INTERACTIVE TACTILE REPRESENTATIONS TO SUPPORT DOCUMENT ACCESSIBILITY FOR PEOPLE WITH VISUAL IMPAIRMENTS

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ABSTRACT

Since the early beginnings of writing, humans have exploited text layout and format as primary means to facilitate reading access to a document. In contrast, it is the norm for visually impaired people to be provided with little to no information about the spatial layout of documents. Braille text, sonification, and Text-To-Speech (TTS) can provide access to digital documents, albeit in a linearized form. This means that structural information, namely a bird's-eye view, is mostly absent. For linear reading, this is a minor inconvenience that users can work around. However, spatial structures can be expected to strongly contribute to activities besides linear reading, such as document skimming, revising for a test, memorizing, understanding concepts, and comparing texts.

This lack of layout cues and structural information can provoke distinct types of reading hindrances. A reader with visual impairment may start reading multiple sidebar paragraphs before starting to read the main text without noticing, which is not optimal for reading a textbook. If readers want to revise a paragraph or access a certain element of the document, they must to go through each element on the page before reaching the targeted paragraph, due screen readers iterate through each paragraph linearly. This can be very frustrating and exhausting, especially in cases where it is required multiple times during a long study session. To identify different elements of a document through a screen reader is also challenging. For example the user would not be able to distinguish between the main text and a sidebar paragraph.

In the present dissertation, we portray in detail the research process where we investigated the access of digital textual contents by readers with visual impairments. Further, we define strength and flaws of this content pursuit process. Then, we aim to provide answers and solutions related to the design and usability of touch and auditory modalities to supply access to digital textual content to readers with visual impairments.

We describe the observations and conclusions related to point out different features and characteristics of the reading process based on auditory screen readers for readers with visual impairments. We studied existing skim-reading strategies in sighted and visually impaired individuals, we identified key features of visual documents that allow sighted users to adopt a highly flexible and goal-oriented approach to skim-reading, elements which are mostly lost when documents are accessed in auditory form, as is commonly the case for readers with visual impairments.

Through three different design stages, we envisioned, designed, and developed *Tactile sheets*, a system which conveys information about visual layout of digital textual documents. This system is based on differentiated tactile elements laid out on the surface of overlays; these overlays are placed on a touchscreen tablet, creating a tactile interface which enables the users to navigate through a document, recognize its layout, acquire implicit information related to the position and classification of different document elements like titles, paragraphs, tables or highlighted text, and access its content through auditory feedback. As a system's design iteration, we have introduced an automatic identification method which allows the user to update the digital content in relation to a concrete tactile overlay placed on the touchscreen device. This improved the usability of tactile overlays and granted an innovative level of interactivity and fluidity to the tactile pages interface system.

This solution was assessed conducting a set of studies with visually impaired participants who were requested to perform different tasks with our system and with auditory screen readers. The approach received positive quantitative and qualitative assessments and was preferred by most participants over the screen readers.

Our experimental setting demonstrated the feasibility of a multimodal interface dedicated for visually impaired users, with modalities based on the tactile and auditory channels. We also demonstrated that this interface can convey a concrete flow of information to the users and those users can interact with that information within the context of this interface. The possibility to generate a refreshable interface based on a mean initially conceived as a fixed setting like tactile cardboard overlays was proved. This feature has been obtained utilizing affordable resources and through an easily replicable method. Thus, we consider that the automatic identified tactile overlays approach is a promising method for touch screens accessibility that improves their usability and gives the users more control over the touch screen and provides more content on the layout structure and element types of a text document.

ZUSAMMENFASSUNG

Seit den frühen Anfängen des Schreibens nutzen Menschen Textlayout und -format als primäres Mittel, um den Lesezugriff auf ein Dokument zu erleichtern. Im Gegensatz dazu werden sehbehinderten Menschen in der Regel wenig bis gar keine Informationen über die räumliche Anordnung von Dokumenten zur Verfügung gestellt. Braille-Text, Sonifikation und Text-To-Speech (TTS) können den Zugang zu digitalen Dokumenten ermöglichen, wenn auch in linearisierter Form. Das bedeutet, dass strukturelle Informationen, und damit die Vogelperspektive, meist fehlen. Für das lineare Lesen ist dies eine kleine Unbequemlichkeit, mit der Leser und Leserinnen umgehen können. Man kann jedoch davon ausgegangen, dass räumliche Strukturen neben dem linearen Lesen sehr wichtig sind für Aktivitäten wie z. B. das überfliegen von Dokumenten, das Wiederholen für einen Test, das Auswendiglernen, das Verstehen von Konzepten und den Vergleich von Texten.

Dieser Mangel an Layout-Hinweisen und strukturellen Informationen kann verschiedene Leseaktivitäten erschweren. Es kann sein, dass ein Leser mit einer Sehbehinderung, ohne es zu bemerken, zunächst einige am Seitenrand platzierte Absätze liest, bevor er mit dem Lesen des Haupttextes beginnt. Für das Lesen eines Lehrbuchs ist dies nicht optimal. Wenn Leser einen Absatz überarbeiten oder auf ein bestimmtes Element des Dokuments zugreifen wollen, müssen sie jedes Element auf der Seite durchgehen, bis sie den gewünschten Absatz erreichen, da die entsprechenden Screenreader jeden Absatz linear durchlaufen. Dies kann sehr frustrierend und anstrengend sein, besonders wenn es während einer langen Sitzung mehrmals erforderlich sein sollte. Auch die Identifizierung verschiedener Dokumentelemente durch einen Screenreader ist eine Herausforderung. Zum Beispiel können Benutzer nicht zwischen dem Haupttext und einem Seitenrand-Absatz unterscheiden.

In der vorliegenden Dissertation stellen wir im Detail den Forschungsprozess dar, bei dem wir den Zugang von Lesern mit Sehbehinderungen zu digitalen Textinhalten untersucht haben. Ferner definieren wir Stärken und Schwächen dieses Prozesses der Inhaltszuordnung. Dann fokussieren wir auf Antworten und Lösungen bezüglich der Gestaltung und Nutzbarkeit von taktilen und auditiven Modalitäten zu finden, um Lesern mit Sehbehinderungen Zugang zu digitalen Textinhalten zu ermöglichen.

Wir beschreiben die Beobachtungen und Schlussfolgerungen im Zusammenhang mit dem Aufzeigen verschiedener Merkmale und Charakteristika des Leseprozesses auf der Grundlage auditiver Bildschirmlesegeräte für Leser mit Sehbehinderungen. Wir untersuchten bestehende Skim-Reading-Strategien bei sehenden und sehbehinderten Personen und identifizierten Schlüsselmerkmale von visuellen Dokumenten, die es sehenden Benutzern ermöglichen, einen sehr flexiblen und zielorientierten Ansatz für das Skim-Reading zu wählen. Diese Elemente gehen beim Zugriff auf Dokumente in auditiver Form meist verloren, wie es bei Lesern mit Sehbehinderungen üblicherweise der Fall ist.

In drei verschiedenen Entwurfsphasen haben wir Tactile Sheets, ein System, das Informationen über das visuelle Layout digitaler Textdokumente vermittelt, konzipiert, gestaltet und entwickelt. Dieses System basiert auf verschiedenen taktilen Elementen, die auf der Oberfläche von Overlays angeordnet sind; diese Overlays werden auf einem Touchscreen-Tablett platziert, wodurch eine taktile Schnittstelle geschaffen wird, die es den Benutzern ermöglicht, durch ein Dokument zu navigieren, dessen Layout zu erkennen, implizite Informationen in Bezug auf die Position und Klassifizierung verschiedener Dokumentelemente wie Titel, Absätze, Tabellen oder hervorgehobenen Text zu erfassen und durch akustisches Feedback auf den Inhalt zuzugreifen. Als Design-Iteration des Systems haben wir eine automatische Identifikationsmethode eingeführt, die es dem Benutzer ermöglicht, den digitalen Inhalt in Bezug auf ein konkretes taktiles Overlay auf dem Touchscreen-Gerät zu aktualisieren. Dies verbesserte die Nutzbarkeit der taktilen Overlays und verlieh dem taktilen Seiteninterface-System ein innovatives Maß an Interaktivität und Flüssigkeit.

Diese Lösung wurde bei der Durchführung einer Reihe von Studien mit sehbehinderten Teilnehmern und Teilnehmerinnen bewertet, die verschiedene Aufgaben mit unserem System und mit auditiven Screenreadern durchführen sollten. Der Ansatz erhielt positive quantitative und qualitative Bewertungen und wurde von den meisten Teilnehmern gegenüber den Screenreadern bevorzugt.

