevation height of the raised texture may drastically prevent or hinder the blind reader from obtaining a holistic, spatial perception of the tactile output presented.

The functional state of the blind user also has a great impact on the use of touch-based technique. In other words, texture, temperature and shape of the object should be inspected and recognized in relaxed, intuitive manner rather than in intense concentration and tense atmosphere. Relaxed manner in texture inspection does guarantee easy perception and appropriate recognition. That is, intuitive use has to be considered as a key factor in the design of the assistive tactile aid.

One of the important contemporary scientific objectives is to represent textual information to the maximal extent with minimal use of mental/cognitive resources. Achieving this goal is especially essential for blind users who are still making use of Braille devices.

Among sighted persons, a prevalent misconception exists that Braille is always the best solution for blind persons. However, tactile techniques (the parameters of the touch-based output techniques described in this chapter are presented for comparison in Appendix V), which employ a single Braille cell, are not being widely used among blind users. Refreshable Braille displays allow only limited textual imaging in a few lines of the screen [Cravotta, 2004]. Large arrays of mechanical pins that are elevated over a flat surface and scanned by the fingertips are mechanically cumbersome to produce in small size. Efforts to use smaller arrays to make tracking with fingertips over a large virtual display like VTD have yielded mixed results. Voltage controlled touch stimulation with an array of electrodes can now provide imaging of the spatial patterns to abdominal skin and tongue. However, extra need for reduction size, weight and power consumption to ease the use of wearable sensory aids has been strongly recognized by handicapped consumers as well.

2.3. Speech output techniques

A substantial body of research on developing speech synthesis related approaches has provided experimental evidence that many attempts have been made to build machines which would emulate speech as this is the one of major means of human communication. Starting with Kratzenstein's acoustic resonators built by analogy to the human vocal tract and producing only five long vowels such as /A/, /E/, /I/, /O/, and /U/ and then von Kempelen's machine, transforming single acoustic signals and some of their combinations into the mechanical speech, speech synthesis techniques underwent considerable changes and transformed into low-cost software and devices producing speech acceptable regarding its naturalness and intelligibility, which are now extensively used by low-vision and blind people. In these ways, visually impaired people would be able to gain access to textual information which otherwise might not be accessible to them. Separately taken milestones in the history of the speech synthesis development are shown below in the Figure 13. In this section, some speech synthesis output techniques adapted to display textual information in several ways, will be discussed.

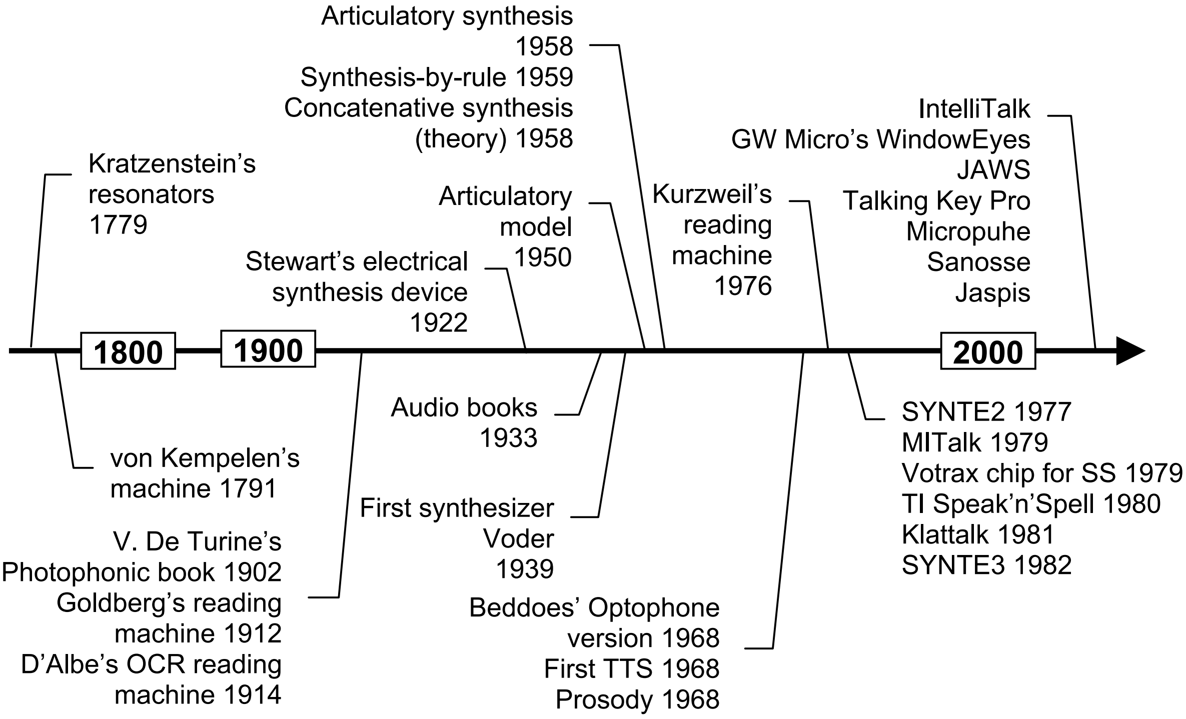


Figure 14. Basic milestones in speech synthesis.
Adapted from Lemmetty [1999].

Reading aid supplies blind and visually impaired users with new opportunities for accessing textual information. There were several attempts to create a machine, which would convert printed characters into some readable code.

In 1902, V. de Turine invented the Photophonic book, which transformed each character of the printed material into a distinct sound. In order to make character-to-sound transformation, the reading material was prepared in a special way so that each letter on a page would be represented as a series of small transparent squares. By shining light at the page a series of flashes were detected and used to modulate an electric current and respectively produce a sound [Cooper et al., 1984].

In 1912, Goldberg introduced the machine that read printed characters, encoded them and converted into paper tape, which generated the Morse code.

In 1914, Fournier d'Albe implemented the optical character recognition reading aid for the blind people. It was a hand-held scanner, which used a vertical row consisting of five spots of light to move across the printed material. Each spot of light was used to produce a different musical note. The device produced a sound having higher intensity when it moved across the lighter areas of the text and did not emit any sound when it moved over the black characters of the text [Cooper et al., 1984]. The reflected light was detected by a row of selenium cells, which were employed to modulate the sound output [O'Hea, 1994]. In 1968, Beddoes undertook an attempt to make the sounds produced with optophone easier to learn and comprehend using time-compressed signals [Beddoes et al., 1961]. However, the optophone was quite hard device to use and it also required acquiring significant practice to reach fairly reasonable reading speed.

The first commercial reading machine with optical scanner for blind people was introduced by Raymond Kurzweil in 1976 [Lemmetty, 1999]. Kurzweil was inspired by the sayings of one blind person who once told him that the one and most crucial obstacle for blind people was their problematic access to the printed material. Kurzweil's machine combined the first flatbed scanner with optical character recognition (OCR) software and a text-to-speech (TTS) voice synthesizer [Taub, 1999]. First, the printed material was scanned and translated into recognizable text with the help of the scanner and OCR software, and then a TTS voice synthesizer provided the blind user with quite an audible analogue of the printed text.

The pioneering reading machines were extremely expensive and therefore did not become as widespread as was expected. These machines had a very low level of character recognition and speech synthesis when scanning and reading printed textual material [Lemmetty, 1999]. In addition, the machines were situated only in public libraries, so an average user had no chance to use them on a daily basis. Nevertheless, the speech output produced by reasonably priced reading machines is very appropriate nowadays, therefore visually impaired people are still widely using this speech output technique. However, there remains considerable need for improvement as far as speech naturalness is concerned.

The recording organization for the Blind and Dyslexic and the American Printing House for the Blind produced audio books, which made it possible for blind persons to listen to the content of a book on audiotape. This kind of assistive technology has significant drawbacks. Audio books may be problematic when used by those persons who have reading disorders and experience difficulties when perceiving spoken information with a preset playback speed. The production of the spoken copy for a large book might take a lot of time and therefore it was expensive for a small group of users.

Another option for visually impaired users is the use of a computer with text-to-speech engine (TTS) and/or Braille output. A typical TTS system consists of the speech synthesizer and the screen reader that controls the spoken performance of the synthesizer. Speech synthesizers are implemented as hardware and/or software solutions for desktop PC, mobile devices as phones and Personal Digital Assistant (PDA) or embedded unit used in other customer products, e.g., speaking watches, health monitoring aids, toys, games and kitchen devices.

Speech synthesizers produce digitized and synthetic speech and vary widely on such specific features as pitch, the voices, the set of different common languages including Finnish and quality. Most linear prediction devices implemented in the late 70’s – early 80’s like TI Speak'n'Spell based on an articulatory model and including a syntactic analysis module were inexpensive but had rather poor quality because of the extreme monotony of the speech in contrast to modern speech synthesis techniques. Lemmetty in his Master’s thesis [Lemmetty, 1999] indicated that researchers had paid quite little attention to Finnish TTS before the early 1970's despite the fact that Finnish text corresponds well to its pronunciation and the text-preprocessing scheme is quite simple. The first proper microprocessor-based portable speech synthesizer for Finnish, SYNTE2, was introduced in Tampere University of Technology [Karjalainen et al., 1980]. An improved version of this synthesizer SYNTE3 was used intensively by Finnish people for a very long time. Such Finnish concatenation-based synthesizers as Mikropuhe implemented by TimeHouse Inc. [http://www.mikropuhe.com/] and Sanosse developed in the Center for Learning Research at the University of Turku [http://www.utu.fi/en/] are in current use for educational purposes and telecommunication applications.

Screen readers or audible readers are available for use with diverse platforms like desktop/pocket/handheld/palm PC and mobile/smart phones. These techniques run in MS–DOS, Microsoft Windows 95/98/NT/XP/Pocket PC, Linux, Java and Symbian programming environments, in which screen appearance and color scheme can be adjusted in many ways to simplify the use of speech output techniques. For instance, Microsoft has released a free TTS utility that can be used in Windows applications.

Each audible reader comprises a different command structure and does supports different speech synthesizers [Kurze, 1995]. To take an example, the Jaspis speech application architecture has been designed to facilitate the use of some speech synthesis techniques within a framework coordinated by agents and managers in a flexible way by means of a special *agents–managers–evaluators paradigm*. That is, compact agents support highly modular systems while managers coordinate agents in a flexible way, allowing highly distributed systems to be constructed [Turunen and Hakulinen, 2003]. Visually impaired users are one type of target user group who could benefit significantly from using Jaspis architecture-based multilingual systems. Several applications were designed to be used in the context of the framework implemented. Researchers from the Speech-Based and Pervasive Interaction Group at the University of Tampere [http://www.cs.uta.fi/hci/spi/] developed Mailman, which is a bilingual (Finnish/English) speech-based e-mail application. It allows the user to access his/her mailbox using a standard mobile or fixed-line telephone and provides the most common e-mail client functions [Turunen and Hakulinen, 2000]. AthosMail is based on the Mailman application and in the EU-funded DUMAS project [http://www.sics.se/dumas/] improved components have been designed to provide the user with context-sensitive help and guidance, which include adaptive prompts, integrated tutoring and universal commands to lead the sequence of the user's actions in the right direction [Turunen, 2004].

Extensive fact sheets containing detailed information on the subject of the technical features of the speech output techniques available nowadays are collected on the Web site of the Royal National Institute of the Blind [http://www.rnib.org.uk/]. At least some of them are worth mentioning here.

Apple computer Inc. (www.apple.com) implemented VoiceOver software built into Mac OS X 10.4, which does facilitate an access to the textual information displayed on the computer screen for the visually impaired user. The interface provides the visually impaired user with comprehensive audible English description of the contents of the web pages, mail messages and word processing files, magnification options and keyboard control for both interface navigation and user interaction with application. VoiceOver also allows the visually impaired user to cooperate with other Mac users.

IntelliTalk TTS software allows blind people to read text in user-defined mode, that is, both by any desirable pieces - letters, words and entire sentences, and any highlighted combinations as it is being typed. It is also possible to review the text by paragraph, sentence, or word. However, it is impossible to work with graphics using IntelliTalk. Other known screen readers are GW Micro's WindowEyes and Freedom Scientific's JAWS (Job Access with Speech for Windows) [Shepherd, 2001]. These techniques support textual output in both spoken and Braille form and include special software tools to detect possible hardware and software problems if any occur [Shepherd, 2001]. JAWS for Windows also allows the user to adjust both preferred language and accent. Graham Inc. provided blind users with Talking Keys Pro software which can be used by both blind and visually impaired users and provides them with spoken output of the typed information as well as enlargement of the typed letters up to font size of about 72. The syntax of the sentences pronounced can also be modified. The speech rate and pitch are adjustable.

Screen readers allow the performing of more complex tasks such as reading user-defined or highlighted screen parts. The screen reader technique gives benefits to the blind and visually impaired users in the sense that it is typically compatible with standard software. However, it is highly likely that to adjust the speed, pitch and volume of the voice, some number of keys is required because some of the speech output applications cannot be operated with a mouse. Therefore, to be able to manipulate the application, the blind user has to remember all the needed key-combinations if s/he is unable to quickly use a manual.

Nowadays, due to technological achievements, increasingly more options are becoming open to blind and visually impaired computer users. A large number of the books in various electronic formats are available through Internet libraries and projects aiming to introduce new reading formats and tools for the talking books [Kutsch, 2003; Kendrick, 2004]. For instance, the aim of the project "the eAudio study" was to explore the usability potential of talking books as well as proprietary magazine and newspaper content AUDIBLE.COM [http://www.audible.com/]. One book was downloaded in a special audio format such as Audible's proprietary Otis player on a pocket or hand-held device and then altogether with usability guideline and headphones sent to all the subjects participating in this case study for a test period of two weeks. The participants reported that the interface of the player was not satisfactory for them as the software buttons on the touchscreen were very small and audible cues were constantly needed to indicate the function of each button [Kendrick, 2004]. This was quite annoying and distracted the user attention from the main task. The majority of subjects also had a problem with controlling the reading speed. Thus, new reading formats still require further elaboration and improvements.

Spoken imaging would seem quite a simple mode for conveying textual information to the blind user if there were no variations in the background tone, timbre, pitches etc. Spoken output imparts textual pieces in a bounded manner. Snyder indicated that such spatial textual features as highlighting through different fonts, indentations have to be either announced explicitly or indicated through background tones or speech features. The first disrupts the reading of the actual text, the latter limits the ways in which special features might be presented [Snyder, 1994]. As a result, the integrity of imaging textual information is rather fragmentary and, therefore, the semantic message of the information being accessed is not properly conveyed to the visually impaired or blind user.

Speech output has to be remembered piece-by-piece to create accurate representation of the screen layout because some letters like p and b have similar phonation. In addition, a blind person is not able to estimate the length of the text or the spatial position of the particular phrases/paragraphs presented on the screen in advance. This requires additional navigation tools. Hence, a cognitive overload of the blind reader when the whole screen parts converts into “spoken image” of the page layout might be irrelevant to the final objective of the blind user [Lazzaro, 1984]. Listening to synthesized speech can be annoying [Brewster and Brown, 2004]. For this reason, spatial and hyper textual features may be presented with touch-based display techniques rather than when making use of sound or speech cues.

Some reading aids for blind users require unlimited vocabulary as the Talking Keys Pro software, for instance, does. The copy synthesis method can be considered only in a case when there is a need in a limited ideolect. This is because of the different ways in which people pronounce some words or sentences.

Speech synthesis has already shown potential benefits for blind users as an additional aid for the imaging of textual information. However, there is still a need to make spoken output more flexible in the sense of integrity with other modalities for alternative input and imaging of the hyper-textual features. It is especially important to expand the functionality of speech synthesizers because many blind people find sole tactile imaging of the textual information insufficient for an interpretation of the graphic pieces of paginal layout. They would essentially benefit from audible presentation, which can be perceived and more easily comprehended by the blind person than tactile information alone [Lazzaro, 1984].

In the next section the auditory display techniques, which attempt to strengthen or substitute for visual imaging of the textual information for the users who are blind or have low vision, will be discussed.

2.4. Auditory displays

Auditory imaging of textual information can provide one of the possible alternative ways to display text or specific textual features like paginal layout to visually impaired computer users e.g., frameset-based sonification across Web pages[4].

In the White Paper on Sonification of the National Science Foundation the sonification term is defined as *the use of non-speech audio to convey information*. More specifically, *data sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation* [Kramer et al., 1999].

Studies in auditory mapping [Blattner et al., 1989; Perrott and Buell, 1982] have actively explored the auditory sense to develop additional navigational cues for textual information presented as a video image. An investigation of both audio spatialization techniques and spatial attributes of virtual sound objects has yielded some mixed results since it is often based on objective measurements of sound propagation within acoustic environment and statistic evaluation of subjective judgments of listeners/experts [Perrott and Buell, 1982; Hollander, 1994, Pulkki, 2001]. Some sonification methods seek to set only quantitative conformity of visual parameters to auditory ones. It is assumed that a person may learn any auditory code like Morse and substitute visual mental images by hearing complicated sound patterns. Other investigators are relying on cognitive transfer, like the synaesthesia phenomenon or intermodal percepts. For instance, independently of modality, decrement of intensity evokes a sense of the direction or motion. But this does not mean that sonification was really cognitively predefined. So far only simple contour objects (geometric or graphic primitives) can be sonified and evoke visual sensations similar to their graphic prototypes.

Meijer [1992] proposed a sonification method of gray level video images captured with camera. In his system, each pixel was associated with a sinusoidal tone, where the frequency corresponded to the vertical position of

---

[4] Using frameset-based sonification, several web pages are "framed" within the browser window. The audio engine of frame running in a (usually hidden) "persistant frame" page that stays constant, while the browsed pages change as the user moves around the site. [Website (2000), http://www.commotion.com/artcenter/iaudio/]

the pixel and the amplitude corresponded to its brightness. Each column of the picture raster was built up while superimposing the associated sinusoidal vertical tones through the sequence of columns, by sampling from left to right. The final signal was obtained by concatenating each resulting column. In this way, enlarged character images or full-page layout could be converted into dynamic sound chord. The proposed method undoubtedly requires a significant amount of practice to learn to interpret sound images.

Lakatos [1993] used a 16-element speaker array with adjacent elements set about 30 cm apart, which sequentially played a tonal sound (Figure 15). The experimental task consisted of recognizing which alphanumeric character from the proposed ten was displayed. Subjects could associate each sonified track with its respective visual image. According to Lakatos' observations, the average accuracy level of subjects' performance was nearly 60–90%.

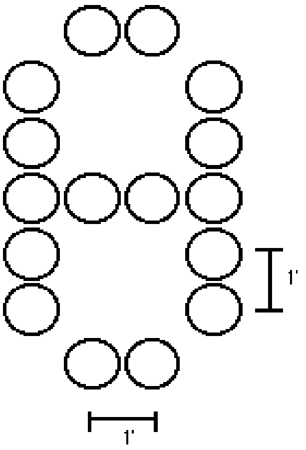


Figure 15. 16-Element Speaker Array [Lakatos, 1993].

Lakatos considered directional hearing as *ineffective in the discrimination of several simultaneous sound sources* [Lakatos, 1993]. In contrast, Hollander believed that it is *admissible to address concurrent spatial sensitivity in audition* [Hollander, 1994]. Therefore, Hollander repeated Lakatos' experimental setup. However, in this case the speaker array consisted of 16 virtual sound sources (VrSS) that directly mapped the visual counterpart of the alphanumeric characters. The shapes used in testing were 10 alphanumeric characters such as "3", "6", "9", "C", "G", "O", "P", "R", "S", "U" designed in a similar way to those Lakatos had taken (Figure 16). Each pattern was rendered by a moving

VrSS, using MIDI synthesis, headphones and head-related transfer function[5] (HRTF) for the spatialization of the VrSS and for an auditory shape presentation.

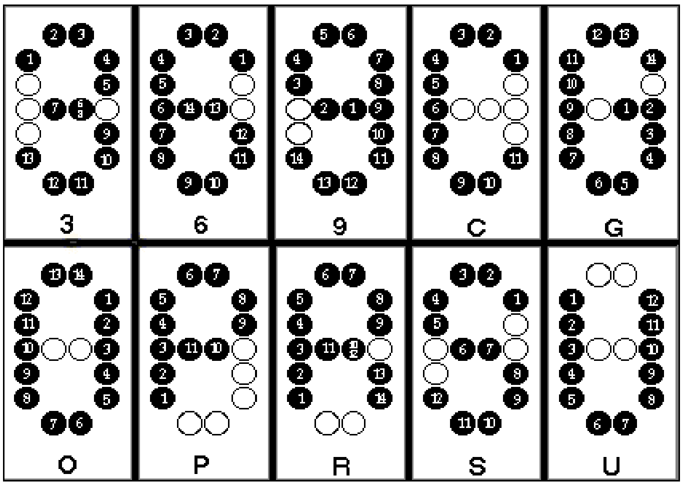


Figure 16. Alphanumeric auditory patterns [Hollander, 1994].

Perhaps the most crucial hindrance in this experiment was that the listener would have been expected to remember first the spatial features of the auditory tracks presented with the help of virtual sound sources in a sequential manner and then perform integration and comparison between the sound pattern and the mental model of the graphs used for testing to recognize them. This would mean that the greatest cognitive load would be placed upon the short-term memory of the user. The results set by Hollander into confusion matrix with columns identifying given shapes and rows identifying subject's choices strongly support the hypothesis regarding the primary cognitive complexity of the task given. Some sonified shapes were very similar in their orthographic features like "O", "G", and "C" and therefore, were frequently misrecognized. Even minor variations in the durations of sound patterns rather hampered the subject's choice. Several subjects reported that they experienced difficulties keeping the recognition track for such patterns and had to guess afterwards which of the characters might be associated with the sound track. In contrast to

---

[5] Wightman and Kistler recorded the eardrum response to white-noise signals containing equal amounts of all perceivable frequencies and coming from 144 locations around the listener. The power spectrum recorded was called a head-related transfer function. See [Wenzel et al., 1993] for more detail.

Lakatos’ experiment, Hollander did not provide the subjects with an opportunity for sufficient training in order to get them well enough acquainted with the interface and method. The starting point of each pattern was not depicted on each pattern choice like those in Lakatos’ studies. Lacking this choice, Hollander expected that the subjects would have been forced to deploy a personal strategy to identify the shapes presented. However, the subjects’ performance only got worse. The subjects were significantly less accurate (average level of accuracy ~ 20–43%) than the subjects in Lakatos’ experiment (average level of accuracy ~ 60–90%).

Although auditory presentation seems to be considered as one of the possible options to facilitate blind navigation when accessing textual information, ten years of extensive auditory display research still leaves room for further improvements. The auditory sense can be used to hear complex musical structures varied in a wide array of frequencies, pitches and timbres. Unlike the image-driven visual attention synchronized with eye-/head-movements, sonification requires an efficient modulation of the parameters of virtual sound sources and strong coordination with behavioral patterns (haptic feedback). Keeping attention in the auditory system continuously focused on the sound sequence developing over time could hamper synchronization of the attention with motor activity due to which mental processing of the presented tracks does happen efficiently. Non-speech auditory imaging of the characters was not intended to directly present textual information. It was employed to prove the feasibility of sonification for graphs. However, sonification of the hyper-textual information could augment text-to-speech transformation. Therefore, this technique was discussed in the scope of the present work.

2.5. Virtual retinal technology

Despite the wide proliferation of the assistive hardware and software used for imaging textual information, these techniques still have problematic features such as low resolution, brightness, contrast, and restricted view field. Assistive alterations of the Windows interface might impede the working process and would result in ineffective outcomes. To give an example, navigation along the computer screen can become more stressful and yield even lower reading performance of the partially sighted user when using the conventional optics for magnification. Kleweno argued that increase in the image size onto the retina by reducing the distance between the eyes and the display screen is a poor solution, because of the induced visual and skeletal strain [Kleweno et al., 2001].

An alternative visual display technology such as the Virtual Retinal Display (VRD) was developed at the University of Washington, HITLab [VRD Group, Web site]. The technique uses a low power laser beam to project video imagery through the pupil directly onto the retina. The laser beam being scanned very quickly over the back of the eye creates an image in a raster pattern which could be dynamically projected onto an intact retinal field. The produced image is essentially brighter than those produced by conventional screen-based displays. The display produces full color and flash-free images having high contrast at 640 × 480 pixels basic resolution that can be easily seen even in daylight conditions [Rash and Becher, 1982] (Figure 17).

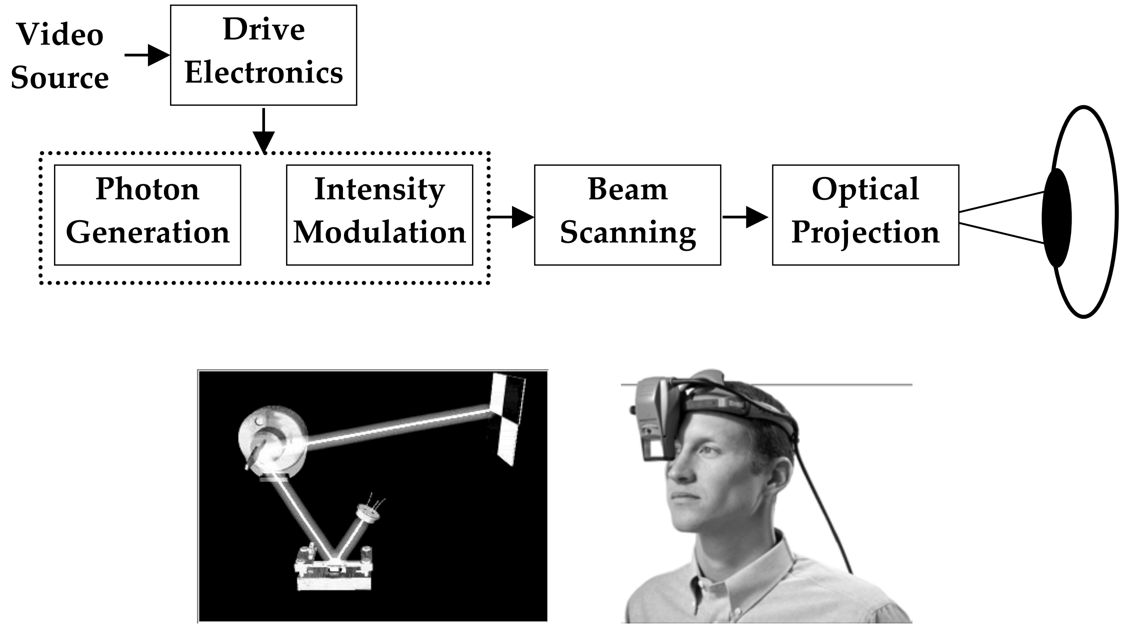


Figure 17. The VRD circuit block diagram (upper picture), the principle of the laser beam's mechanical modulation (bottom left picture) and the device in use (bottom right picture) [Suthau et al., 2002].

Kleweno et al. [Kleweno et al., 2001] reported that several researchers [Cornelissen et al., 1991; Webb et al., 1980; Culham et al., 1992] had already tested the low-power laser beam technique with partially sighted individuals. These explorations suggest that the use of residual diffuse color vision in the retinal area would yield certain benefits for persons having distinct macular degeneration over resorting to virtual retinal technology. For instance, drastic changes in visual acuity (up to 20/70) at greater luminance level resulted in achieving quite a reasonable reading speed nearly of 63.1 wpm with the use of increased display power and about of 62.8 wpm when viewing words on black-on-white contrast mode for words presented in an unrelated manner[6].

The present technology can provide a partially sighted user with one of the possible ways to perform imaging of textual information as a color imagery having high resolution and brightness controlled by the low-power laser. However, scanning complexity, susceptibility to degradation in high vibration environments and safety concerns [Rash and Becher, 1982] are still considered to be as problematic features of the VRD approach and require further study and improvement.

2.6. Summary

The present chapter gave an answer to the following question "*If a computer user is blind or has low vision, how may s/he access textual information?*" by means of presenting a literature overview of currently existing alternative means for imaging textual information that employ the residual senses the disabled user has.

New forms of methods for text imaging are being developed, some being found beneficial to assist an ordinary user in producing accurate output. Some alternative methods/techniques involve auditory and speech interfaces that make use of hearing sense and display textual information in audible form. Other approaches include tactile sense that provides blind/deafblind readers with access and creating a tactile image of any text. The use of residual vision in the retinal area makes it possible to adapt and deliver textual information via sequential projecting piece-by-piece onto the intact retina (virtual retinal technology).