Unsere Versuchsanordnung demonstrierte die Machbarkeit eines multimodalen Interface für sehbehinderte Benutzer, wobei die Modalitäten auf dem Tast- und dem Hörsinn basieren. Wir zeigten auch, dass dieses Interface den Benutzern einen konkreten Informationsfluss vermitteln kann und dass die Benutzer dadurch mit den Informationen interagieren können. Die Möglichkeit, ein aktualisierbares Interface auf der Grundlage eines ursprünglich als feste Einstellung konzipierten Mittels wie taktile Kartonüberlagerungen zu erzeugen, wurde nachgewiesen. Diese Funktion wurde unter Verwendung konstengünstiger Ressourcen und durch eine leicht reproduzierbare Methode erreicht. Daher sind wir der Ansicht, dass der Ansatz der automatisch identifizierten taktilen Overlays eine vielversprechende Methode für die Barrierefreiheit von Touchscreens ist, die ihre Benutzerfreundlichkeit verbessert und den Benutzern mehr Kontrolle über den Touchscreen gibt und mehr Inhalte über die Layout-Struktur und Elementtypen eines Textdokuments liefert.

PREFACE

This thesis originated from the research that I conducted at the University of Stuttgart in the context of a Panama's National Secretary of Science, Technology and Innovation project funded via the Excellence Program. My work and decisions were influenced by many conversations and discussions with colleagues, students, and external researchers working on the topic of tactile and auditory interfaces for document accessibility. As a research associate at the University of Stuttgart, I also supervised student projects including Bachelor and Master theses. These theses were all related to my research topic and supported me in realizing my ideas. During my whole time as PhD student, I very much valued the scientific exchange with other researchers and practitioners when attending conferences, workshops, or doctoral colloquiums. Hence, I decided to write this thesis using the scientific plural instead of the singular. Additionally, parts of the presented work are based on scientific publications arising from the collaboration with colleagues and students. The respective chapters contain references to these publications at the introductory part of the chapter.

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Thanks to Valentina for coming just in the right moment, this is for you.

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LIST OF ACRONYMS

ADR	abstract document representation
ASR	auditory screen reader
ASRS	auditory screen reader software
CAD	computer aided design
CLI	command line interface
CNC	computer numerical control
dB	decibel
FTW	Future Technology Workshop
G2T	Graphics to Tactile Project
GIOM	General Input and Output Methodologies
GUI	graphical user interface
HCI	Human-Computer Interaction
OCR	optical character recognition
OIS	Overlay Identifying System
OSI	onscreen interface
PDF	Portable Document Format

SUS System Usability Scale

TGA Tactile Graphics Assistant

TGH tactile graphics helper

TOC table of contents

TTP Talking Tactile Pen

TTS Text-To-Speech

UCD user centered design

UX user experience

VI visual impairments

wpm words per minute

Chapter 1

Introduction

Worldwide, approximately 285 million people experience visual impairments, according to the World Health Organization [244]. Of these, around 40% are within the school-age range. The community of people with visual impairments faces important challenges related to accessing distinct types of textual material in diverse formats, as much in regular printed as digital contents [231, 244]. Consequently, those challenges integrally affect how people with visual impairments access educational materials, creating drawbacks and margination in the didactic and professional development of populations with visual impairments [86].

Braille text has granted means for readers with visual impairments to access textual contents over almost two centuries, although diverse issues arise from the production of this aid modality: Documents and books adapted to Braille are substantially more voluminous and unwieldy than their printed counterparts; only a small percentage of the population with visual impairment can read Braille; and due to its features Braille is limited in formatting possibilities [114, 145, 196]. At the same time, textbooks have changed a lot in the last decades with the gradual arrival and establishment of textual contents in an electronic format.

The debate on the relative merits of physical vs. digital books has been around for many years. In practical terms, not having to carry heavy books in the backpack is an important benefit of digital books. Digital books are also more affordable than their paper counterparts, because the payment is solely for the content of the book and not for transportation, printing, etc. Concurrently, having most human knowledge available within a few clicks on your mobile phone is another advantage. These assets account for most students favoring digital books over paper books.

In conjunction and more recently, sonification, and TTS can provide access to digital documents to readers with visual impairments. The most common method of accessing digital textbooks for readers with visual impairments is through Text-To-Speech based screen readers [10, 61, 193], which have proven their effectiveness for performing certain tasks (e.g., reading-writing emails or reading novels and articles). Readers with visual impairments can access these contents albeit in a linearized form. This means that layout information like a document's design or structural arrangement, namely a birds-eye-view, is mostly absent.

This lack of layout cues and structural information can result in distinct types of reading hindrances. A reader with visual impairment may start reading multiple sidebar paragraphs before starting to read the main text without noticing, which is not optimal for reading a textbook [138]. If readers want to revise a paragraph or access a certain element of the document, they must to go through each element on the page before reaching the targeted paragraph, due to screen readers' linear iteration through each paragraph. This can be very frustrating and exhausting, especially if required multiple times during a long study session. Identifying different document elements through a screen reader is also challenging. For example, the user would not be able to distinguish between the main text and a sidebar paragraph.

These shortcomings are minor inconveniences for linear reading, and readers with visual impairments can work around them. However, for a more elaborate reading approach, the document's spatial structures can be expected to strongly contribute to the didactic activities essential in a learning environment beyond linear reading, such as document skimming, revising for a test, memorizing, understanding concepts, and text comparison.

Humans have exploited text organization and distribution as a primary means to facilitate reading access to a document from the early beginnings of written text. Spatial arrangements of text symbols and elements on a sheet, blank spaces, font sizes, and font-weight are but a few examples. These features are aptly employed to structure the document visually, in order to emphasize its logical structure.

Sighted users enjoy the advantages that a well-designed layout confers, often without even realizing it. Only when documents suffer from illogical layouts (e.g. missing white spaces or clear sections) do users perceive the implications of a well-organized document layout. In contrast, it is a benchmark for people with visual impairments to be provided little to no information about the spatial distribution of different document elements, or in the best case, this information shall be cumbersome to obtain [57]. This issue presents a social challenge as well as providing an important research area.

In the present dissertation, we portray in detail the research process where we investigated the access of digital textual contents by readers with visual impairments. We define the strengths and flaws of this content pursuit process, aiming to provide answers and solutions related to the design and usability of touchable and auditory modalities to supply access to digital textual content to readers with visual impairments.

We describe the observations and conclusions to point out different features and characteristics of the reading process based on TTS screen readers for readers with visual impairments. We studied existing skim-reading strategies in sighted and visually impaired individuals, and identified key features of visual documents that allow sighted users to adopt a highly flexible and goal-oriented approach to skim-reading, elements which are mostly lost when documents are accessed in auditory form, as is commonly the case for readers with visual impairments.

We observed how touchable content's adaptations can enhance the navigation of readers with visual impairments into contents adapted to a tactual and auditory interaction space. The sense of touch provides a high spatial resolution of object features, second only to vision. Systems that engage the tactile sense of visually-impaired users provide spatio-temporal markers that aid memory. This allows users to familiarize themselves with the system with ease, and to understand presented content [155]. In addition, visually impaired people typically acquire a higher proficiency at recognizing tactile patterns compared to sighted people [73, 79]. In light of this, tactile graphics have been previously exploited to represent maps, diagrams, and other kinds of pictorial and spatially distributed elements in an accessible way for people with visual impairments. Different approaches have been proposed to combine electronic devices with tactile media, such as combining tactile elements with touch screen devices to produce interactive tactile maps [31, 33, 38]. El-Glaly et al. [57] and Rodrigues et al. [192] have added tactile and tangible elements to mainstream touch screen interfaces to enhance their accessibility.

Based on this scrutiny we envisioned a touch-based solution. We introduced engraved paper sheets that represent the layout of a specific page and that are used as an overlay on a capacitive touch-screen device. These tactile overlays were enriched with differentiated touchable patterns and auditory feedback that get autonomously identified by a capacitive touch-screen to switch between different interfaces.

We have named this apparatus *Tactile Sheets*. Via these engraved tactile patterns and textures, users can locate and discriminate different content areas, navigate the spatially-distributed content non-sequentially and access speech feedback with gestures.

This investigation aims to provide knowledge and guidelines concerning to the implementation of tactile overlays supported by an auditory modality to assist readers with visual impairments.

1.1 Statement and Research Questions

The core contribution of this work is to demonstrate that tactile overlays enriched with differentiated touchable patterns and auditory feedback *(Tactile Sheets)* are a usable and appropriate means to convey content and information implicitly supplied by structures and spatial distribution of a digital document's elements to readers with visual impairments. Hence, the following thesis statement is propounded:

Tactile overlays enriched with differentiated touchable patterns and auditory feedback (Tactile Sheets) are suitable and accessible tools to display textual digital documents' content and layout knowledge to readers with visual impairments. These overlays offer enhanced usability in comparison with regular Text-To-Speech screen reader applications, and their functionality can be further augmented through an advanced tactual interaction which supports a non-visual interface.

Thus, in the following subsections we address the research questions below:

RQ1 *How do readers with visual impairments access digital documentation and how much information can they acquire using existing accessibility tools?*

Regarding different drawbacks suffered by people with visual impairments during the reading of digital documents, any inquiry should begin with which methods they currently use to access textual documents in digital formats, which limitations these methods present in comparison with similar methods used by sighted readers, and what are the most relevant opportunities to improve these mentioned processes of information acquisition.