Still, the problem remains of how to adapt the current highly interactive visual interface to the needs of blind or visually impaired users and how to visualize any text so that the output produced could be interpreted in a proper and easy way. There will always be those users who may experience some difficulties when employing one or another assistive device designed for text

---

[6] The unrelated manner of the words' presentation rather than textual presentation in a scrolled or Rapid Serial Visual manner was chosen because Legge's studies [1989] have shown that the reading speed of the unrelated words correlates directly with normal sentence reading and such a word order could more closely simulate the selective reading process involved in actual computing [Kleweno et al., 2001].

imaging. This is because some visually impaired people may have additional physical disorders that may also affect the manner in which they communicate. Therefore, display techniques and usability research undergo continuous exploration of accessibility to provide solutions to this problem.

Improved usability requires the user to be able easily handle the use of an assistive aid when s/he is about to access information in textual form and there is a need to edit the text. For non-impaired users visual cues (indentations, spacing, bullets, hyper-links) act as signposts, landmarks, or indicators that help them to navigate through the textual information given. In order to comprehend specific features of the text being visualized (for example, highlighting some paginal features) blind and visually impaired people need additional cues, which could possibly come in the form of diffuse color patterns, tactile markers, speech and non-speech audio signals (earcons) or special haptic patterns (tactons). Thus, residual visual, tactile or hearing sense cannot always be considered as a separate and unique modality to be used for whole information imaging.

The key concern of the scientists should be to find the optimal combination and coordination of residual modalities so that possible limitations in comprehension of the textual semantics and other informative features would not confound user abilities and experience. Moreover, text imaging is a kind of external memory aid. Therefore, alternative imaging should augment and facilitate interaction with the text but not distract and hamper cognitive processing of the content when the whole mental capacity is used exceptionally to decode the new (alternative) patterns.

4. DISPLAY TECHNIQUES FOR DEAF AND HARD-OF-HEARING USERS

People with hearing impairments have several alternatives to gain access to information sources. Imaging textual information for hearing impaired users can employ symbolic languages, assistive listening and tactile aids, telecommunication strategies, and wearable alarming devices producing vibratory output. Problematic aspects impeding the easy use of these display techniques constitute an extensive basis for the developer to learn how to improve and facilitate the ways in which hearing impaired people acquire and comprehend textual information, that is, to create robust display techniques, which would enable imaging of textual information in a simple and intuitive manner. In particular, it would be highly desirable to find out how it is possible to combine both residual hearing and vision to assist people with a sensory impairment in reading textual information.

3.1. Assistive hearing aids and verbal communication strategies

Starting with mechanical ear trumpets, assistive hearing aids smoothly developed into efficient and advanced microelectronics products, which are now extensively used by hearing-impaired people (Figure 18). Recent digital signal processing chips of the hearing aid include up to 10 independently programmable channels with respective automatic gain control [Roland-Mieszkowski and Clements, 1991].

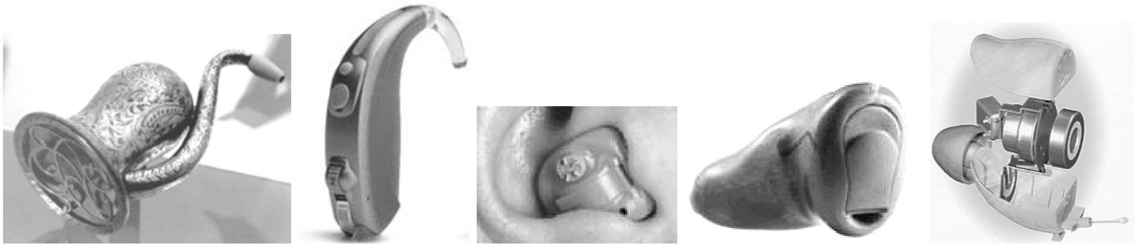


Figure 18. From the mechanical trumpet to the modern disposable hearing aid [Fels and Degan, 2001; 21st Century Hearing Ltd, Web Site; Unitron Hearing, Web Site; Boys Town National Research Hospital, Web Site].

The combination of small size and low weight seems to make mobile phones ideal for use together with a behind-the-ear hearing aid. Vibratory signals are widely used instead of a "bell"/buzzer to alert to incoming calls and are being transmitted into a wearable handset receiver. Nevertheless, some of the 6 million hearing aid users across Europe still experience substantial difficulties when they attempt to use the phones because of annoying interfering noises like whistling, buzzing, screeching or howling impair the sound quality and restrict the effective gain for stable operation [Roland-Mieszkowski and Clements, 1991; COST 219]. Because of unfortunate conversation, text messages are often essentially shortened; some phrases are not completed so that the addressee can easily misinterpret the primary meaning of the spoken content.

The majority of people having hearing impairments use sign language as their first or preferred language [Zak, 1998]. Therefore, text entry and reading during a conversation may be more problematic than helpful. Due to small-size screens some of the phone controls have a low resolution so hard-of-hearing people with low vision are not able to use such a phone.

Amplified handsets assist the hearing impaired user in overcoming sound distortion problems, especially in the case of sounds of high frequency such as fricative consonants **f**, **p**, **k**, **s** and **t** [Mercinelli, 2001]. Non-expensive amplifiers have only filters to correct an individual audiogram within a limited frequency range. More expensive signal processing techniques use an adaptive cancellation system or notch filtering to reduce or eliminate the acoustic feedback loop [Kim and Roy, 2001; Roland-Mieszkowski and Clements, 1991]. However, some hearing-impaired users still experience substantial difficulties learning how to tune out unfavorable background noise from the general vocal stream containing important information or the service problems of power supply.

Some in-the-ear hearing aids have a battery life as long as only 100 hours so a new battery is needed every few days [Roland-Mieszkowski and Clements, 1991]. Another solution was proposed by Songbird Hearing Inc. They introduced a 70-day digital disposable hearing aid for those people who have mild or moderate hearing loss to provide them with low distortion and very broad frequency response [Rametta, Web Site].

The use of a hearing aid may also have other negative consequences. Sometimes the human physiological limit to the maximum acoustic power that a hearing aid should deliver is being exceeded [Darlington, 2000]. The UK Department of Health and Social Security has given information that some hearing aids which are considered to be low powered have a maximum sound pressure level of 125 dB and higher-powered aids produce a maximum sound pressure level of 138 dB. Meanwhile, the more sound exceeds 85 dB the greater the probability of already damaged hearing sense being even further damaged due to noise-induced hearing loss [Dangerous Decibels]. That is, users of hearing aids often receive sound pressure levels that would normally be considered dangerous.

Some people with hearing and speech impairments use mobile textphones, for instance, Nokia 9210 Communicator to transmit messages over a special telephone service by typing them on a custom built-in keyboard. Special software compatible with this kind of communicators allows the user to edit textual features of the message like changing font size from small to large, scrolling over the body of the message, sending/receiving faxes and mails with attachments as well seeing the message of the interlocutor because they appear in a different color. For more detailed information see the RNID Web site [http://www.rnid.org.uk/].

Though the current textphones with thin-film transistor (TTF) LCD displays are much brighter and clearer, they have high power consumption and may be problematic to use for people with retinal damage or patchy vision. Hearing substitution also leads to visual overload and switching attention on text recognition.

It is very possible that non-visual tactile imaging could strengthen non-verbal communication and facilitate the use of visual symbolic languages. The capacity of the touch as an alternative mechanism to display semantic information has been a subject of research for a long time. A number of studies have provided experimental evidence that the dynamic range for the tactile analyzer is rather narrow in comparison to its visual and auditory counterparts. Shimoga argued that the human threshold for the detection of vibration at about 28 dB for frequencies is in the range of 0.4 – 3 Hz, the threshold decreases for frequencies in the range of 3 to about 250 Hz and the threshold increases for frequencies higher than 250 Hz [Shimoga, 1993].

Gault [1927] created a communication system for deaf children. Using the system, it was possible to convert the acoustic energy from speech into vibrations delivered to the hand. Unfortunately, there was no possibility to discriminate these vibrations in a correct way due to physiological restrictions of the skin receptors to perceive the upper speech frequencies, which are greater than 1 kHz.

Geldard suggested that subjects might easily perceive diffuse vibratory patterns if they would have been distributed through several vibrators placed on distinctive body parts [Geldard, 1960; Geldard and Sherrick, 1972]. Thus, each single vibratory pattern would code a symbol of the alphabet. Guided by this reasoning, Geldard designed Vibratese language. The five calibrated vibrators were located in four corners and one placed in the center of the rectangle on the chest. Vibratory patterns were shaped by three durations (0.1, 0.3, and 0.5 sec) and three intensities (soft, medium and low within 20 to 400 micrometers in vibratory magnitude), so that each vibrator could display up to nine different symbols [Conway, 2001; Tan, 1996]. 45 patterns could be employed to present textual messages through five vibrators [Fels and Degan, 2001]. The patterns having shortest duration were intended to be assigned to the most frequently used English letters and short words; digits were coded by the patterns with longest duration (Figure 19).

Three subjects learnt the language and one of them achieved a reading comprehension rate of 38 five-letter words per minute with 90% accuracy under 35 hours of training. According to Geldard's observations, about 12 hours of practice was required to become an experienced user in a single-letter recognition task and to learn how to interpret received vibratory stimuli to interpret whole words. The major drawback of Vibratese language was that the dimensions of duration and intensity were easily confused [Conway, 2001]. The subjects were not able to interpret continuous sequences of the patterns correctly even though separate letters were well perceived.

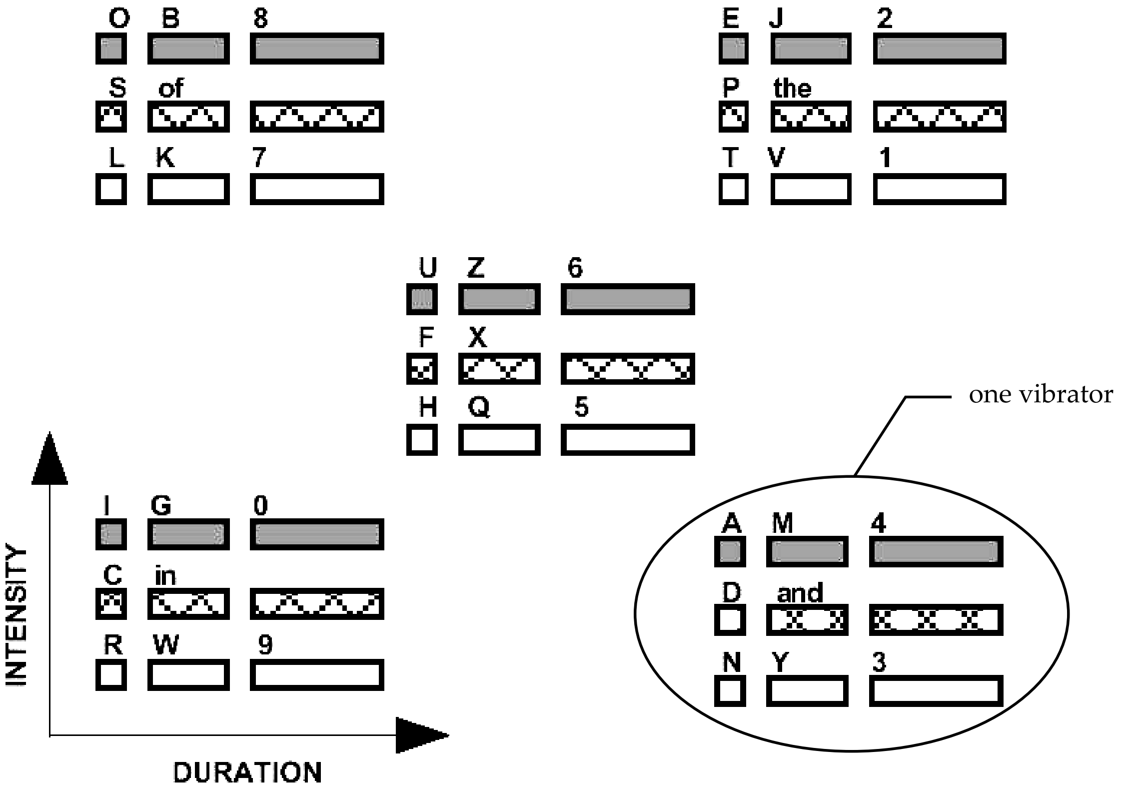


Figure 19. Coding logic of the Vibratese language [Tan, 1996].

To strengthen the interrelation between mental notion and symbolic imaging, Bliss introduced an alternative logographic-like system. Blissymbolics comprised pictographs, ideographs and a few special symbols [Muter and Johns, 1985]. Hearing-impaired people use the proposed system as the one of the possible communication methods. It includes about 100 basic shapes and symbols, which semantically resemble their referents [Bliss, 1961]. Some samples of Bliss symbols are shown in Figure 20. Following specific rules, shapes and symbols can be recombined to construct semantic sequences, phrases and sentences.

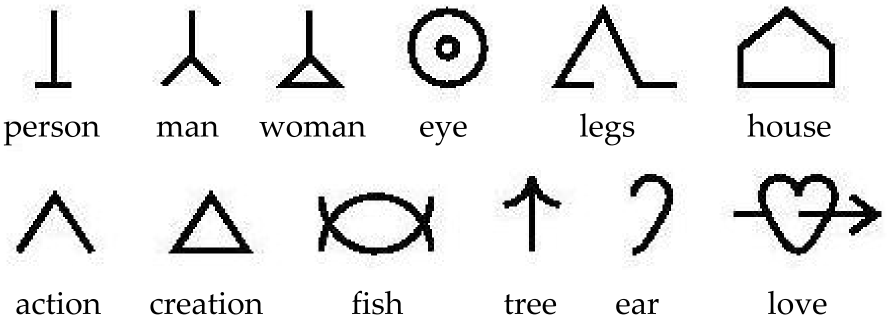


Figure 20. Several examples of Bliss symbols [Helmer, 1980].

The system requires a lot of creativity to interpret the sentences. However, several studies [Muter and Johns, 1985; Brooks, 1977; Helmer, 1980] have shown that learning logographs like Blissymbols took less time and resulted in better recall than their alphabetic counterparts. In contrast to abstract shorthand tokens, graphic similarity to well-known (or well-detected) contour and symbolic images facilitates memorizing and interpretation of the proposed communication set.

People with a hearing deficit can employ lip-reading to support communication with people having normal hearing abilities. Those using this method should aim at language comprehension through articulatory movements of the lip, tongue and facial muscles of the speaker. Lip-reading can be very stressful for those people with grammatical disorders and aphasia. Some phonemes are indistinguishable because of the ambiguity of visual articulatory movements in combination with a large number of guttural or post-guttural articulatory movements that are only vaguely visible in the speaker's face [Bothe et al., 2004]. Bothe et al., argued that the articulation of phonemes such as /**p**/, /**b**/, or /**m**/ creates similar visual sensations yielding the same perception, and phonemes such as /**g**/, /**k**/ or /**h**/ do not significantly change the facial movements of a speaker at all. In addition, unpredictable words might not be properly understood. This makes the task of decoding mouth movements extremely difficult [Kilborn, 1993]. The small number of people who communicate using lip-reading mainly succeed by relying on guesswork while people who do not so, can interpret only 30% of the entire speech signal. Lip-reading is still expensive in terms of the cost of skilled sign language interpreters [Luyken, 1991].

The issue of qualified sign language interpreters has always been crucial for the deaf community. Some deaf individuals are not aware of the amount of information which many interpreters filter out, because they cannot interpret everything in group situations, for instance during cross-talk when people interrupt each other or/and talk using specific terms, which cannot be decoded by means of gestures using Sign Language [Kilborn, 1993; Luyken, 1991]. The interpreter has to spend time fingerspelling them and/or to explain the issue using a longer sequence of gestures. Some interpreters totally ignore this kind of information. Furthermore, the number of students with hearing impairments in the majority of universities essentially exceeds the number of interpreters and causes additional difficulties during studies [Zak, 1998].

Closed captioning provides a textual description of audible signals/cues that the television programmes use in a predetermined order at a preset speed. Textual subtitling does not include signing or the written translation of the spoken language (the source language) of a television programme or movie into the language of the viewing audience (the target language) [U.S. House of Representatives, 1990]. Nevertheless, the use of closed captioning does involve certain technical and typographic compromises regarding implementing typeface design used at translation process.

To present the best balance the space available for captions is up to 30% of the screen field. The text is displayed at less than 140 words per minute, that is, the speech dialogues should be essentially shortened [Luyken, 1991; Mercinelli, 2001]. The latter aggravates the phonological awareness and logical clarity of the speech semantics.

Typeface visibility should also be considered. Recent captions consist of light characters on a solid black background, quite the opposite of what readers are used to. Captioners are virtually forced to caption in upper case because the letters **j**, **q**, **y**, **p**, and **g** in lower case captioning fonts do not have descenders [Mercinelli, 2001]. In this way, closed captioning contradicts a basic principle of text design, that is, the use of dark-on-light type in upper and lower case for extended text. The problem of imaging typefaces in the format which should be available to deaf viewers should be considered too. For instance, one of the common approaches is to use a semitransparent background and contrast the edges of the characters only. This does not affect the subtitling typeface and increases readability though it may lead to some loss of visual contrast of the text. Another way is to stretch the picture; this might involve stretching the subtitling typeface, which would improve legibility [Zak, 1998].

Some of deaf viewers prefer to improve their access to digital television content and watch signed television programme where sign-language interpreters are involved to translate the speaking part of the programme. The picture of the interpreter is usually shown in a corner of the screen. The usage of signing for profoundly deaf people is expensive in terms of the cost of skilled signers and the sign-duplication of television programmes [Luyken, 1991]. In addition, some of the signing-specific aspects such as sign language and the visibility of the oral components of signs should be improved. Feedback from deaf viewers indicates that there is a high level of translation difficulty in signing readability across all types of programs. People read and assimilate information at different speeds and there are particular problems in relation to children because of both their age, reading proficiency and the degree of deafness [Mercinelli, 2001].

Another option for the persons with residual hearing who do not use cochlear implants, is to employ wearable tactile aids which convert sound into vibro-tactile cues. Both lipreading and vibro-tactile cues could be useful for practicing oral skills. Recent wearable tactile aids convert sound into vibro-tactile sensations and use electro-mechanical transducers that can be attached to the chest, shoulder, finger or built into the belt in order to provide hearing-impaired users with information displayed via vibro-tactile signals and composite patterns having different structure, rhythm, duration and intensity [Bothe et al., 2004]. These aids are preferable to conventional hearing aids in that they can surely serve as a reliable perceptive substitute for some part of spoken information which is otherwise inaccessible. However, due to the lack of signal transfer onto the skin surface and the difficulties in interpreting composite patterns, users with hearing impairments experience substantial difficulties when employing wearable vibro-tactile devices. Therefore, vibrating aids present a rich ground for further elaboration.

As can be seen from this section, there is a wide range of AT designed for those who have hearing disorders. Because not all of these techniques suggest facility in use regarding gaining access to textual information, it is important to continue the improvement of the existing methods. Signals and patterns used to display the information content should not only be properly recognizable and distinguishable but also have to be coded in an explicitly strict and compact way in order to avoid cognitive overload of the user. To enhance access to communication with ordinary individuals deaf and hard-of-hearing people use videophones, which are discussed in the next section.

3.2. Videotelephony

Videotelephony can be considered as possible non-verbal communication between the hearing and hearing impaired, profoundly/totally deaf persons. In this case, the conversation is supported by sign language or with the help of a qualified interpreter. A videophone has a built-in camera and a screen. Along with voice transmission, such a phone can send and receive a video image (Figure 21) [Hyper-dictionary, Web Site].

Figure 21. A general view of the videophone [Toolsonline Ltd, Web Site; Videophones].

Videophones for home use are accessible in a wide array of prices and sizes [Toolsonline Ltd. Videophones, DDTP]. The types nowadays available fall into two categories: stand-alone videophones making use of a digital telephone line, videophone simulation on a desktop/laptop PC and employing a web camera in mobile devices such as a PDA (and Wrist PDA), and smartphones with embedded cameras. An intermediate range of videophones operates over Integrated Services Digital Network, providing better quality of the video output, high data rate e.g., 512 kbps using modem (wireless local-area network allows speed up transmission beyond 54 Mbps), and costing nearly 1000 euros [RNIB, Web site]. Many private organizations provide deaf and hard-of-hearing people with a video telecommunication service. For example, The Finnish Association of Deaf People [DeafTech, Web Site] provides hearing-impaired Finns with videophones supporting Finnish sign language communication. This community is currently about to launch a videophone-based service which will include remote sign language interpretation.

On the one hand, the hearing impaired users can benefit from the use of a videophone. Text-based imaging takes more time than signed conversation via videophone. Deaf people who have gone deaf in youth use only sign language as their preferred communication medium. The use of text telephony may cause some difficulties for them. On the other hand, many elderly people rely only on the lip-reading method during non-verbal communication.

Unlike textphones, a videophone does not require the use of written English. However, the quality of video output still depends heavily on connection speed and price, including the service charge. Cheaper videophones provide interpretation support for signing, but the quality of the video output is not good enough to be lip-read. The time lag between the video signal and the imaging of the signed information is still long; therefore the spontaneity in the communication may significantly impair the video quality [RNIB, Web Site]. The information received by videophone could possibly be repeated before the image is properly recognized. The quality of video communication also depends on how the speaker's face is lighted [DDTP]. The video output is greatly impaired if the speaker face has even a little shadow. Furthermore, not all videophones are firmware upgradeable and some of them require the use of the same software for interpersonal communication [DeafTech, Web Site].

3.3. Summary

The ability to acquire communication skills and to gain access to spoken textual information is important for users with hearing impairments. Numerous attempts were undertaken to improve verbal communication with ordinary individuals and to provide efficient access to the mass media. Technological advances in the development of hearing aids and amplification systems has led to the reduction of sound distortion concern and improved service facilities (extending battery life, automatic and accurate personal tuning) of the hearing aid devices. Videotelephony services for hearing impaired people have become more sensitive to the special needs of the user, ensuring qualified interpretation support and fairly good quality of video imaging. The appearance of small-sized and light-weight mobile phones, text messaging services has opened additional communication facilities for deaf and hard-of-hearing people.

This chapter consolidated some problematic aspects affecting the use of assistive approaches/aids, which are worth pointing out to developers regarding future improvements in information imaging strategies from the perspective of the ways in which hearing-impaired users communicate, acquire and comprehend information. The present technology lacks alternative medium/distinctive communication language to provide deaf or hard-of-hearing users with efficient information imaging, therefore it is not powerful enough yet to be used in full measure. It is possible that in the near future incorporation of non-visual tactile feedback into non-verbal interaction between hearing impaired and ordinary individuals could enhance the communication medium for people with a sensory impairment. The shortcomings in the recent assistive methods can be overcome only when appropriate strategies are addressed in information imaging and vocational training is carefully considered in order to adapt assistive technology to personal needs.

4. ASSISTIVE AIDS FOR PEOPLE WITH SENSORY IMPAIRMENT: SUMMARY OF RESEARCH PAPERS

This chapter gives a summary of the eight research papers which represent the main scientific contribution of the dissertation. Careful combination of the constructive research, an experimental evaluation and further analysis of the outcomes in which the developed approaches resulted, was the key principle for the exploration done in these studies.

Four ways to display textual information for people with a sensory impairment were investigated. They are:

1) Dynamic and/or quasi-static imaging of the symbolic information (Paper I);
2) Diffuse color blinking imaging of the textual information and the data described by a long alphabet or music notation (Papers II, III, IV, V);
3) Pseudo-graphic imaging of the textual information (Papers VI and VII);
4) Vibro-tactile alphabet (Paper VIII).

Two prototypes of the wearable assistive devices such as BlinkGlasses and TactilePointer as well as a set of software prototypes were constructed to carry out empirical research in these subjects and examine which of the interaction scenarios developed could be introduced to compensate the sensory deficit.

Series of extensive empirical and usability studies were performed to evaluate the strength, usefulness and appropriateness of implemented assistive aids. The research approaches and results are explained in detail in the papers.

4.1. Paper I: Alternative Textured Display

The Alternative textured tactile element (TTE) has been implemented to generate a greater number of easily recognizable states of the display surface making use of a minimal number of discrete components in order to provide a blind computer user with dynamic and/or quasi-static imaging symbolic information. The TTE implemented was oriented to the separate stimulation of the functionally specific tactile receptors of touch, pressure and temperature. The proposed TTE could be integrated into the lines or matrices of the tactile display, which could be then built into input devices such as keyboard, mouse and joystick and wearable widgets, mobile phones, PDAs etc.

The main elements of the display surface are spring coils, which have cylindrical form and shape the texton with controlled parameters. The active display area of the prototype implemented was 15mm x 5mm. The quality of the perceived surface depends on the density of the spring's coils (i.e., the thickness of the wire used, the diameter of the spring's coils and the distance between each coil). The number of possible display states can vary from 9 (if frequency f = 5Hz, temperature t° = +20°C) up to 57 (if frequency f = 5, 10, 20Hz, temperature t° = +20°C, +30°C, +40°C) and is determined by the density of the tactile elements shaping a display surface, which can be controlled by stretching or compressing the spring with the help of two electromagnets.

The Alternative textured tactile element was originally Grigori Evreinov's idea. The author's contribution included technical calculation, developing a prototype of the alternative textured element and writing the paper in close cooperation with Grigori Evreinov. Ben Challis and John Hankinson were responsible for supervising the language of the paper.

4.2. Paper II: Color-Blinking Code and Low Cost Peripheral Monitor for People Who are Deaf or Have Low Vision

In this paper an alternative way is introduced of how to provide the profoundly deaf and persons having visual impairment varied in its severity with real-time imaging of textual messages by means of visual color patterns. The prototype of the peripheral monitor called BlinkGlasses was developed to display visual color patterns through a single two-color light emitting diode (LED), which was coupled with the eyeglasses and located close to an eye in paracentral unfocused position. Thus, this assistive aid does not require recognizing a precise form of the characters to be displayed.

Morse code and the Phonetic Alphabet were taken as the analogues of the brightness modulation coded over a time while implementing a variant of the compressed light code for imaging the English alphabet. According to the results of the empirical evaluation of the proposed approach, such a method can be sub-cognitively perceived likewise Morse code. The use of the proposed aid may result in achieving greater dynamic perception characteristics of the signals than monochrome Morse code with further practice.

Designing of the peripheral monitor is only the first step to introduce a way to implement inexpensive wearable communication devices for people with sensory deficiency. These devices do not demand the use of any visual acuity for the perception of the textual information.

The proposed method can be used with mobile devices (phones or PDAs). It is possible that such a way of textual imaging would be informative enough for deaf people and easier to perceive than subtitling or sign language. For instance, Nokia, a well-known mobile phone producer, already manufactured model Nokia 3220 which is able to produce so-called "light" messages making use of 12 LEDs mounted on the back of the mobile phone. A motion sensor in the phone makes the lights blink in a sequence that spells out letters when the handset is waved in the air (Figure 22). The user of such a phone can write "light" messages having a length of only 15 characters at maximum [for more detail see Nokia's www-pages, http://www.nokia.com/].

It is also very likely that in the near future dynamic lighting signals could be efficiently used to get visually impaired people better oriented in the outside environment. Akita et al. [2004] implemented a dynamic lighting sign (DLS) coding system employing the lighting units with two-colored LEDs and providing the user with a line of lights, which would serve as awareness cues to direct the user's moves in a certain way. Color and duration for each lighting pattern can be managed by the special controller or directly via RS232C serial port using DTR and RTS output signals.

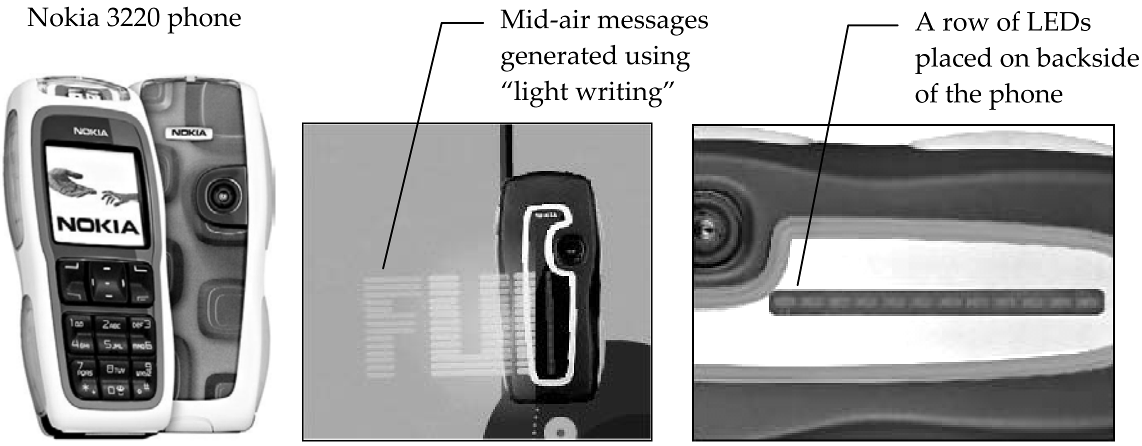


Figure 22. Generating light messages using a row of LEDs placed on back of the Nokia 3220 phone.