This question is approached in chapter 2 and 3 through our investigation into background knowledge and related works which offer helpful reference elements to partially build up a concrete answer. Moreover, in chapter 4 we describe a set of experimental works we conducted to elucidate the reading process of digital textual contents by readers with visual impairments.

RQ2 *What is the most suitable design solution to provide a deeper access to the subtextual implicit information in digital textual documents?*

Once the process of reading usually conducted by people with visual impairment and its features is understood, a design process took place to find an appropriate model that offered satisfactory solutions. The answer to this question has been found through a progressive procedure described in chapter 3 and 4. In chapter 5 we detail a concrete design solution.

RQ3 *What are the functional and non-functional requirements for a system to provide access for readers with visual impairments to the subtextual implicit information in digital textual documents?*

A fundamental step to design and build any kind of system is to define adequately a set of requirements to be satisfied. During the design process some work guidelines were established regarding the definition of a design solution and the concrete needs of the group of target users. In chapter 4 this question is approached through a user-centered design process.

RQ4 *How usable can be a platform to display digital textual content composed of a combination of tactile overlays with differentiated touchable patterns and auditory feedback?*

This question is investigated in chapter 6. With outputs from the answers of research questions 1, 2 and 3, we envisioned a concrete solution to assist readers with visual impairments to access textual digital content. It was necessary to assess objectively the usability of our proposed approach.

Taking into consideration the features and characteristics of the target user group, the information acquisition process and the proposed system, we conducted a set of experimental studies with nine visually impaired participants in the first stage and seventeen in the second stage. These participants compared the proposed tactile overlays solution with a standard auditory screen reader approach. For a better understanding of the usability assessment we have subdivided this research question into the following points:

RQ4.1 *Can a tactile interaction model supported by tactile overlays with differentiated touchable patterns based in tactual recognition and gestures offer a better usability than the standard screen reader model based on keyboard's shortcuts?*

RQ4.2 *Does the implementation of differentiated touchable patterns distributed on a tactile overlay laying out the visual structure of a textual digital document convey effectively to readers with visual impairment the logical structure of that document?*

RQ4.3 *Are touchable differentiated patterns more effective than standard text to speech cues offered by mainstream screen readers to locate and recognize elements in a digital textual document?*

This pertinent question was addressed by evaluating the usability in a comparative point of view. We considered the users' satisfaction in the use of the Tactile Sheets approach, measured the completion time for concrete tasks, and observed the cognitive load. The qualitative feedback from the participants was then analyzed through a thematic focus to afford a usability assessment.

RQ5 *How can a non-refreshable interactive space based on self-identified tactile overlays offer a fluid display of digital textual content for users with visual impairments?*

As part of the first stages in our investigation process, we regarded the technological approach of refreshable touchable displays. Although this technology offers interactivity in a deeper way than a fixed engraved paper sheet and there is previous work studying the functionality of that focus, the low spreading and affordability of that type of hardware led us to focus on the use of touchable overlays that are not able to refresh their tactual content. To overcome this functional limitation, we enhanced the tactile overlays providing them the technical functionality to be autonomously identified by the electronic device. This feature brings the capability to refresh the digital content in the function of a specific placed overlay.

This relevant question is addressed in chapter 5 as part of the design process, and in chapter 6 as part of the usability assessment, where we observed and pointed out the different strengthening and undertaking elements of the self-identified overlays approach. Those observations granted starting points for future work which aims to improve the functionality of a tactile overlays-based interface.

1.2 Methodology

The research work detailed in this thesis has employed methodologies based on a user-centered design approach. The research work followed an iterative process; we walked through a number of stages to satisfy the different research inquiries related to the utilization of a combination of tactile overlays with differentiated touchable patterns and auditory feedback, to convey implicit information displayed in digital textual documents.

Within the methodological context of this work, it is relevant to mention that the conceptualization of research approaches was carried out by a person with visual disability of level 4 according to the classification shown in chapter 2, section 2.1.1. Research methods that have considered the direct participation of users and those that raised a deeper understanding of technical aspects had to be adapted in such a way that they were functional to researchers, designers, evaluators, and study subjects who presented with visual disability. The adaptation and accessibility of the entire methodological set have been core aspects of each of the stages of this research, with special emphasis on the phases of information collection, design and evaluation.

An exhaustive bibliographic scrutiny was conducted. We investigated background literature related to visual impairment and its effect on human perception and cognition, including tactual and auditory perception. Previous related work was analyzed for foundational knowledge in reference to tactile computerized interaction, touchable graphics, auditory interfaces, and tactual overlays to support our research. Taking into consideration basic established knowledge we developed a taxonomical classification to facilitate the conceptualization of terms and ideas connected to the utilization of touchable elements to display information for people with visual impairments.

The research process was an iterative and progressive sequence of three different stages which we have denominated according to the used physical media: Pin display stage; fixed overlays stage; and self-identified overlays stage. Each of these stages was integrated into three other well-defined steps of research: Querying, prototyping and testing. In the first phase we inquired a set of subjects as part of our targeted group of users; in this case readers with visual impairments. We collected information from our subjects about their requirements and needs, and analyzed this information to obtain interactivity design implications to guide the next phase.

During the second phase we developed functional prototypes which fulfilled the outcomes from the first phase. In the third phase we evaluated the approaches, in general, comparing the usability of the proposed interaction model with a standard model of an auditory screen reader.

1.3 Thesis Outline

Chapter 1 - Introduction This chapter presents the main context of the work, the thesis statement and research questions, and establishes used methodologies, to provide a walk-through of the dissertation document.

Chapter 2 - Theoretical framework and background In this chapter we discuss in the first place our subject of study: People with visual impairments, their needs, capabilities and characteristics. We discuss the cognitive components related to spatial navigation, tactile exploration, and non-visual navigation through different digital contents, and define a taxonomical classification of terms and concepts related to the use of tactile elements to display information for users with visual impairments.

Chapter 3 - Related work and state of the art We establish state of the art related to spatial navigation aids, tactile representation of digital contents, and multimodal non-visual support to display information. We establish a correlation among these different concepts.

Chapter 4 - Requirements In this chapter, we have described the process of how we defined use cases, functional and non-functional requirements, which the proposed system aims to fulfill. We have also described components and their operative relationship with delineated requirements and arranged and detailed a set of interaction concepts.

Chapter 5 - Design of representations based in tactile layouts and auditory feedback This chapter points out cognitive parallelisms between non-visual spatial navigation and non-visual exploration of contents. We establish a design space where we exploit spatial distribution implementing representations beyond regular linear approaches given by Braille or auditory screen readers, to use two-dimensional codings in diverse interactive tactile representations supported by auditory feedback.

Chapter 6 - Evaluation of interactive tactile representations We describe material and methodologies to evaluate the impact of interactive tactile representations on the exploration of contents by subjects with visual impairments. We present and discuss results related to efficiency accessing information and user experience.

Chapter 7 - Discussion, conclusions and description of further works We summarize the thesis, point out future work into the field of interactive tactile representations, and highlight the relevant findings of the work.

Chapter 2

Theoretical Framework and Background

In the previous chapter we defined a problem related to the lack of access to the information implicit in textual documents by readers with a visual disability, and established a specific line of research within the domains of access to information and human-computer interaction centered on users with visual impairments. In this chapter we raise the set of ideas, procedures and theories that provide the basis for our research line, and define a theoretical framework to inform our investigative work.

As a starting point we give an overview of visual impairment, and how this set of conditions affects the perceptions and lives of those affected. We delineate a set of users with visual impairments who are the object of our investigated circumstances, and who can be the subject of our potential solutions.

We explain how we use spatial navigation for the visually impaired as a referential framework, and illustrate how the theoretical propositions and empirical regularities in this framework serve as an analogous context to explore digital textual documents for readers with visual disabilities. We then describe the basis for the adaptation of digital interfaces for users with visual impairments, emphasizing auditory screen reader software as a predominant method to grant access to computerized interfaces and contents.

Within the domain of Human-Computer Interaction we present main concepts related to the paradigm of Multimodality, Deepening in the aspects of tactual and auditory channels as established solutions to provide non-visual accessibility. UCD is a relevant aspect which has offered a foundation to generate accessibility solutions to Human-Computer Interaction concrete requirements for users with disabilities. Hence, we discuss this paradigm as part of our methodological framework.

To conclude, we will draw from the different points dealt with in order to establish a referential framework, a thematic framework, the scientific paradigm that serves as a model and the general theory of the subject matter of our research.

2.1 Visual Impairment

Disability or impairment is that condition under which certain persons have long-term or permanent physical, mental, intellectual or sensory impairments that, by interacting with various barriers, can prevent their full and effective participation in society and on equal terms with others [86, 231].