The proposed approach was estimated in [Akita et al., 2004] with subjects having normal vision in terms of the light-flashing time of the blinking stimuli, spatial interval between stimuli during dynamic imaging, color and intensity of the lighting patterns. According to the experimenter's observations, a delay of

25 ms between blinks' onsets improved the readability of the dynamic blinking imaging. The red color of the lighting pattern was defined as best recognizable along with green color in a chain of lights, where the color intensity had eight levels. Though the efficiency of the DLS system as awareness cues for the navigation of visually impaired users over the outside environment has not still been explored thoroughly, the authors suggest that subjects coped well enough with recognition of the pathway lights to properly move in a certain direction.

The paper was written in close cooperation between myself and Grigori Evreinov and includes contributions from both authors. Roope Raisamo supervised the technical soundness, organization and the language of the paper.

4.3. Paper III: A Wearable Monitor of Music Notation for Visually Impaired Musicians

In this paper we continue to explore an idea of diffuse color blinking imaging. This method may have other important implications in information visualization. In particular, easily recognizable spatial-temporal composite patterns could be employed to assign music notation symbols for visually impaired musicians and equation symbols for visually impaired mathematicians.

An assistive approach for imaging music notation making use of the wearable peripheral monitor was developed. Music tokens were displayed with the help of four LEDs, which were coupled with the eyeglasses. Software emulation of the peripheral display, the development and pilot testing of recognition of the spatial-temporal patterns consisting of eight light units with three gradations of brightness and three colors were performed. The light units within the composite patterns were not separated by time delay.

The results obtained showed that the semantic groups of the symbols and associated indicators reduce cognitive load based on complementary strategy and support an associative perception of the music symbols coded by means of diffuse color blinks. The method of symbolic coding of the graphic information with a large length of the alphabet (music notation) requires minimal resources of visual perception and can be used for designing an inexpensive wearable monitor for visually impaired musicians.

The study was conducted by the author under the supervision of Roope Raisamo.

4.4. Paper IV: The Text Entry Self-Training System with Color Blinking Imaging

The aim of this work was to facilitate learning of the visually impaired persons to type on a conventional keyboard by employing a multi-sensory approach to learning typing i.e., combining kinesthetic and visual modalities during text entry. Every character entered was augmented with the diffuse color blinks provided through a single 2-color light emitting diode coupled to eyeglasses, and speech feedback cues used as an audible analogue for imaging each character within test sentences and whole phrases or commands. The testing was conducted using a modified variant of the color blinking code introduced in Paper II.

The approach implemented resulted in a significantly great text entry rate of about 17 wpm with an error rate of only 1.07 % under 8 hours of practice with the use of visual and audible feedback. As reported in the study, the proposed multimodal approach for text entry would promote learning the conventional keyboard and increase the blind typing accuracy. The method could be applied in the development of various educational applications for visually impaired children and adults.

Like Paper II, this paper was also written in close cooperation between myself and Grigori Evreinov, and includes contributions from both authors. Roope Raisamo supervised the arranging of the usability studies and the language of the paper.

4.5. Paper V: The Text Input Training System through Touch Screen and Color Blinking Imaging for People with Low Vision

This research was aimed at facilitating access to software applications over touchscreen for visually impaired computer users. Another goal of this study was to improve interaction technique making use of an accessible virtual keyboard augmented by diffuse visual and audible cues.

To provide 15 clearly detectable positions on the touchscreen, corresponding to the software buttons of the virtual keyboard, the tactile pointer of 110×40 sq. mm was implemented with a transparency film. The universal embossed tactile pattern shaped with thin copper wire and special “three-finger navigation” technique were designed. Ten positions of the tactile layout were intended for input of the English alphabet characters, one position was used to switch letter case (lower/upper) and two keys provided the space character. The tactile pointer has a minimal number of easily recognizable tactile markers (angles and lines) and does not impede the normal use of the touch screen.

To evaluate efficiency in the use of the implemented tactile layout, the testing software was developed. Diffuse color blinks were provided through a single 2-color light emitting diode coupled with eyeglasses and described in Paper II.

Audible and visual cues accompanied the entering of each character. The approach implemented resulted in a fast text entry rate of about 15 wpm with an error rate of only 1.17 % under 5 hours of practice with the use of the visual and audible feedback. The experimental results indicated that during blind typing manipulations on the virtual keyboard tactile feedback received using special textured pattern i.e. tactile pointer makes it possible to strengthen touchscreen navigation and typing on a virtual keyboard using residual visual resources reduces a period for tutoring. Using a peripheral monitor and color blinking alphabet helps to access the textual information.

Grigori Evreinov constructed the prototype of the Tactile Pointer. The author's contribution included implementing software and method development for the usability studies as well as arranging studies, analyzing the results obtained and writing the paper under the supervision of Roope Raisamo.

4.6. Paper VI: Pseudo-Graphic Typeface: Design and Evaluation

This paper introduces pseudo-graphic typeface, which could improve visibility and readability in dynamic forms of textual imaging for people with hearing disorders. For that purpose, the pseudo-graphic typeface was implemented. The typeface consists of 26 pseudo-graphic tokens that are very similar to standard typeface and could be perceived fairly preattentively by relying on previous user experience. The particular emphasis in this case was on strengthening the phonological awareness and logical clarity of the language transfer in subtitling within a digital television environment.

Several series of empirical tests were conducted to estimate the visibility of the typeface implemented in comparison with five conventional phonetic typefaces currently used for subtitling. The objective assessment of the visibility of the tested typefaces was carried out making use of eye-tracking technique. The eye movements on pseudo-graphic and syllabic tokens as well as number of areas of visual interest (AVI)[7] were recorded, and visual scan time was measured during tachistoscopic exposition of different pseudo-graphic tokens in comparison to that of the conventional syllabic tokens[8]. Phonetic typefaces resulted in a higher number of AVI, 5 – 7 and pseudo-graphic typeface resulted in a lower number of AVI that is only 4. These results demonstrated that the pseudo-graphic typeface was perceived more easily and seemed to be more legible than phonetic typefaces. The number of visual fixations was measured for each of the typefaces explored. The pattern of our results showed that pseudo-graphic typeface required a lower number of visual fixations, only 14, to perceive than conventional typefaces, which required a greater number of visual fixations to perceive, about 17 – 21. When we examined the visual scan time of selected typefaces, we found that the pseudo-graphic typeface exhibited a smaller visual scan time of only 1523 ms compared to conventional typefaces, which required 1434 – 1698 ms to perceive.

Pseudo-graphic typeface is Grigori Evreinov's original idea. Oleg Spakov was responsible for developing the software for the usability studies and post-test interviews with participants, which were arranged and conducted by the author. The author also analyzed the results obtained and wrote the paper.

4.7. Paper VII: Hearing Communication Aid Based on Pseudo-Graphic Typeface

This work continues to explore possible applications for the idea introduced in Paper VI. The purpose of the previous research was to improve visibility and readability in dynamical forms of textual imaging (that is, phonetic typefaces, which are currently used for subtitling) for people with hearing disorders. The goal of the new study was to examine the degree of reading comprehension of the textual passages composed of the pseudo-graphic symbols. To simulate a viewing field similar to the subtitling angular location of the subtitle line, the graphic field of imaging pseudo-graphic symbols was located in the peripheral

---

[7] A number of areas of visual interest (AVI) are defined as the areas where the most densely packed points of visual fixation are grouped.

[8] Tachistocopic presentation of visual stimuli means that the stimuli should be exposed in the same place for extremely short periods of time using the limits of unconscious visual perception to define how easily or with how much difficulty the stimuli presented might be preattentively perceived by a subject.

position of the screen. Therefore, the textual passages were projected onto the paracentral field of the retina.

In the present study, the subjects were asked to learn the pseudo-graphic typeface prior to testing. The reading comprehension score of the textual passages composed of pseudo-graphic symbols was measured by the number of repeated playbacks needed to recognize the exposed passage. The comprehension accuracy gained at tested exposition times (95%) and overall user-perceived performances suggest a facility in reading typeface. It is possible that the proposed pseudo-graphic typeface might bring some benefits in dynamically displayed textual messages (see "lighting writing", Paper II) and strengthening awareness in small-screen devices.

This paper was written in close cooperation between myself and Roope Raisamo and includes contributions from both authors.

4.8. Paper VIII: Alternative Approach to Strengthening Tactile Memory for Sensory Disabled People

A number of studies in vibro-tactile pattern perception provided strong evidence that tactile memory is a crucial factor in coding and imaging semantic information for hearing impaired people. It was also hypothesized that frequent use of the intact senses such as touch and haptics might affect further development of the people with hearing deficit. The limitations of the human touch mostly depend on the contact provided between a vibration source and the skin of the user, on spatial-temporal mapping and parameters of the output signals that imaging techniques address.

In the present study, a special gameplay training methodology was introduced to facilitate learning and manipulating of a set of 27 composite vibro-tactile patterns (tactons). The patterns were composed of one, two and three serial bursts and called as mono-frequency, bi-frequency and three-frequency tactons displayed with the Logitech tactile feedback mouse. Tactons were shaped employing rectangular pulses of the current with a maximal magnitude. Five vibration frequencies were used to form the bursts which comprise the vibro-tactile composite patterns. They were 0, 9, 111, 250 and 333 Hz.

The matching game was designed to make the tactons a key of the game intrigue. It was hypothesized that the particular framework and the game intrigue would induce players to mobilize the perceptive skills and deploy individual gameplay tactics to memorize the tactons when progressing through the game. The game was evaluated with the ten test subjects using soundproof headphones. The performance of the subjects was investigated in terms of the number of repetitions required to memorize the tactons, and selection time needed to match the tactons with the sample. The analysis of the data collected indicated that the subjects showed good potential to play and manipulate by tactons and the novice-to-expert transition was significantly above chance when the results obtained in the first and the last test sessions were statistically assessed and compared ($F_{2,40} = 32.28$ for mono-frequency tactons; $F_{13,29} = 9.52$ for bi-frequency tactons; $F_{9,33} = 3.65$ for three-frequency tactons; $p < 0.001$). The particular gameplay tactics chosen by the players to progress through the matching game significantly affected their tactile performance. In particular, the players attempted to remember the tactons not as whole patterns but by recalling how many bursts they consisted of.

The simple game script and the set of vibro-tactile composite patterns designed constitute a novel approach to strengthening the short-term tactile memory of the hearing impaired adults in a simple way. The next stage of the research will imply an exploration of the efficiency in the use of improved vibro-tactile composite patterns as an alternative medium of non-verbal communication signals which might be employed to assign alphabet characters (words or abbreviations) or symbols to convey textual or symbolic information to deaf and hearing-impaired people. The solution will be based on the results of the careful investigation and assessment of the human cognitive abilities involved in the perception and comprehension of the long semantic sequences composed of the vibro-tactile patterns.

A set of 27 vibro-tactile composite patterns was designed by the author. The author also proposed to apply a method of sequential learning based on the game script which had earlier been implemented by Grigori Evreinov. The author was responsible for arranging usability studies and post-test interviews with participants as well as for analyzing the results and writing the paper. Roope Raisamo supervised the technical soundness, organization and language of the paper.

4.9. Summary

The eight research papers which constitute the main part of the dissertation were introduced in this chapter. Taken altogether, these papers raise a very important question: *how to synthesize an optimal method for proper information imaging to user with perception deficit in such a way that the modality-specific spatial-*

temporal patterns and semantic constructions used for imaging textual content could not demand greater mental/cognitive resources from the user to recognize it when the environment has different constraints. Apparently, more thorough exploration and longitudinal involving of the impaired persons in research studies on this subject is needed to further define the functionality and improve usability parameters of the implemented scenarios for the textual imaging. It is necessary to investigate how to combine the intact and residual modalities in order to augment and facilitate the perception and comprehension of the "hidden" content and semantics for the sensory impaired users to the maximum extent.

There are some problematic issues that have to be addressed in the future work. One of these is that the amount of thermal levels produced by a TTE discussed in the Paper I and being recognizable well enough, is limited to only three, that is when t° = +20°C, +30°C, +40°C. This fact results in significant delay of the dynamic imaging of the explored surface structure to the blind user. In the future, the improvement of the thermal characteristics of a TTE will need to be done by means of additional ventilation of the heated element.

As similarly reported in Papers II, III, IV and V, the test subjects showed a high error rate when recognizing color blinking characters alone in the case of textual passage or music notation coded with color blinks and during text entry accompanied with diffuse color feedback. One of the possibilities to decrease error rate and consequently decrease cognitive load when recognizing color blinking code, could be to develop a color blinking code with alternative/adaptive exposition duration of the light units within the composite pattern.

The main problematic concern in reading of the pseudo-graphic typeface discussed in Papers VI and VII was that the subjects experienced some difficulties in perceiving pre-attentively the changing of the pseudo-graphic tokens when they were dynamically displayed in the same place. In order to obviate these difficulties, retinal stabilization of the dynamically displayed pseudo-graphic tokens will need to be done by means of smoothing the strong influence of the negative afterimage[9] received after gazing at a previous pseudo-graphic token onto the visual perception of the follow-up pseudo-graphic token. This issue can be resolved through exposing complementary pseudo-graphic tokens on the span between previous and follow-up tokens.

---

[9] Negative afterimage is a sensation which occurs after fixating eyes on stimuli presented for less than a few seconds.

These complementary tokens will have to be identical to previously exposed tokens and should have brightness and color needed to compensate the negative afterimage similar to the background on which the token is exposed.

Certain conclusions can be drawn from the study on the exploration of the vibro-tactile composite patterns perception described in Paper VIII. The main problematic aspect in this research was that the subjects attempted to remember the tactons not as whole patterns but by recalling how many components they comprised. In the future, the strength of the components used to generate the vibro-tactile composite patterns will need to be better normalized regarding the differential perceptive threshold to contrast as much as possible those components and thus strengthen the clarity of the vibrations forming the whole tactile image of the composite pattern and avert further difficulties in its learning and recognition.