According to the World Health Organization [231] around 15% of the world population lives with some kind of disability. This same organization proposes the following classifications of disabilities [3, 162]:

Sensorial Includes people with visual impairments, the deaf and those who have problems in communication and language.

Motor Defined as the decrease or absence of motor or physical functions (absence of a hand, leg, foot, or others), decreasing normal daily performance.

Cognitive A decrease in the cognitive and intellectual abilities of the individual. Among the best known cognitive disabilities are autism, Downs Syndrome, Asperger's Syndrome and mental retardation.

Within the category of sensory disability, we find visual disability, hearing disability and other types of disabilities are related to diminution of some of the other senses, for example Hypogeusia; the decrease in the taste sensation.

2.1.1 Classification of visual impairment

Visual disability is the lack, deficiency or diminution of vision. For many people the term *visual impairment* means total lack of vision, however the visual disability is divided into moderate and severe vision impairment, and total blindness or amaurosis. Different conditions are included within the definition of visual impairment such as reduced visual field, astigmatism, myopia, night blindness, far-sightedness, color blindness, extreme sensitivity to light, dimness, haziness, foggy vision or spots in the visual field.

According to the Resnikoff's report and the World Health Organization [39, 189] the *visual impairment* is classified based on *visual acuity*. The visual acuity is the faculty of the eye, in combination with the brain, to perceive the shape of objects at a given distance. It is measured by the smallest image the eye can distinguish. To determine visual acuity a standardized chart is used, containing letters or drawings whose size decreases progressively. The smallest size the individual can see gives us the measure of their visual acuity. The test is done with each eye, from near and far. The numerical expression of the visual acuity is made by a fraction whose numerator is the distance to which is seen and the denominator is the distance to which a hemitrope eye would perceive it (eye with normal vision); thus, for example: 6/6: normal vision. A visual acuity of 1/60, 2/60, 3/60 means that a subject sees one, two or three meters (respectively) of what a person with hemitrope vision sees at sixty meters. Thus, for example, a visual acuity of 0.8 is considered normal, a vision of 0.3 is below normal. The vision of 0.1 corresponds to legal visual impairment, and vision 0 is amaurosis, or total visual impairment. When there are difficulties in visual acuity, there will be problems in reading and writing, contrast perception, blackboard vision and colour vision. For a good visual acuity the eye refraction must be correct, the transparent structures of the eye must be in good condition and the macula, optic pathway and cerebral cortex must have adequate anatomy and physiology.

The visual field (or peripheral vision) is the space that the eye can perceive, the area that can be seen without moving the eyes. A person with a normal visual field, facing forward, is able to see objects in an amplitude of 180 degrees in the horizontal plane and 140 degrees in the vertical. The visual field is measured with the campimeter. When pathologies affect peripheral vision (retinitis pigments, optic nerve lesions) there will be difficulties in interpreting and following moving scenes, locating elements or globalized reading. Visiual field can also be impaired by the presence of lesions in the visual field such as scotomas, or islets without vision, whose importance varies according to their extension and location.

Moderate vision impairment Covers cases of visual acuity less than 6/18, excluding cases of acuity equal to or greater than 3/60, and likewise covers reductions of visual field to twenty degrees.

According to *the international classification of diseases in its version 10* [243], these are the category of visual impairment in levels 1 and 2.

Severe vision impairment and blindness Covers cases of visual acuity less than 3/60 or visual field reductions to ten degrees or less.

According to *the international classification of diseases in its version 10* [243], this would be the category of visual impairment in levels 3, 4 and 5.

This classification can be better understood as follows:

1. I can read text in size 16 or higher with the help of a magnifying lens or special lighting.
2. I distinguish colors and shapes, but I do not have depth perception.
3. I can distinguish colors and shapes with adequate lighting.
4. I can perceive light and shadow, but this is not useful in my displacement.
5. I have no visual perception.

Considering that the approached solution described in this work is dedicated to support people who cannot access textual digital contents through eyesight, all of our examples, cases and subjects were among the third and fifth grade of visual impairment mentioned in the previous list.

2.1.2 Further affecting circumstances and components of visual impairment

Additionally to the level and causes of the visual diminution, different aspects can determine cognitive and affective features of people with visual impairments.

Nature of the condition

This aspect refers to how the affected person has acquired the disability. Visual impairments related to an illness or an accidental nature suddenly causing the condition, might likely to lead to depressive disorders [216]. On the other hand, autism and stereotyped behaviors are more likely asociated with congenital blindness.

Early or late visually impaired

Another relevant factor is related to the moment in life when the visual impairment was acquired. Different researchers have not defined a clear parameter about early or late blindness. Some specify early blindness as occurring around the first year of life; others extend the definition to the first three years.

The proportion of life-time without visual experience has been proposed by Lebaz, Picard, and Jouffrais [133]. This value is calculated as the ratio between the life-time spent with blindness and the current age. As an example; a ratio of 0.10 indicates that the person has spent 10% of his/her life without visual experience.

It has been found that the proportion of life-time without visual experience directly affects the set of functional rules used by people with visual impairments to process information at the first encounter with a new situation until the externalization of the spatial knowledge [216]. Thus, the age at onset of visual disability influences cognition [221]. For instance, congenital blindness might lead to a delayed development of sensorimotor coordination which then again may negatively impact spatial cognition [216].

2.1.3 Psychosocial implications related to visual impairment

Besides functional affectations, visual impairment may result in a reduction of autonomy in daily life activities. This has psychosocial implications which impact upon affected people's everyday lives.

It is unusual for information to be presented exclusively in a visual way and people with visual impairments are thus excluded from accessing non-visual contents. This affects important domains such as education and administrative tasks, hindering an equitable academic and professional development [111, 144, 205].

- The inability to freely access diverse contents negatively affects the complete integration of individuals in collective training and education activities [76, 106, 125].
- Tasks like approaching inaccessible means or materials, mobilizing in an unfamiliar environment without support, and the continual self-perception of dependence, can become situations of great frustration for people with visual disability, being an ongoing source of anxiety and stress [139, 106, 91].
- Often people with visual impairments travel less, which also influences their personal and professional life and represents a drawback for their social integration [170].

2.1.4 Accessibility of digital contents

Specificities and circumstances faced by people with visual impairments embody a set of functional, educational and social challenges, as well as an important research area to generate operative solutions which aid to overcome disadvantaging situations of the visual disability. The field of Assistive Technologies aims to provide support in those activities where the lack of eye-sight represents a significant constraint.

Different approaches are employed to face the different aspects of limitations related to visual impairment. Vanderheiden [225] discusses some of these:

Navigation aids White canes, navigation systems and talking signs.

Reading and writing aids Braille text, tactile symbols, speech recorders or Braille-based portable note takers.

Accessibility aids for pictorical and electronically displayed contents Raised-line drawings, Braille displays, synthetic speech, talking clocks and calculators, screen readers and audio description for television.

Regardless of the situation that the assistive technology intends to cover, it is very important to consider the capabilities of the person with disabilities. In other words, it is necessary to focus on what people are capable of doing and not on what they are limited for [240].

Some other relevant aspects to consider are the cost of such assistive solutions due to their specialized nature and low consumption, and that the use and implementation of assistive technologies involve learning and training processes for both direct users and special education staff. These aspects also affect the accessibility of mentioned solutions.

2.2 Non-Visual Traveling and Navigation

The displacement of people is a very complex process, for people without any level of visual impairment, observation is the optimal way to visualize where the facilities are, how to access them and other information based on the position [76, 106, 139]. Furthermore, this group is also able to perceive spatial layouts and reading markers on textual contents [144]. Based on this assumption, it can be inferred that the navigation process has particular characteristics and aspects for the population with visual impairment in physical spaces as well in textual contents. It has also been established that there are different levels of difficulty they must face in the use of any visual reference, signaling, cue or positional marker in the navigable environment, whether spatial, textual or virtual.

Hence, we explore in the following statements the functional analogies between spatial navigation and virtual navigation in digital textual documents. We search for a methodological foundation to define requirements and design implication aspects to conceive an assistive application to support readers with visual impairment. In this way we intend to establish if solutions proposed to support spatial navigation for travelers with visual impairments, are feasible to be applied to aid readers with eyesight disabilities in the exploration of digital textual contents.

2.2.1 Non-visual navigation methodology

Blind people need to know in detail where they are located and where they can move from that position, require information about people, the objects around them, accurate information about the appropriate paths, hazards, distances and critical points. Any information about the objects and their characteristics are relevant [92]. In studies of human navigation Kammoun shows that there are two differentiated methods to keep track of position and orientation during the displacement [105, 198]:

Marker-based navigation In this method, location markers give feedback regarding position and orientation. These markers are by convention visual, however, when considering the displacement of blind people, can be replaced by auditory, olfactory or somatosensory identifiers.

Path integration In this method the person in movement uses the sense of movement of the body (kinesthetic feedback) to update their position and orientation relative to their starting point. This method is functional for blind people, however, position estimates can easily be derived.