5. CONCLUSIONS

Assistive technology has been developed to provide access to information sources for people with sensory impairment. These people can benefit from the use of alternative methods/techniques widely available at present on the market with some producing output with fairly high accuracy. Nevertheless, the problem of synthesizing a suitable method for proper information imaging to the impaired user still remains unsolved. For this reason, display techniques undergo continuous experimentation and usability research in order to resolve this issue. At the stage of designing advanced transformation techniques, human cognitive abilities and pre-existing knowledge of the sensory impaired user must be thoroughly assessed and considered as they may facilitate or impede the learning of using a new technique.

This work provided an analytical survey of the currently existing assistive methods/techniques for imaging textual information that employ the residual senses of the impaired user. The problematic aspects affecting the use of computer help for people having ocular pathology and hearing disorders were the particular subject of our study and must be considered by the developers of advanced assistive user interfaces in order to appropriately improve existing information imaging strategies.

To present some samples of how augmenting and expanding access to textual information could possibly be achieved for people who cannot use conventional means, special methods and devices were designed and briefly introduced in the empirical part of the dissertation. Selected examples and approaches were considered to reproduce the cases of the recognizable modal-specific spatial-temporal patterns and semantic constructions such as color, audio-tactile and vibro-tactile presented through minimal array of the coding units used for information imaging. Eight empirical studies were presented here to illustrate which of the new interaction ideas could really be introduced and exploited by the person in a critical situation of sensory deficit. Careful combination of constructive research, empirical evaluation and further analysis of the outcomes in which the approaches developed resulted was the main principle for the completion of these empirical studies. In order to conduct the empirical research and to structure the observations and hypotheses, constructive research was carried out to implement special prototypes based on new ideas. The basic concepts, interaction techniques implemented and the practical consequences of the empirical studies were discussed as well as some improvements that were or could be applied to the techniques presented.

Improved usability of the assistive product makes users able to easily handle its use when they are about to access textual information. In order to comprehend the specific features of the textual information being visualized and manipulate acquired information as effectively as non-impaired users do, sensory impaired users need constant feedback, which could possibly come in the form of diffuse color patterns, tactile markers, speech and non-speech audio signals (earcons) or special haptic patterns (tactons). The required techniques should provide real time or close to real time processing and imaging of the textual information so that both ordinary users and people with a sensory impairment would be able to use it autonomously without assistance. At that, residual visual, tactile or hearing sense cannot be always considered as a separate modality to be used for information imaging. The major concern of the scientists should be to find the optimal combination of residual modalities so that possible limitations in comprehension of the textual information by the impaired user might be overcome. Once this issue is solved, the assistive aid may become a powerful instrument for both optimal visualization of the textual information and efficient encoding of its semantics.

REFERENCES

[AFB, Web Site] American Foundation for the Blind online. `[http://www.afb.org/]` (checked 03 Oct 2005)

[Akita et al., 2004] Akita, J., Ito K., Gyobu, I., Kimura, K., Mihara, A., Mizuno, R., Nakakoji, J., and Yanagihara, K. *Dynamic lighting sign system for way-finding by people with low vision.* In H.Murphy, K.Miesenberger, D. Burger (Eds.), Proceedings of the 9th International Conference on Computers Helping People with Special Needs. ICCHP 2004 Paris, France, 7-9 July 2004, LNCS Vol. 3118, Springer-Verlag Berlin Heidelberg 2004, pp. 450-453.

[ASPHI Web site] *The photo of the Optacon I device.* `[www.asphi.it/english/ ChiSiamo/Tappe.htm]` (checked 03 Oct 2005)

[Bach-y-Rita et al., 1969] Bach-y Rita, P., Collins, C. C., Sauders, F., White, B., and Scadden, L. (1969). *Vision substitution by tactile image projection. Nature,* 221:963-964, 1969.

[Bach-y-Rita and Kaczmarek, 1969] Bach-y-Rita, P., and Kaczmarek, K. *Tongue placed tactile output device.* US Patent 6,430,450, 8/6/02.

[Bach-y-Rita, 1972] Bach-Y-Rita, P. *Brain Mechanisms in Sensory Substitution.* Academic Press, NewYork-London, 1972.

[Ballieu, 2000] Ballieu L. C. *The Importance of Information Technology for Visually Impaired Children and Youngsters and the Expectations for Future Development.* `[http://www.sensus.dk/ICEVI2000.htm]` (checked 03 Oct 2005)

[Beddoes et al., 1961] Beddoes, M.P., Belyea, E., Gibson, W. C. *A reading machine for the blind.* Nature. 1961 June 3; 190: 874-5.

[Bergman and Johnson, 1995] Bergman, E., and Johnson, E. (1995). *Towards accessible human-computer interaction.* In J. Nielsen (Ed.), Advances in human-computer interaction, Volume 5. Norwood, NJ: Ablex Publishing.

[Blattner et al., 1989] Blattner, M., Sumikawa, D., and Greenberg, R. (1989). *Earcons and icons: Their structure and common design principles.* Human Computer Interaction, 4(1), 11-44.

[Bliss, 1961] Bliss, JC (1961) *Communication via the kinesthetic and tactile senses.* Ph.D. Dissertation, EECS, M.I.T.

[Bolanowski et al., 1988] Bolanowski, S.J., Gescheider G.A., Verrillo R.T., and Checkosky C.M. (1988). *Four Channels Mediate the Mechanical Aspects of Touch.* Journal of the Acoustical Society of America, 84(5), 1680-1694.

[Bothe et al., 2004] Bothe, H. H., Mohamad, A. F., and Jensen, M. R. FLIIPPS: *Fingertip stimulation for improved speechreading.* K. Miezenberger et al. (Eds.): ICCHP2004, LNCS 3118, pp. 1152-1159, 2004. © Springer-Verlag Berlin Heilderberg 2004.

[Boyd et al., 1990] Boyd, L. H., Boyd, W. L., Vanderheiden, G. C. (1990). *The Graphical User Interface: Crisis, Danger, and Opportunity.* Journal of Visual Impairment & Blindness, Dec. 1990, vol. 84, no. 10, pp. 496-502.

[Boys Town National Research Hospital, Web Site] Boys Town National Research Hospital Web site. *Hearing and amplification. Hearing aid choices.* `[http://www.babyhearing.org/]` (checked 03 Oct 2005)

[Brewster and Brown, 2004] Brewster, S. and Brown, L.M. *Tactons: Structured Tactile Messages for Non-Visual Information Display.* In Proc. Fifth Australasian User Interface Conference (AUIC2004), Dunedin, New Zealand. CRPIT, 28. Cockburn, A., Ed. ACS. 15-23.

[British Deaf Association, Web Site] British Deaf Association. *Videophones for deaf people.* `[http://www.britishdeafassociation.org.uk/]` (checked 03 Oct 2005)

[Brooks, 1977] Brooks, L., (1977). *Visual pattern in fluent word identification.* In A.S. Reber & D.L. Scarborough (Eds.), Toward a psychology of reading. New York: Erlbaum.

[Burdea et al., 1996] Burdea, G. Richardand P., Coiffet, P. *Multimodal Virtual Reality: Input/Output Devices, System Integration and Human Factors. International Journal of Human-Computer Interaction, Special Issue on Human-Virutal Environment Interaction,* invited article 8, No. 1, 5-24, 1996.

[Burgstahler, 2002] Burgstahler, S. (2002) *Working together: people with disabilities and computer technology.* `[http://www.washington.edu/doit/Brochures/Technology/wtcomp.html]` (checked 03 Oct 2005)

[Cavanaugh, 2002] Cavanaugh, T. *The Need for Assistive Technology in Educational Technology.* Educational Technology Review (ETR), Vol. 10, No. 1, 2002 `[http://www.aace.org/pubs/etr/cavanaugh.cfm]`(checked 03 Oct 2005)

[CforAT, Web Site] Official Web site of The Center for Accessible Technology (CforAT). *Talking programs for MAC.* `[http://www.cforat.org/articles/talking.html]` (checked 03 Oct 2005)

[Challman, 1978] Challman, B.E. *Variables influencing the identification of single Braille characters.* Unpublished master's thesis, University of Louisville, 1978.

[Cholewiak et al., 1993] Cholewiak, R. W, Sherrick, CE, and Collins, AA (1993) *Princeton Cutaneous Res. Proj. (No.62*). Princeton Univ.

[Cooper et al., 1984] Cooper, F. S., Gaitenby, J. H., and Nye, P. W. *Evolution of Reading machines for the Blind: Haskin's Laboratories' Research as Case History,* Journal of Rehabilitation Research and Development, Vol. 21, No. 1, pp. 51-87.

[Conway, 2001] Conway, C. M. (2001) *Tactile sequential learning: artifical learning by touch.* `[http://cnl.psych.cornell.edu/papers/cmc-ma-thesis.pdf]` (checked 03 Oct 2005)

[Cornelissen et al., 1991] Cornelissen, F.W., Kooijman, A.C., Dumbar, G., Van der Wildt, G., Nijland, R. *Illumination research as part of a visual assessment of visually impaired individuals.* Ophthalomologica 1991; 78:195–203.

[COST 219] COST 219, Olsen, K.G. (Ed.) et al. *Survey of text telephones and relay services in Europe.* Published by the European Commission. ISBN 92-826-4395-6, EUR 14242 EN, 1992.

[Cravotta, 2004] Cravotta, D.(2004) *Hot wired Braille reader.* `[http://www.wired.com/wired/archive/2.12/eword.html?pg=7]` (checked 03 Oct 2005)

[Culham et al., 1992] Culham, L. E., Fitzke, R. W., Timberlake, G. T., Marshall, J. *Use of scrolled text in a scanning laser ophthalmoscope to assess reading performance at different retinal locations.* Ophthalmic Physiol Opt 1992;12:281–6.

[Davidson, 1972] Davidson, M. *Louis Braille: The Boy Who Invented Books for the Blind.* New York: Hastings House, 1972.

[Dangerous Decibels] Dangerous Decibels. `[http://dangerousdecibels.org/]` (checked 03 Oct 2005)

[Darlington, 2000] Darlington, P. *Acoustic Shock from Terminal Equipment; An Investigation on Standards and Approval Documents.* Acoustic safety report. © European Telecommunications Standards Institute 2000. 55 pp.

[DDTP] The Deaf and Disabled Telecommunication Program (DDTP). *Telecommunication equipment.* `[http://www.ddtp.org]` (checked 03 Oct 2005)

[DeafTech, Web Site] DeafTech. *Technological reviews of equipment for deaf.* `[http://www.deaftech.info/]` (checked 03 Oct 2005)

[Disabilities Act, 1998] Technology-Related Assistance for Individuals with Disabilities Act, 1988 (PL 100-407). Retrieved from the World Wide Web February 10, 2002: `[http://www.resna.org/taproject/library/laws/techact94.htm]` (checked 03 Oct 2005)

[Dolphin group, Web Site] *Computer equipment for the blind.* Speech synthesizers. `[http://www.dolphinuk.co.uk/]` (checked 03 Oct 2005)

[Evreinov, 2003] Evreinov, G. (ed). *Proceedings of "New Interaction Techniques 2003",* Dept. of Computer and Information Sciences, University of Tampere, Report B-2003-5, June 2003, ISBN 951-44-5713-7, ISSN 1457-2079, 64 pp. `[http://www.cs.uta.fi/~grse/NIT_2003/Report_NIT2003.pdf]` (checked 03 Oct 2005)

[Fant, 1982] Fant, A., Jr. *Braille Writing in Pascal.* Byte. September 1982, 250-268.

[Fels and Degan, 2001] Fels, D.I., and Degan, S.S. (2001). *Expressing non-speech information and emotion to the deaf and hard of hearing.* CD-ROM Proceedings IEEE Systems, Man & Cybernetics. Tuscon. `[http://www.ryerson.ca/clt/publications/337.pdf]` (checked 03 Oct 2005)

[Fisher and Petrie, 2002] Fisher, W., and Petrie, H. (2002) *User requirements for technologies for personal communication and information use for deafblind people.* Proceedings of the 8th International Conference on Computers Helping People with Special Needs. ICCHP 2002 Linz, Austria, 15-20 July 2002, 583-584.

[Foulke, 1979] Foulke, E. *Investigative approaches to the study of Braille reading. Journal of Visual Impairment and Blindness* 73, 298-308. `[http://www.braille.org/papers/invea/invea.html]` (checked 03 Oct 2005)

[Foulke, 1991] Foulke, E. (1991) *Braille*. In The Psychology of Touch edited by Heller M. A. and Schiff W., 1991.

[Foulke, 1996] Foulke, E. *Tangible Graphic Displays. Tactile Graphics and Raised Representations*. (1996) 21 Jan. 2001.

[Fricke, 1991] Fricke, J. (1991) *A Tactile Graphic Computer Screen and Input Tablet for Blind Persons.* In *Proceedings of the First World Congress on Technology for Disabled Person*s, Washington, D.C.

[Fukumoto and Sugimura, 2001] Fukumoto, M. and Sugimura, T.: *Active Click: Tactile Feedback for Touch Panels.* In: Proc. CHI 2001, Interactive Posters, ACM (2001), pp. 121-122.

[Gappa and Mermet, 1997] Gappa, H. and Mermet, S. *Interface Adaptation in a Teleworking Environment for Disabled People.* ERCIM News No.28 - January 1997. `[www.ercim.org/publication/Ercim_News/enw28/gappa.html]` (checked 03 Oct 2005)

[Gault, 1927] Gault, R.H. *Hearing through the sense organs of touch and vibration.* Journal of the Franklin Institute, 204, 1927, 329-358.

[Gaver, 1997] Gaver, W. *Auditory Interfaces.* In M. Helander & T. Landauer & P. Prabhu (Eds.), Handbook of Human-Computer Interaction (2nd ed., 1003-1042). Amsterdam: Elsevier, 1997.

[Geldard and Sherrick, 1972] Geldard, F.A., and Sherrick, C. *The cutaneous rabbit: A perceptual illusion*. Science, 178, 1972, 178-179.

[Geldard, 1960] Geldard, F.A. *Some Neglected Possibilities of Communication.* Science, 131, 1960, 1583-1588.

[Gill, 1985] Gill, J.M. *New Moon.* British Journal of Visual Impairment, III (3), 1985, pp. 85-86.

[Gougoux et al., 2004] Gougoux, F., Lepore, F., Lassonde, M., Voss, P., Zatorre, R.J., and Belin P. *Pitch discrimination in the early blind.* Nature 430, 2004, 309.