Thus, a person with visual impairment requires the collection of sufficient information to generate an abstract idea of the concrete space where it is intended to mobilize [104, 125, 91, 47]. The most common way for the collection of such information is through the physical exploration of the environments. Likewise, the referencing by third parties of the locations is another method by which a blind person collects information about a place to where he wants to move [113].

- It has been established that this process is predominantly peripheral. Notable elements are explored in the contours, all remitted to the perimeter [47, 91, 125].
- When walking in the center of an area the body perception of the position of a visually impaired person can easily fail [105, 198], so the approach of an imaginary grid is not functional [47, 91, 125].
- Linear (one-dimensional) scan methods are preferred over two-dimensional methods [47, 76].
- People with visual impairment are able to generate an abstract conception of the location where they have performed the physical examination through the integral sensory feedback they receive during the aforementioned exploration [47].
- During and after the exploration the visually impaired person compiles the perceptions of specific points into a set of abstract references that result in a *cognitive map* of the explored location [125].

Micro and macro navigation

To move autonomously and efficiently a person with visual impairment requires two fundamental operations [106]:

Mobilization or micro-navigation This consists of evading obstacles in the immediate environment. Micro-navigation implies a specific perception of the immediate environment and surrounding objects. Fixed objects can be detected by means of tactile exploration, either manually or with the use of a guide cane, so these objects can be added to the repertoire of *reference points* once their location has been learned. On the other hand, mobile objects require perception in the act.

Mobilization depends on skilfully coordinated actions based on detecting routes and avoiding obstacles in the immediate environment [104]. It is based on spatial orientation and routing in locations. Routing refers to the cognitive and behavioral ability to locate a route from a point of origin to a destination point [76].

Orientation or macro-navigation This is the ability to establish and maintain awareness of one's own position in relation to both the markers in the surrounding area and with the destination to which it is intended to arrive. Macro-navigation or orientation makes extensive use of the cognitive abstractions with which a person with visual impairment manages to perceive the spaces before reaching them, in them and after having left them.

Macro-navigation, unlike micro-navigation, is a predominantly cognitive process. In macro-navigation, the location both of oneself and the destination is required, as well as the route joining these points [104, 47].

Cognitive structures to support non-visual navigation

According to Fletcher and the *deficiency theory*, it has originally been assumed that visually impaired people were incapable of creating mental representations [62]. Today, it is known that mental representations can be created without sight but that these representations differ from those developed by sighted individuals *difference or inefficiency theory*.

In the context of linear, superficial or spatial displacement, visual perceptions are replaced by corporal, tactile referential elements, auditory or olfactory. With these referential elements and notions such as *proprioceptive* [47, 60, 124] stimuli and environmental relevant information as placeholders in spaces and other points of confirmation or redirection, people with visual disabilities can generate a *mental representation of space* [198] as the basis for the conception of *mental maps of spaces*. The construction of these maps and of the possible routes to move into them are essential for the efficient development of ways to overcome displacement [47, 60, 104].

Mental representation of space Abstract and subjective perception that a person possesses of the dimension, disposition and other generalities of a place [198, 104, 47, 60].

Mental map of space Abstract knowledge that a person generates from a mental representation of space in order to move within of an area. It differs from the mental representation of the space in which the mental map only contemplates the useful information to move, leaving aside several generalities of the locations [104, 47, 60].

The generation of a *mental representation of space* and *mental maps* requires a preliminary exploration process [91, 125] through which is established the points and reference lines that go on to form these cognitive, abstract and logical structures. These elements present characteristics of a logical structure which has the potential for systematization and analysis. This representation can be achieved even using virtualized or scaled models of the environments [152], always contemplating the learning of the areas and spaces performing an exploration which can be more or less systematized.

2.2.2 Non-visual navigation commonalities with non-visual exploration of digital documents

For a person with visual impairment, the process to navigate from point A to point B presents similarities to the process of exploring a digital textual document. Required cognitive representations to navigate can be achieved even using virtualized or scaled models of physical environments.

Nowadays, with the available assistive technologies based on auditory screen reader applications, the exploration of digital textual contents resembles the travel through virtualized ambiances, deploying elements like *marker-based navigation* and an adapted variation of *path integration*, where kinesthetic feedback is used to internalize keyboard shorcuts or gestures which attempt to provide positional awareness within a digital textual content.

The non-visual exploration process of a digital textual content presents similar components as those mentioned for the non-navigation process (see section 2.2.1):

- The process is predominantly linear considering the available interactivity provided by auditory screen readers.

- The exploration requires markers which can be predefined or defined by the user.
- Acquired cognitive structures like mental maps provide support in the exploration.

In a comparative study, Machulla [144] observed a segmentation of the explored content when sighted and visually impaired readers explored textual material. This segmentation maintained a nesting pattern of *micro and macro structures*, which resemble the *micro and macro navigation* processes previously described in section 2.2.1. In the same way, the skim-reading process conducted by readers with visual impairments on digital textual contents presents functional commonalities with the preliminar exploration process of spaces conducted by travelers with visual impairments to gather relevant navigational information before walking through a physical environment.

2.2.3 Empirical context of navigational aids related to documents exploration

At present there are various aids to assist blind people in navigation, such as white canes, navigation systems and talking signs [225].

Assistive technology has made use of different senses to offer a more efficient information deployment to support blind people in their displacement [99]. Verbal indications have been a natural means of providing navigational information, with details of diverse complexity such as turning to the right or to the left, the location of points of interest, cardinal points or streets, or the description of obstacles [47, 91, 116]. Jointly, haptic experiences have been studied as a method to enrich the display of information provided by the assisted navigation systems.

Elements such as vibrating wearables [103, 217, 248], smart-canes [71, 228], or small leached guide vehicles [13, 15] have also demonstrated experimentally how to combine auditory experience and haptic experience, and has been able to offer more effective support to users with visual impairment in various tasks of navigation both indoors and outdoors.

If we establish an analogy between the processes of space navigation and the exploration of digital documents by users with visual disabilities, including their cognitive processes, it is possible to infer that the implementation of auditory and haptic elements must provide a more powerful aid to access digital text content as it has been observed in other previous works [203, 204].

2.3 Providing Content Access Through Assistive Technologies

People with different levels of visual impairments are differently able to perceive visual stimuli as a function of their visual limitation. Although this observation might be obvious, it is the starting concept to outline the different issues to access distinct materials and contents by people with visual impairments, especially in a media mainly designed to be visualized in an eyesight modality [249].

Assistive technologies that provide accessibility to content for people with visual impairment can be grouped into two large groups:

Adaptive resources Those technologies which can adapt a medium originally developed to not be accessible and through specific procedures a part or all of the content becomes accessible. The implementation of these resources will always involve a processing phase. Users without training or without visual impairment can always access the original content. In this group are screen readers and audio description techniques.

Adapted resources Those media which have been produced in a way that is accessible from out of the box. These resources have the particularity that by being designed and developed so that they are immediately accessible, they might exclude users who do not have visual disabilities and have not been trained in their use. Within this group we can mention the Braille text, graphics and tactile maps, and Braille-based note takers, among others.

2.3.1 Adaptation of textual contents

In the first ages of writing scribes used malleable elements like tablets of clay, wax or stone easy to cut. The implementation of these techniques at those ancient times produced relief writing cut on a touchable surface. It is not difficult to infer that for a person with some level of visual impairment it was feasible to perceive relief writing using touch. Ink turned writing from a cutting craft into a painting work on flat surfaces like papyrus or parchment, relegating the tactual access to writing in only very rare and concrete cases [41, 97].

In this historical context we found a deep lack of interest for many centuries to give access to written content to those who cannot visually read writen characters. Before the 18th century there were few concrete efforts to provide literacy to people who could not read using eyesight. Memorization of oral lectures was the main method used for those few people with visual impairments able to access any education [41, 196]. Later, the use of characters in relief, embossed on paper, wooden sculpted, or wire-shaped became techniques to teach reading to those with visual disabilities who could access and afford this kind of instruction [41].

Characters in relief adapted the set of regular known types from figures designed to be recognized by eye-sight to touchable elements. This adaptation implied an increment of size to facilitate touch recognition, the embossing method was complex and only a few words could fit in a single page. A system to write in a way which allows one to recongnize characters came after a process of *User centered observation*, informally conducted for different purposes[97].

The system to adapt writen text into the touchable medium known as *Braille* was introduced in France during the nineteenth century. The army captain Charles Barbier proposed to the teachers of the first school for the blind in France that their students try out a writing and reading method he had developed to transmit messages during warfare. With that system, based on an array of twelve embossed dots, soldiers were able to read and write messages at night requiring no ilumination. A student of the school named Louis Braille observed this method and worked to optimize it [97, 196].

Braille simplified the size of the array from twelve to six dots distributed in two columns and three rows, and by 1832 the basic system was defined and people were already writing, reading and teaching using this method [196].

Other tactile writing systems

The Braille system was not the only method to deploy a touchable reading and writing code. In United States of America and England other systems were developed to grant literacy to people with visual impairment [41, 145, 97].

New York Point William Bell Wait, who worked in New York in the mid nineteenth century developed a points based reading system for blind readers. The system worked with characters of 2 points of height and 1, 2, 3 or 4 points of width. Bell Wait taught this system in the Institute for the Blind of New York, and also built a type-writer machine to write with this method.

Moon type William Moon from Great Britain lost most of his eye-sight during his childhood due to scarlet fever. After finishing school in the mid-1800s, Dr. William Moon experimented with a variety of alphabets to help blind students read and write. Finally, he created the Moon-type, a code of lines in relief based on printed letters. Supporters of Moon-type, which is still used in the UK for people with learning disabilities or fine motor difficulties and for those who have lost their sight later in life, consider that this system is easier to learn and simpler to discriminate using touch than standard Braille.

Fishburne tactile writing system The Fishburne tactile writing system was developed in 1972 by S.B. Fishburne, who discovered that many blind adults could not read Braille. He developed a tactile alphabet, which is more extensive than Braille, to use primarily to label elements used by people in daily activities.

Tactile symbols Although not traditionally considered as a means of literacy, *tactile or tangible symbols* have become widely used by students with deafblindness or visual impairments with additional disabilities. Educators, in their quest to expand opportunities for these students to communicate and participate in literacy experiences with classroom support, are using tactile symbols in a variety of learning activities. These symbols are used in communication boards, classroom tags, and children's literature and stories of language experience.

During the first years educators of people with visual impairments considered that by having a tactile code with different characters from those that sighted people read, people with visual impairment would be outside the normal tendency of society and that this would limit the amount of reading material to those who had access. Having special reading codes would also mean that the training of teachers would be more demanding and more difficult to find teachers capable of working with the students' visual impairments. Nevertheless, Braille dot-based characters became the most widely accepted tactile code in English-speaking countries and in most of the world. Even so, only around 40% of of people with severe visual impairments know and use Braille on a regular basis [41, 145].

Standard Braille

The Braille reading and writing system is based on six-dot basic characters. These dots are laid out in a two per three array. With the marking or absence of some of the dots it can represent all the basic characters of the latin alphabet, most of the punctuation symbols, and decimal digits (0 to 9). Additionally, the Braille system has worked to adapt other writing methods like Arabic, simplified Chinese, and syllabic Japanese characters.

The characters which form Braille signs must have certain measures for their correct reading by touch. These dimensional parameters grant a correct differentiation of the characters [196].

We list here some of the most relevant parameters for standardized Braille characters. Distances are measured from center to center point [145].

- Dimensions of the Braille cell: Height: between 6.2 mm and 7.1 mm. Width: between 3.7 mm and 4.5 mm.
- Horizontal distance between the centers of contiguous points in the same cell: from 2.4 to 2.75 millimeters.
- Vertical distance between the centers of contiguous points in the same cell: from 2.4 to 2.75 millimeters.
- Distance between the centers of identical points of contiguous cells: from 6 to 6.91 millimeters.
- Distance between the centers of identical points of contiguous lines: 10 to 11.26 millimeters.
- Diameter of the base of the points: between 1.2 and 1.9 millimeters.
- Recommended height of the points: between 0.5 and 0.2 millimeters.

The space required to write Braille on a sheet of paper is larger than the requirements to print standard text. This means that Braille books are bulkier than regular ones. To manage this detail different adaptations of Braille to some languages have developed syllabic contractions to save space, representing character and phonetic combinations in a single sign. This contraction method has been named *grade 2* [145].

A newer addition to the Braille standard system has been the inclusion of two more dots, making a two per eight dots array. Those additional dots are used to make more versatile representations of different symbols which formerly required two different signs (e.g. indications for capital letters or numerical signs) [145, 196, 201].

Braille production

Braille characters can be displayed on any surface hard enough to support a repeated sliding contact of hands and fingers. Paper and cardboard can be embossed with different mechanical methods, and metal plates can also be embossed. Braille dots can also be produced by adding plastic dots on a predisposed surface.

In principle, Braille handwriting is made with a *Braille slate* and an awl or pin, which enables one to emboss a sheet of paper. The slate has a set of boxes where a Braille writer can generate Braille signs in the boxes with guides to make the dots.

A Perkins machine allows one to type-write Braille signs on a sheet of paper with a mechanical device. The Perkins keyboard consists of seven keys; two sets of three keys, each one separated by a seventh key, which works as a spacebar. The sets of three keys are related to the layout of a standard Braille dot array, relating the position of the keys with the place of dots in a Braille sign. A person who type-writes in Braille must simultaneously press the corresponding set of keys to generate a Braille sign. This keyboard design has prevailed as the standard for any Braille text entry in different mechanical and electronic devices.

Braille electronic embossers are devices that can produce Braille printings controlled by a computerized system, these kinds of equipment let on to produce also graphics based in the same Braille dots. These devices are usually used to handle high-scale production of material in Braille.

Braille can also be generated with devices that deploy electro-mechanical machinery to generate raised dots. In this way, we can get Braille characters, which can be controlled and refreshed with a computerized system. These kinds of devices are called Braille displays. If the device only displays a single line of Braille signs, it is named Braille line; there are also multi-line Braille displays that can generate drawings and graphics based on those dots.

2.3.2 Access to computerized contents

Computerized content has traditionally been accessed through visual means. Elements like printed text, electronically generated images, and characters, displayed on a screen or projected on a wall, are the mainstream output methods. Conjointly, to interact with those same contents or workspaces, it is required to see them, in function to interact with them reading, selecting or navigating [96, 218].

Regular image documents like photographs, drawings, or other pictorial elements will not be accessible for this group. Text, printed, hand-written, or shown on a display will not be perceived for a suitable visual reading process. Mixed graphics between images and text, like diagrams or charts, will not be accessible like as previous cases. These types of materials require a process of adaptation to turn them into an accessible mode. These adaptations will bring the original visual representation into an alternative sensorial field. Common examples of this adaptations are the translation from printed text to Braille, which deploys a tactile mode to represent basic textual information, or sonification of mathematical charts which deploys 3D sound and pitch variations to give non-visual access to different types of geometrical and statistical graphics [3, 165, 193].

Adaptation of computerized contents

Computerized contents are a particular challenge for people with visual impairments. Some of these contents are explicitly non-visual, like different kind of audio files, however, computerized information is mostly represented in images or text, and these representations present their own requirements of processing to be properly adapted [99, 225, 249].

Computerized digital material is basically a piece of binary information that is represented in a particular way to the user. A similar piece of information can be represented as a visual pattern, a sound with different tones or even as a set of instructions for an automated system. This plasticity can be used to adapt digital contents from their original representation into another. In a general overview, this feature makes digital materials receptive to be processed by *adaptive resources* (see section 2.3). As we mentioned before, For people with severe visual impairments, modes are mainly constrained to non-visual representations. Thus, auditory and haptic modes [88, 117, 165] use to be the optimal alternative to adapt digital contents for people with visual impairments.

Adaptation of computerized images

Computerized images are digital representations of shapes and colors which produce an image recognizable as a visual pattern. There are two basic types of these representations, byte maps, and vectorized images. Nevertheless, both formats are produced based on pixels.

A pixel is the basic unit component of a computerized image. They are blocks of light and shade or blocks with a specified color from where computerized images are structured. These pixels are arranged in a particular coordinate system to generate from a simple black and white drawing to an ultra-high-resolution picture. Pixels are also the base to generate computerized videos. The information contained in a pixel, like its color range or position on a coordinate plane, can be accessed and represented in a different modality.

The adaptation of digital images presents specific features. Information contained in pixels can be used to run an image recognition procedure where elements in a digital picture or a video frame can be identified and described based on very complex algorithms. Very recently, this type of service is available specifically to offer accessibility for users with visual impairments.

2.3.3 Adaptation of computerized textual material

Computerized text is the representation of characters based in an alphabet defined by a characters table, ASCI and UTF are examples of these kind of characters tables. Characters are arranged in strings which are shown to be read by users, however, characters and strings can also be read, compiled and processed by computers.

Although externally computerized text is also visualized in pixels, they handle different kind of information. These differences with computerized images allow to process adaptation of computerized text in different ways. Character tables can be translate from one table system to another. Thus, regular visual characters can be transform into a Braille characters table, then this "digital Braille text" can be embossed on paper or displayed in a Braille device.

Digital characters and strings can be also processed to build auditory output. Text to speech tools can read out loud chunks of digital text.

Old school text line interfaces can easily be adapted using text to speech tools, however, graphic user interfaces offer a combination of digital texts arranged in concrete positions on a display. This combination of digital text with graphical elements can be processed to provide a speech output, and the visual structure of graphical elements are usually adapted in virtual linear layouts. These are the basis for modern screen reader tools dedicated to graphic user interfaces [10, 138, 245].