[Guhl, 2002] Guhl, P. PLC & Associates. *Practicing The Art & Science of Eye Care.* `[http://www.contacts-vision.com/syntonic_vision_phototherapy.htm]` (checked 03 Oct 2005)

[Hadley, 1999] Hadley, D. A. (1999) *Alternative user interfaces.* `[http://eies.njit.edu/~turoff/coursenotes/CIS732/samplepro/dan.html]` (checked 03 Oct 2005)

[Hasser and Daniels, 1996] Hasser, C.J. and Daniels, M.W. *Tactile Feedback with Adaptive Controller for a Force-Reflecting Haptic Display. Part 2: Improvements and Evaluation.* In *Proc. 15th Southern Biomedical Engineering Conferenc*e, Dayton, OH, March, 29-31, 1996.

[Heller, 1987] Heller, M.A. *Haptic dominance in form perception with blurred vision.* Perception, 12, 1987, 607-613.

[Heller, 1987] Heller, M.A. *The effect of orientation on visual and tactual Braille recognition.* Perception, 16, 1987, 291-298.

[Helmer, 1980] Helmer, B. (1980). *Blissymbols for use.* Toronto: Blissymbolics Communication Institute.

[Hollander, 1994] Hollander, A., *An Exploration of Virtual Auditory Shape Perception.* Master's Thesis, University of Washington, Seattle (1994). `[http://www.hitl.washington.edu/publications/hollander]` (checked 03 Oct 2005)

[Hughes, 1979] Hughes, C.C. *A comparison of Braille and compressed speech as learning modes for legally blind adults.* Dissertation Abstracts International, 41(04A), 1979, 1532

[Hyperdictionary, Web Site] *The definition of the tactile sense.* `[http://www.hyperdictionary.com/dictionary/tactile+sensation]` (checked 03 Oct 2005)

[Ikei and Stiratori, 2002] Ikei Y., and Stiratori M. *TextureExplorer; A tactile and force display for virtual textures.* Proceedings of the 10th Symp. On Haptic Interfaces For Virtual Envir. & Teleoperator Systs. (HAPTICS.02) 0-7695-1489-8/02 $17.00 © 2002 IEEE

[Suthau et al., 2002] Suthau, T., Vetter, M., Hassenpflug, P., Meinzer, H. P., Hellwich, O. *A concept work for Augmented Reality visualisation based on a medical application in liver surgery.* ISPRS Commission V Symposium 2002, Close-Range Vision Techniques, Corfu, Greece. `[http://www.fpk.tu-berlin.de/forschung/AR/medizin_AR.phtml]` (checked 03 Oct 2005)

[Jacob, 1996] Jacob, R. J. K. *Human-Computer Interaction: Input Devices.* ACM Comput. Surv. 28(1), 177-179, 1996.

[Jungmann and Schlaak, 2002] Jungmann, M., and Schlaak, H. F. *Miniaturised Electrostatic Tactile Display with High Structural Compliance,* Proceedings of the Conference "Eurohaptics 2002", Edinburgh, U.K.

[Karjalainen et al., 1980] Karjalainen, M., Laine, U., Toivonen, R. Aids for the Handicapped Based on "SYNTE 2" Speech Synthesizer. *Proceedings of ICASSP 80* (3): 851-854, 1980.

[Kay, 1984] Kay, L. (1984) *Electronic aids for blind persons: an interdisciplinary subject.* In *IEE Proceedings,* Vol. 131, Pt. A, No. 7, Sept., 1984.

[Kelley and Gale, 1998] Kelley, P., and Gale, G. (1998). *Towards excellence: Effective education for students with vision impairments.* North Rocks, NSW: North Rocks Press.

[Kendrick, 2004] Kendrick, D. *How Do I Read Thee? A Librarian Expands the Ways.* In Access Issues, Vol. 5/Nr. 4, July 2004.

[Kilborn, 1993] Kilborn, R. *Speak my Language: Current Attitudes to Television Subtitling and Dubbing.* Media, Culture and Society (London), 1993.

[Kleweno et al., 2001] Kleweno, C. P., Seibel, E. J., Viirre, E. S., Kelly, J. P., PhD; Furness III T. A. *The virtual retinal display as a low-vision computer interface: A pilot study.* Journal of Rehabilitation Research and Development Vol. 38 No. 4, July/August 2001, 431–442.

[Kops and Gardner, 1996] Kops, C. E., and Gardner, E. P. (1996). *Discrimination of simulated texture patterns on the human hand*. J Neurophysiol, Aug 1996; 76: 1145 - 1165. [`www.uth.tmc.edu/apstracts/1996/jn/March/54n.html`] (checked 03 Oct 2005)

[Kramer et al., 1999] Kramer, G., Walker, Br., Bonebright, T., Cook, P., Flowers J., Miner N., Neuhoff J., Bargar R., Barrass St., Berger J., Evreinov G. et al. *Sonification Report: Status of the Field and Research Agenda.* Prepared for the National Science Foundation by members of the International Community for Auditory Display. Published by The Int. Community for Auditory Display , ISBN Number 0-9670904-0-7, March 6, 1999.

[Kurze, 1995] Kurze, M. (1995) *Giving Blind People Access to Graphics (Example: Business Graphics.* In: Proc. Software-Ergonomie '95 Workshop "Nicht-visuelle graphische Benutzungsoberflächen" ; Darmstadt 22.02.1995, 17 pages. [`http://page.mi.fu-erlin.de/~kurze/publications/se_95/swerg95.htm`] (checked 03 Oct 2005)

[Kutsch, 2003] Kutsch J. *Books on Tape Without the Tape.* In Access Issues, Vol. 4/ Nr. 1, January 2003.

[Lakatos, 1993] Lakatos, S. *Recognition of complex auditory-spatial patterns.* In Perception, 22(3), 363-374, 1993.

[Lazzaro, 1984] Lazzaro, J. *The Search for Speech.* Byte. December 1984, A48-A56.

[Lederman and Campbell, 1983] Lederman, Susan J. and Campbell, James I. *Tangible Line Graphics: An Evaluation and Some Systematic Strategies for*

Exploration. Journal of Visual Impairment and Blindness (March 1983): 108-12.

[Legge et al., 1989] Legge, G.E., Ross, J.A., Luebker, A. Psychophysics of reading VIII. *The Minnesota low-vision reading test.* Optom Vis Sci 1989; 66(12), pp. 843-53.

[Legge et al., 2000] Legge, G.E., Madison, C. and Mansfield, J.S. *Measuring Braille reading speed with the MNREAD test.* Visual Impairment Research, 2000.

[Lemmetty, 1999] Lemmetty, S. M. Sc. Thesis. (1999) *Review of speech synthesis technology.* `[http://www.acoustics.hut.fi/~slemmett/dippa/thesis.pdf]` (checked 03 Oct 2005)

[Leotta et al., 1988] Leotta, D.F., Rabinowitz, W.M., Reed, C.M., and Durlach, N.I. *Preliminary results of speech-reception tests obtained with the synthetic Tadoma system.* J. Rehab. Res. Devel., 25(4), 1988, 45Ð52.

[Levesque, 2002] Levesque, V. M.Sc. thesis, McGill University. (2002) *Measurement of Skin Deformation Using Fingerprint Feature Tracking.* (Chapter 2) `[http://www.cim.mcgill.ca/~vleves/homepage/master/]` (checked 03 Oct 2005)

[Lindecker, 1981] Lindecker, R.C. *A comparison of Braille and optacon reading comprehension in seven blind public school students.* Dissertation Abstracts International, 42(06A), 1981, 2613.

[Loomis, 1985] Loomis, J.M. *Tactile Recognition of Raised Characters: A Parametric Study.* Bulletin of the Psychonomic Society. Jan. Vol 23. No 12. , 1985, 18 - 20.

[Lorimer, 1996] Lorimer, P. Doctoral dissertation. (1996) *A critical evaluation of the historical development of the tactile modes of reading and an analysis and evaluation of researches carried out in endeavours to make the Braille code easier to read and write.*

[Luyken, 1991] Luyken, G. M. *Overcoming Language Barriers in Television: Dubbing and Subtitling for the European Audience.* Manchester: The European Institute for the Media, 1991.

[MacKenzie and Soukoreff, 2002] MacKenzie, I. S., and Soukoreff, R. W. Text entry for mobile computing: Models and methods, theory and practice. *Human-Computer Interaction*, *17*, 147-198, 2002.

[Maucher et al., 2001] Maucher, T., Meier, K., and Schemmel, J. *An interactive tactile graphics display.* In I. Kamisian M. Deriche, N. Shaikh-Husin, editor, The Sixth International Symposium on Signal Processing and its Applications (ISSAP2001), 2001.

[McCall, 1997] McCall, S. (1997). *The development of literacy through touch.* In H. Mason & S.

[Meijer, 1992] Meijer, P.B.L. *An Experimental System for Auditory Image Representations.* In IEEE Transactions on Biomedical Engineering, Vol. 39, No. 2, 112-121, Feb. 1992.

[Mercinelli, 2001] Mercinelli, M. (2001) *Guidelines-Accessibility requirements for new telecommunication equipment.* [http://www.stakes.fi/]

[Middleton, 1988] Middleton, J. (1988). *Moon, matches and microchips: A history of being blind in Brighton.* `[www.bsblind.co.uk/large/moon/mmmicro.htm]` (checked 03 Oct 2005)

[Muter and Johns, 1985] Muter, P., and Johns, E.E. *Learning logographies and alphabetic codes.* Human Learning (now Applied Cognitive Psychology), 4, 105-125, 1985.

[Nashel and Razzaque, 2003] Nashel, A. and Razzaque, S.: *Tactile Virtual Buttons for Mobile Devices.* CHI 2003, ACM (2003), 854-855.

[National Federation of the Blind, Web Site] National Federation of the Blind online. *Comparison of Braille to other mediums.* `[http://www.nfb.org/braille/chap2.htm]` (checked 03 Oct 2005)

[Neimark, 1970] Neimark, Anne E. *Touch of Light: The Story of Louis Braille.* New York: Harcourt, Brace & World, 1970.

[Neville and Schmidt, 1983] Neville, H. J., Schmidt, A., Kutas, M. *Altered visual-evoked potentials in congenitally deaf adults.* Brain Res 1983, 266:127-132.

[Neville and Lawson, 1987] Neville, H. J., and Lawson, D. *Attention to central and peripheral visual space in movement detection task: an event-related potential and behavioural study. II. Congenitally deaf adults.* Brain Res 1987, 405:268-283.

[Nolan and Kederis, 1969] Nolan, C.Y. and Kederis, C.J. *Perceptual factors in Braille word recognition.* New York: AFB.

[O'Hea, 1994] O'Hea, A.R. "Optophone Design", PhD Thesis, The Open University, UK.

[Omniglot, Web site] Omniglot Web site. *The image of the Moon type.* `[http://www.omniglot.com/writing/moon.htm]` (checked 03 Oct 2005)

[Perera, 2002] Perera, S. *Tactile Perception and Design.* Scientific report, April 2002. `[http://www.tiresias.org/reports/tpd1.htm]` (checked 03 Oct 2005)

[Perrott and Buell, 1982] Perrott, D. and Buell, T., *Judgements of sound volume: Effects of signal duration, level, and interaural characteristics on the perceived extensity of broadband noise. Journal Acoust. Soc. Am.*, vol. 72, no. 5, 1413-1417, 1982.

[Petrie et al., 1998] Petrie, H., Morley, S., McNally, P. and Graziani, P. *Authoring hypermedia systems for blind people.* `[http://phoenix.herts.ac.uk/SDRU/ACCESS/iee.html]` (checked 03 Oct 2005)

[Poupyrev et al., 2002] Poupyrev, I., Maruyama, S. and Rekimoto, J.: *Ambient Touch: Designing Tactile Interfaces for Handheld Devices.* In: Proc. UIST 2002, ACM (2002) 51-60.

[Pulkki, 2001] Pulkki, V., *Spatial Sound Generation and Perception by Amplitude Panning Techniques.* Report 62, ISSN 1456-6303, HUT, Espoo, Finland (2001).

[Rametta, Web Site] Rametta Audiology & Hearing Aid Center Web Site. *The revolutionary SONGBIRD digital disposable hearing aid.* `[http://ramettahearing.com/songbird.htm]` (checked 03 Oct 2005)

[Rash and Becher, 1982] Rash, C. E., and Becher, J. *Analysis of image smear in CRT displays due to scan rate and phosphor persistence*. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 83-5, 1982.

[Reed et al., 1992] Reed, C.M., Durlach, N.I., & Delhorne, L.A. *The tactual reception of speech, fingerspelling, and sign language by the deaf-blind. SID 92 Digest,* 102Ð105, 1992.

[RNIB, Web site] Royal National Institute of the Blind (RNIB). *Helpful facts on communicating with blind and partially sighted people.* `[http://www.rnib.org.uk/`] (checked 03 Oct 2005)

[RNIBa, Web site] Information resources for people working in the field of visual disabilities. *Braille cell dimensions.* [`http://www.tiresias.org/reports/braille_cell.htm`] (checked 03 Oct 2005)

[RNIBb, Web site] Information resources for people working in the field of visual disabilities. *Braille layout and dimensions.* [`http://dots.physics.orst.edu/gs_layout.html`] (checked 03 Oct 2005)

[RNIBc, Web site] Information resources for people working in the field of visual disabilities. *Table comparing prices and features of the Braille displays.* [`http://www.tiresias.org/equipment/eb7table.htm`] (checked 03 Oct 2005)

[RNIB, Case study, Web site] Royal National Institute of the Blind (RNIB). *Case study - an investigation into the potential of the embossed "dotted" Moon as production method for children using Moon as a route for literacy.* [`http://www.teachernet.gov.uk`] (checked 03 Oct 2005)

[Roberts et al., 2000] Roberts, J., Slattery, O., Kardos, D., and Swope, B. *New technology enables many-fold reduction in the cost of refreshable Braille displays.* Proceedings of the fourth international ACM conference on Assistive technologies, Arlington, Virginia, United States, 2000, 42-49.

[Roland-Mieszkowski and Clements, 1991] Roland-Mieszkowski, M. and Clements, S. D. *Digital Hearing Aids - the Way of the Future.* In proceedings from "Acoustic Week in Canada 1991", CAA Conference, Edmonton, Alberta, Canada, October 7 - 10, 1991. [`http://www.digital-recordings.com/publ/pubaids.html`] (checked 03 Oct 2005)

[Sadato et al., 1996] Sadato, N., Pascual-Leone, A., Grafman, J., Ibanez, V., Deiber, M. P., Dold, G., Hallett, M. *Activation of the primary visual cortex by Braille reading in blind subjects.* Nature 1996, 380: 526-528.