Auditory screen reader software

As we mentioned before, text to speech tools give access to text by an auditory output. These tools can gather and organize the information recognized as digital text presented in a display, and the level of organization given to the textual information can provide the capability to read out loud concrete pieces of information as the user requires. This is the basic functionality of an ASRS [10, 121, 138, 202, 245].

An ASRS needs to identify different categories of textual information to organize it; for example it can identify the title of a window or the time shown by the system clock. Then, with a specifical trigger, the ASRS reads out loud the desired content. To make functional this interaction model the ASRS needs to attach to the desired content an accessory identificator to notify the user what content is being read out; for example, the phrase "Window's title" should be attached to the read text string corresponding to the desired title. As in this example, particular identifiers can be attached to chunks of information from the same group or category. In this way, an ASRS can offer speech descriptions of elements like the components of a graphic user interface, pixel regions of a particular color, or cell coordinates in a table layout.

As information categories become more granular, they require more detailed identifiers, for example, to indicate a location based on an absolute or relative system of coordinates will need to give references of coordinate values, reference points, and other property indicators. Thus, the complexity and cumbersomeness of speech descriptions will increase. On the other hand, an ASRS offers an auditory environment that can be implemented using sound and audio resources currently available in today's computer systems.

Exploration of computerized documents based in auditory modality is currently based in the ASRS paradigm, transforming a document's environments into chunks of auditory speech information arranged in a linear layout where chunk A is followed by chunk B and so on. Properties and categories of each chunk are conveyed by textual descriptions, and the sequential access to those segments of content is associated to specific interaction archetypes which keep up a relation with the logical and visual layout of the explored element; whether a digital text document or a graphic user interface [10, 121, 142].

Interaction archetypes to access the ASRS paradigm will depend on the input modes available to the user [10]. Nowadays, mobile and portable devices equipped with touch screens require interaction archetypes based on gestures. On the other hand, more traditional configurations like desktop personal computers implement dedicated keyboard shortcuts to interact with the ASRS. Intuitive keystrokes like arrow keys up and down to read up text lines or menu items, or Enter key to activate clickable GUI elements are examples of basic keyboard-based interaction archetypes.

2.4 Multimodal Interaction

Human interaction with the world is inherently multimodal; we primarily interact with the world through our five major senses of sight, hearing, touch, smell, and taste. We explore passively and actively our environment, to confirm expectations about the world and to perceive new information employing multiple senses, both sequentially and in parallel [34, 185, 218]. Multiple sensing modalities give us a plenty of information to support interaction with the world and with other people.

In contrast to human experience with the natural world, human-computer interaction has historically been focused on *unimodal* information or data communication between human and computer primarily through a single mode or channel, such as text on a screen with a keyboard for input. The model of a single primary channel for data input, and perhaps a different primary channel for data output, has been the norm. Nevertheless, technically, almost all interaction with computers has been multimodal to some degree, combining typed text with switches, buttons, mouse movement and clicks, and providing various visual and auditory output signals like the unintentional but useful audio cues such as the sound of a hard drive being accessed [218].

Multimodal interfaces are interactive systems that aim to implement natural human capabilities to communicate via speech, gesture, touch, facial expression and other modalities, bringing more sophisticated pattern recognition and classification methods to human-computer interaction [34, 55].

A mode or modality refers to receiving stimuli from a particular sense. A communication channel is a particular pathway through which information is transmitted. In typical HCI usage, a channel describes an interaction technique that utilizes a particular combination of user ability and device capability (such as the keyboard for inputting text, a mouse for pointing or selecting, or a 3D sensor used for gesture recognition). In this view, the following are all channels: text (which may use multiple modalities when typing in text or reading text on a monitor), sound, speech recognition, images/video, and mouse pointing and clicking. Multimodal interaction, then, may refer to systems that use either multiple modalities or multiple channels. Multimodal systems and architectures vary along several key dimensions or characteristics, including the number and type of input modalities; the number and type of communication channels; the ability to use modes in parallel, serially, or both; the size and type of recognition vocabularies; the methods of sensor and channel integration; and the kinds of applications supported.

Multimodal interfaces are growing in relevance due to advances in hardware and software, the benefits that they can grant to users, and the natural fit with the increasingly ubiquitous mobile computing environment [44]. While multimodal interfaces and interactions are unlikely to fully displace traditional desktop and GUI-based interfaces, these can be viewed as expanding the traditional desktop experience, where much of the focus in multimodal interaction has been on alternative, or *post-WIMP* computing environments. Van Dam [222] described post-WIMP user interfaces as like those moving beyond the desktop GUI paradigm; relying more on elements like speech, gesture, sketching, or touchables. An interface which understands the user's context, preferences, and profiles act accordingly, sometimes without needing explicit direction.

2.4.1 Multimodal interaction for accessibility

The development of multimodal interaction methods and interfaces seeks to lift existing constraints on what is possible in human-computer interaction, towards the full use of human communication and interaction capabilities bearing on understanding the user, the system, and the interaction [55]. Hence, *Multimodality* supports the Accessibility paradigm offering interaction alternatives to meet better the needs of diverse users.

In general the pursuit of multimodal interfaces presents different advantages for users with special interaction needs [165]:

- It permits the flexible use of input modes, including alternation and integrated use.
- It supports shorter and simpler speech utterances than a speech-only interface, which results in fewer disfluencies and more robust speech recognition.
- It supports greater precision of spatial information than a speech-only interface, since a pen or fingertip input can be quite precise.
- It gives users alternatives in their interaction techniques.

- It leads to enhanced error avoidance and ease of error resolution.
- It accommodates a wider range of users, tasks, and environmental situations.
- It is adaptable during continuously changing environmental conditions.
- It accommodates individual differences, such as permanent or temporary handicaps.
- It helps prevent overuse of any individual mode during extended computer usage.

2.4.2 Tactual and auditory modalities

We experience external stimuli through sight, hearing, touch, and smell, and we sense our internal kinesthetic state through proprioception. A given sensing modality may be used to simultaneously estimate several useful properties of one environment; for example, audio cues may be used to determine a speaker's identity and location, to recognize the speaker's words and interpret the prosody of the utterance, to estimate the size and other characteristics of the surrounding physical space, and to identify other characteristics of the environment and simultaneous activities. Thus, people may process information faster and better when it is presented in multiple modalities [224]. In summary, to create a usable and enjoyable Human-Computer Interface, human abilities have to be carefully studied and taken into consideration.

In the context of this research we aim to study the implementation of a *multimodal interface* based in tactile and auditory channels to assist users with visual impairments to access digital content. Due to the fact that modalities may have different temporal constraints and different signal and semantic endurance, users with disability have to be understood, as well as the capabilities and disadvantages their impairment condition comes with. In this process focus should be made on their capabilities rather than their known limitations.

In the following explanatory content we explore the features of channels engaged as interaction modalities for users with visual impairments within the implementation of the studied interface.

Somatosensory system - Tactile channel

The somatic sensory system gives us some of our most enjoyable experiences in life, as well as some of the most unpleasant ones. Somatic sensitivity allows our bodies to feel, experience pain, have chills and know the position and movements of our body parts. It is sensitive to many types of stimuli: pressure of objects against the skin, position of muscles and joints, distention of the bladder and temperature of the different parts of the body. When the stimuli can be harmful there is a somatic sensation that allows us to perceive these circumstances: pain. An individual stimulus usually activates many receptors and a single receptor is already capable of encoding characteristics of the stimulus, such as intensity, duration, position, speed. Unlike other senses, its receptors are distributed throughout the body. Somatic sensitivity addresses many types of information from almost every part of the body, beginning with the sensory receptors on the skin, the muscles, tendons, ligaments, and connective tissue of the joints and the internal organs. The system reacts to the stimuli using different receptors: thermoreceptors, nocireceptors, mechanoreceptors and chemoreceptors.

The sensory information processed by the somatosensory systems travels along different anatomical pathways depending on the information carried. The transmission of information from the receptors passes through the sensory nerves through tracts in the spinal cord and in the brain. The processing occurs mainly in the primary somatosensory area located in the parietal lobe of the cerebral cortex. In short, the system is activated when a sensory neuron is driven by some specific stimulus, such as heat, this neuron passes into an area of the brain especially attributed to the area of the body that has received the stimulus.

Somatosensory Receptors We will focus primarily on the mechanoreceptors of the skin. They are present inside the two types of skin that exist in the body since each of these types contains different mechanoreceptors: The hairless or glabrous skin (with no hair appearing on the palms of the hands), and hairy skin that appears, for example, on the back of the hand and arms.

The tactile stimuli are external forces in physical contact with the skin that give rise to the sensations of touch, pressure, flutter or vibration and they are detected by the mechanoreceptors.

There are four to five main types of receptors, which will be described below [50, 184]:

Merkel’s corpuscles These nerve endings are found in the basal epidermis and hair follicles. They react to low vibrations (5v15 Hz) and static pressure such as shapes and edges. Merkel's corpuscles are mechanoreceptors located at the internal base of the epidermis (at the bottom of sweat duct ridges). They are responsible for tactile perception at high resolution, such as reading Braille, or vibro-haptic cues.