[Scherer, 2002] Scherer, M. (2002) *The Importance of Assistive Technology Outcomes.* [`http://e-bility.com/articles/at.shtml`] (checked 03 Oct 2005)

[Schneider, 1988] Schneider, W. 1988. *The Tactile Array Stimulator. John Hopkins APL Technical Diges*t, 9(1), 39-43.

[Shepherd, 2001] Shepherd, I. (2001) *Providing learning support for blind and visually impaired students undertaking fieldwork and related activities.* [`http://www.glos.ac.uk/gdn/disabil/blind/ch6_3.htm`] (checked 03 Oct 2005)

[Shimoga, 1993] Shimoga, K.B. *A Survey of Perceptual Feedback Issues in Dexterous Telemanipulation: Part II. Finger Touch Feedback.* In Proc. IEEE Annual Virtual Reality International Symposium, Seattle, Washington, Sept. 18-22, 1993, 271-279

[Shimojo and Shams, 2001] Shimojo, S., and Shams, L. *Sensory Modalities Are Not Separate Modalities: Plasticity and Interactions.* Current Opinion in Neurobiology 2001, 11: 505–509

[Snyder, 1994] Snyder, J. G. *Human-computer interface specifications for people with blindness.* Technical report CS 94-112 May 11, 1994. [`http://www.cs.colostate.edu/~ftppub/TechReports/1994/tr-112.pdf`] (checked 03 Oct 2005)

[Sonic Eye project Web site] *Sonic Eye project.* [`www.chaospark.com/inventions/sonic.htm`] (checked 03 Oct 2005)

[STAKES] National Research and Development Centre for Welfare and Health (STAKES). *The Promise of the Information Society. Good Practice in Using the Information Society for the Benefit of Older People and Disabled People. CASE 11. Good to See You. Signing, lip-reading and general communication by videophone.* [`http://www.stakes.fi/promise/book/pr11see.htm#see`] (checked 03 Oct 2005)

[Suan Hsi Yong homepage] Suan Hsi Yong homepage. *The image of the Braille type.* [`http://www.cs.wisc.edu/~suan/misc/braille.gif`] (checked 03 Oct 2005)

[Summers et al., 2001] Summers, I. R, Chanter, C. M., Southall, A. L and Brady, A. C. *Results from a Tactile Array on the Fingertip.* Biomedical Physics Group, University of Exeter, UK. [`http://www.mle.ie/~ian/EuroHapticsNet/2001/summers.pdf`] (checked 03 Oct 2005)

[Summers] Summers, I. *Tactile aids – an overview.* [`http://newton.ex.ac.uk/medphys/pages/isasb.html`] (checked 03 Oct 2005)

[Tabatabaei, 2002] Tabatabaei, M. *Information technology for protected individuals: A Survey of Current status.* Disability Studies, Spring 2002, Volume 22, No. 2, 159-174, 2002 `[http://www.afb.org/dsq/_articles_html/2002/Spring/]` (checked 03 Oct 2005)

[Tan and Rabinowitz, 1996] Tan, H. Z., and Rabinowitz, W. M. *A new multi-finger tactual display.* In *Proceedings of the ASME Dynamics Systems and Control Division*, ASME 1996, DSC-Vol. 58, 515-522.

[Tan et al., 1989] Tan H. Z., Rabinowitz W. M., and Durlach N. I., (1989) *Analysis of a synthetic Tadoma system as a multidimensional tactile display.* Journal of the Acoustical Society of America, Vol. 86, No. 3, 981-988, Sept. 1989.

[Tan et al., 1994.] Tan, H.Z., M.A. Srinivasan, B. Eberman, and B. Cheng. *Human Factors for the Design of Force-Reflecting Haptic Interfaces.* In DSC, Vol. 55-1, Dynamic Systems and Control: Vol. 1. 353-359, 1994.

[Tan, 1996] Tan H. Z. (1996). *Information Transmission with a Multi-Finger Tactual Display*. Ph.D. dissertation, Dept. of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 1996.

[Tan et al., 1997] Tan H. Z., Rabinowitz W. M., and Durlach N. I., Reed C. M., and Santos J. R. *Reception of Morse code through motional, vibrotactile and auditory stimulation.* Perception & Psychophysics, Vol. 59, No. 7, 1004-1017, 1997.

[Taub, 1999] Taub E. A. *The Blind Lead the Sighted Technology for People With Disabilities Finds a Broader Market.* Article from October 28, 1999, New York Times. `[http://www.jwen.com/rp/articles/blindsighted.html]` (checked 03 Oct 2005)

[Telesensory Corporation, Web site] Telesensory Corporation Web site. *The photo of the Optacon II device.* `[http://www.telesensory.com]` (checked 03 Oct 2005)

[The National Council for the Blind of Ireland, , Web Site] The National Council for the Blind of Ireland online. *Embossed communication.* `[http://www.ncbi.ie/library/embossed_communication.php]` (checked 03 Oct 2005)

[The New York Institute for Special Education, Web Site] The New York Institute for Special Education online. *Reading codes for the blind.* `[http://www.nyise.org/blind/gallmoon.htm]` (checked 03 Oct 2005)

[Tobin and Hill, 1989] Tobin, M. J., & Hill, E. W. *Harnessing the community: Moon script, the Moon-Writer and sighted volunteers.* The British Journal of Visual Impairment, VII (1), 3-5, 1989.

[Toolsonline Ltd. Videophones, Web Site] *Toolsonline Ltd. Videophones.* `[http://www.videophones.co.uk/]` (checked 03 Oct 2005)

[Turunen and Hakulinen, 2000] Turunen, M. and Hakulinen, J. Mailman - a Multilingual Speech-only E-mail Client based on an Adaptive Speech Application Framework. In *Proceedings of Workshop on Multi-Lingual Speech Communication (MSC 2000)*, 2000: 7-12. Also available: presentation.

[Turunen and Hakulinen, 2003] Turunen, M. and Hakulinen, J. Jaspis - An Architecture For Supporting Distributed Spoken Dialogues. In *Proceedings of the Eurospeech 2003: 1913-1916*.

[Turunen, 2004] Turunen, M., *Jaspis - an Adaptive Speech Application Architecture.* In *Proceedings of 7th IFHOH World Congress*, 2004, pages 51-57.

[U.S. House of Representatives, 1990] *Television Closed Captioning.* On H.R. 4267. U.S. House of Representatives, One Hundred First Congress, Second Session, May 1990.

[Veen and van Erp, 2001] Veen V. H. and van Erp, J. B. F. *Tactile information presentation in the cockpit.* In *Haptic Human-Computer Interaction (LNCS2058)*, Vol. 2058 (Eds., Brewster, S. A. and Murray-Smith, R.) Springer, Berlin, Germany, 174-181, 2001.

[VirTouch Ltd, Web Site] VirTouch Ltd online. *Tactile viewing of imagery: new possibilities.* `[http://www.virtouch.com/Tactile_Perception.htm]` (checked 03 Oct 2005)

[von Tetzchner, 1991] *COST 219 book: Issues in Telecommunications and Disability.* Edited by S von Tetzchner, published by the Commission of the European Communities, 1991, ISBN 92- 826-3128-1. Catalogue number CD-NA-13845-EB-C.

[Warren, 1994] Warren, D. H. *Blindness and Children: An Individual Differences Approach.* New York: Cambridge University Press, 1994.

[Watkins, 1987] Watkins, K.W. *Towards systematic education of the blind in Australia.* Unpublished doctoral dissertation, Macquarie University, Sydney, 1987.

[Webb et al., 1980] Webb, R.H., Hughes G.W., Pomerantzeff O. *Flying spot ophthalmoscope.* Applied Optics 1980;19:2991–7.

[Wenzel et al., 1993] Wenzel, E., Wightman, F., and Kistler, D. *Localization using non-individualized head-related transfer functions.* Journal of the Acoustical Society of America, 94(1), 111-123, 1993.

[Wilson and Rajan, 1999] Wilson, J.R., and Rajan, J.A. *Human Machine Interfaces for Systems Control.* In J.R. Wilson & E.N. Corlett. (Eds.). Evaluation of Human Work. Taylor and Francis. UK, 1999.

[Youngblut et al., 1996] Youngblut, C., Johnston, R. E., Nash, S. H., Wienclaw, R. A., Will, C. A. Institute for Defense Analyses (IDA), Paper P-3186 (1996). *Review of Virtual Environment Interface Technology. Haptic interfaces.* `[http://www.hitl.washington.edu/scivw/scivw-ftp/publications/IDA-pdf/HAPTIC1.PDF]` (checked 03 Oct 2005)

[Zigger and Barrett, 1927] Zigger, M.J., and Barrett, F. *A Further Contribution to the Tactual Perception of Form.* Journal of Experimental Psychology. Vol. 10. 184 – 192, 1927.

[Zak, 1998] Zak O. *Quality of Sign Language Interpreters.* (1998). `[http://www.zak.co.il/deaf-info/old/interp_quality.html]` (checked 03 Oct 2005)

[21st Century Hearing Ltd, Web Site] 21st Century Hearing Ltd online. *Digital hearing aids.* `[http://www.21stcenturyhearing.com/]` (checked 03 Oct 2005)

[Unitron Hearing, Web Site] Unitron Hearing online. *Digital products. Liaison^{tm}.* `[http://www.unitronhearing.com/site/pro/products/digital-liaison.html]` (checked 03 Oct 2005)

APPENDICES

Appendix I

Legibility threshold and recognition times for the alphabet characters in Braille code [Nolan and Kederis, 1969].

Print symbol	Dotted pattern	Legibility threshold, ms.	Recognition time, ms.	Print symbol	Dotted pattern	Legibility threshold, ms.	Recognition time, ms.
A	⠁	40	930	N	⠝	60	1130
B	⠃	40	1180	O	⠕	40	1020
C	⠉	40	1230	P	⠏	40	1070
D	⠙	40	1150	Q	⠟	18	1420
E	⠑	40	1200	R	⠗	60	1100
F	⠋	70	1100	S	⠎	60	990
G	⠛	50	1250	T	⠞	50	1380
H	⠓	60	1140	U	⠥	40	1090
I	⠊	40	1150	V	⠧	60	1220
J	⠚	50	1200	W	⠺	50	1220
K	⠅	40	1190	X	⠭	60	1090
L	⠇	60	970	Y	⠽	60	870
M	⠍	40	1020	Z	⠵	90	1150

Appendix II

Legibility threshold and recognition times for the digraphs and trigraphs in Braille code [Nolan and Kederis, 1969].

Print symbol	Dotted pattern	Legibility threshold, ms.	Recognition times, ms.
ch	⠡	40	1220
ow	⠪	70	1160
sh	⠩	40	1180
th	⠹	70	1220
wh	⠱	50	1260
of	⠷	16	1340
gh	⠣	60	1290
ed	⠫	50	1350
er	⠻	15	1390
ou	⠳	50	1560
the	⠮	80	1280
and	⠯	90	1140
for	⠿	19	1380
with	⠾	10	1430

● raised location in Braille cell

Appendix III

The dotted Moon characters identified as unacceptable or unsure by respondents (N=25) [RNIB, case study].

Dotted character	Unacceptable	Unsure
A	3	6
B	None	1
F	None	1
G	None	1
H	4	None
I	None	1
K	6	9
N	None	2
O	1	1
P	None	2
Q	None	1
U	1	1
V	2	1
X	7	8
Z	1	3

Appendix IV

Comparison of tactual displays with different actuation principles ("n.s." - not specified) [Jungmann and Schlaak, 2002].

Actuation principle	**Element number**	**Pin diameter, mm**	**Stimulator distance, mm**	**Max. displacement, mm**	**Force per pin, mN**	**Max. frequency, Hz**	**Advantages**	**Disadvantages**
Thermoelectric	64	0.1	n.s.	0.8	n.s.	1.3	Power-to-mass ratio	Heat dissipation problems limit relaxation rate of wires
	24	0.075	2.1	3	1000	10		
	16	0.1	2	6	1320	1		
Electromagnetic	9	n.s.	4.5	4	6	100	High temporal resolution relatively small size, does not obstruct normal movement ranges of the fingers	Low spatial resolution; limited scalability
	4096	n.s.	3	10	3000	n.s.		
Pneumatic	16	1.75	n.s.	5	3000	11	Low mass	Low efficiency during contraction
	25	1	2.5	0.6	180	5		
Piezoelectric	100	1	2	0.05	5	400	High spatial resolution	Low spatial and temporal frequency; limited bandwidth
	48	n.s.	2.45	0.7	150	n.s.		

Appendix V

Characteristics of the touch-based output techniques

[RNIBc; Snyder, 1994; Telesensory Corporation, Web site; Summers et al., 2001; Tan, 1996; Cravotta, 2004; Bach-y-Rita et al., 1969; Bach-y-Rita and Kaczmarek, 1969].

Output technique	Actuator type	Body surface involved in interaction	Output pattern	Active surface area	Weight, kg	Drawback
Braille display	Piezoelectric	Fingertips	Embossed pins	Cell: 6 pins, 2.5x5.0 mm^2 Line: 40 cells, 5x250 mm^2 Page: 121.9×279.4 mm^2	0.79	Very expensive software and hardware
Optacon	Piezoelectric	Fingertips, hand	Vibrating pins 230 Hz	Matrix: 5x20 pins, 12.7×25.4 mm^2	~2.2 (Device is not issued anymore)	Optical scan and tactile imaging were separated in space. Direct mapping is not adequate in such a case to rebuilt/integrate visual image prototype
Exeter Array	Piezoelectric	Fingertips	Vibrating pins (25 – 400 Hz)	100 pins, 10 × 20 mm^2	Experimental prototype	Low signal-noise ratio
TVSS	Piezoelectric	Thorax, abdomen, back	Vibratory	20x20 vibrators, 254 × 254 mm^2	~ 2.5 - 4	Low parameters of optical scan system Big weight
VTD	Piezoelectric or pneumatic	Fingertips	Vibratory, refresh rate 20Hz	48 pins, 16 × 43 mm^2	3.25	Kinesthetic feedback not coordinated to tactile imaging
TDU	Electrical	Tongue	Voltage pulses, magnitude	12x12 electrodes, 23.4×23.4 mm^2	Experimental prototype	Discomfort of exploitation Unnatural location and disturbance, tingling, pain