Meissner's corpuscles They are a type of nerve ending in the skin that is responsible for sensitivity to soft touch. In particular, they have the highest sensitivity to vibrations (10-50 Hz) and are fast adaptive receptors. They are particularly concentrated on the finger pads. They are also responsible for reading Braille.

Pacinian corpuscles These are sensory receptors of the skin that respond to rapid vibrations (250 Hz) and deep mechanical pressure, determine gross touch and distinguish rough and soft substances. They are rapid adaptation receivers which respond only at the beginning and end of deviation mechanics and high frequency vibrations.

Ruffini corpuscles These are sensory receptors responsible to perceive temperature changes related to heat and record their stretching. They identify the continuous deformation of the skin and are in the deep part of the Dermis. They are a type of mechanoreceptor small in size and low in abundance.

Free nerve endings These do not have complex sensory structures and are located in most of the tissues. They are responsible for detecting temperature, mechanical stimuli (touch, pressure, stretching) and pain *(nociception)*.

Tactile resolution Tactile capacities can be evaluated with haptic test batteries [175]. Findings of different studies on tactile capacities are again not consistent and depend on inter-subject variability and task type [21, 186, 241]. Moreover, it is well known that with touch we perceive the pressure, the shape and extension of the objects, their roughness, softness, hardness, etc. But for the visually impaired touch takes on a much more noticeable value, because thanks to touch they can feel, examine, observe, and know an immense quantity of beings and objects. Also, thanks to touch they can read and assimilate in this way all the information that is in the books. It should also be emphasized that people with visual impairments can play musical instruments and write on the ordinary keyboard of any computer using only the sense of touch.

The approximate size of receptive fields transmitting light touch can be measured by the two-point touch threshold test. In this procedure, the skin is touched slightly with the two ends of a compass in the same place. If the distance between the points is large enough, each point will stimulate a different receptive field and a different sensory neuron; thus, you will feel two separate touch points. If the distance is small enough, both ends will touch the receptive field of only one sensory neuron, and only one touch point will be felt. The two-point touch threshold, the minimum distance at which two touch points can be perceived as being separate, is a measure of the distance between the receptive fields. If the distance between the two ends of the compass is less than this minimum distance, only an undefined touch point can be felt. Thus, the two-point touch threshold is an indication of tactile sharpness, or acuity of touch perception.

The tactile acuity of the fingertips is explored in the Braille reading. The Braille code consists of a 6-cell, 3 X 2 rectangular matrix, with dots being present in some or all of the cells for a given character. Braille symbols are formed by raised points on the page, separated from each other by 2.5 mm and 4 mm wide, with the point height not less than 0.4 mm. This is slightly larger than the two-finger touch threshold at the fingertips. Experienced Braille readers can explore words almost as quickly as a sighted person can read aloud; a speed of about 100 words per minute, due to the high sensitivity of the fingertips containing a large number of mechanoreceptors, especially small receptive fields, and also because there is more brain tissue dedicated to the sensory information coming from the tips of the fingers [241].

The transmission of information The transmission of information from the sensors to the central nervous system is done through various types of nerves. The thickness of each nerve determines its transmission speed. They have been grouped into four classes: *AI, AII, AIII and C* (ordered from the thickest and fastest to the finest and slowest). The transmission speed can vary from more than 100 m/s to less than 1 m/s. Thus, the time it takes for a sensation to reach the central nervous system from the feet or hands can range from about 10 ms to more than 1 s. The sensations of the proprioceptors use the faster nerves (quick response times are needed to coordinate the movement of the limbs), while for sensations such as temperature, slower transmission channels are sufficient (this is a way to optimize the consumption Energy and protein requirements).

The difference in the speed of sensation's transmission is perceptible; for example when a bee sting occurs, the sensation of pain will be felt after a few seconds, however the sensation of the puncture will be perceived quickly since the penetration of the stinger will also have stimulated the much faster mechanoreceptors of the skin.

Nerves that transmit somato-sensory sensations enter the spine, being organized by areas of the body dermatomes. Each zone corresponds to a group of nerves and a segment of the column. There are two main ascending paths to the brain:

- Mechanical and proprioceptive receptors use a faster pathway, in which the first synapse does not reach the marrow (although synapses may be synapses to nearby, mainly motor neurons, in the same segment of the spine).
- Heat and pain receptors use slower nerves and form a synapse just entering the spine.

This information is transmitted through the dorsal columns of the spinal cord, transmitting the tactile sensation. Upon reaching the medulla oblongata, a synapse occurs with the cells of the nuclei of the dorsal column, reducing a cross of the mechanoreceptor afferents passing through the medial lemniscus of the medulla. Then another synapse occurs at the level of the thalamus to end up projecting into the specific regions of the somatosensory cortex. It is structured by zones, all within the parietal lobe. The postcentral gyrus includes the S1 or primary somatosensory cortex (Brodmann areas 3a, 3b, 2 and 1). BA3 receives the densest projections from the thalamus. BA3a is involved with the sense of relative position of neighbouring body parts and amount of effort being used during movement. BA3b is responsible for distributing somatosensory information; it projects information about texture information to BA1, and shape and size information by BA2. S2 or secondary somatosensory cortex divides into Area S2 and the parietal ventral area. Area S2 is involved with specific touch perception and is integrally linked with the amygdala and hippocampus to encode and reinforce memories. Also, area S2 processes light touch, pain, visceral sensation, and tactile attention. The parietal ventral area is the somatosensory relay to the premotor cortex and somatosensory memory hub, BA5 (BA5 is the topographically organized somatosensory memory field and association area). The posterior Parietal Cortex is composed of two other areas of Brodmann (5 and 7). In it complex processes occur that relate different sensations for the identification of objects (such as differentiating a key from a spoon) and BA7 integrates visual and proprioceptive information to locate objects in space.

The somatosensory cortex, like the visual and auditory cortex, is organized into columns; each specializing in the different sensations of the same region of the body, where the information is integrated so that objects are perceived, rather than separate characteristics. The sensations of texture, size, and shape are understood as characteristics of the same object.

Tactile sensitivity is divided into two types, which to reach the encephalus follow different sensory pathways:

Protopathic sensitivity This is the most primitive and diffuse sensibility. Little or nothing is differentiated; it responds to all the painful cutaneous exciters, the extreme heat and cold, and strong touch. The subject cannot accurately locate the stimulus, or discriminate between different stimuli.

Epicritic sensitivity This is the one that ensures a finer, localized and accurate discrimination, allows to appreciate the stimulus of little intensity, and normally exerts inhibitory influence on the protopathic system.

The Somatosensory Map The representation of the body of our sense of touch in the cortex of the brain is called the homunculus; mapped by Wilder Penfield. The cortex has the equivalent of a map of the whole body, reflecting the origin of each sensation. The correspondence between superficial sensations and cerebral cortex is called cortical somatotopic. The surface dedicated to each organ depends on the number of nerve endings in it, being very different for some parts of the body than for others and especially great for the mouth, tongue and fingers, because these areas are really sensitive, so have a much bigger area than the others parts of the body given their importance to the brain.

Audition - Auditory and verbal channel

The sensors of the auditory sense are the hair cells in the inner ear. Sound is transmitted as a wave of air particles. The sound causes movements of the tympanic membrane and the ossicles of the middle ear, which are transmitted to the cochlea filled with fluid. This produces vibrations of the basilar membrane, which is covered with hair cells [23]. The flexing of the hair cell's stereocilia causes the production of action potentials, which the brain interprets as sound. Sound waves are alternating zones of high and low pressure traveling in a medium, usually air or water. Sound waves travel in all directions from their source, like waves in a pond where a stone has been dropped. These waves are characterized by their frequency and intensity. The tone of a sound is directly related to its frequency; the greater the frequency of a sound, the higher its pitch. The intensity, or force, of a sound is directly related to the amplitude of the sound waves, and is measured in units called dB. A sound that is barely audible - at the threshold of the audition - has an intensity of 0 dB. Every 10 dB indicates an increase of 10 times the intensity of the sound; a sound is 10 times stronger than the threshold at 10 dB, 100 times stronger at 20 dB, a million times stronger at 60 dB, and 10 billion times stronger at 100 dB [36, 107].

Sensory neurons in the spiral ganglion of each ear send their axons in the vestibulocochlear nerve (VIII) to one of two cochlear nuclei in the junction of the spinal bulb and the annular bulge of the encephalic stem. Neurons in the cochlear nuclei send axons either directly to the inferior colliculi of the mesencephalon or to the superior olive, a set of nuclei of the encephalic stem. The axons from the superior olive pass through the lateral lemniscus to the lower colliculus. Whatever the route, all auditory pathways synapse in the lower colic. The neurons in the lower colic then send axons to the medial geniculate body of the thalamus, which in turn projects to the auditory cortex of the temporal lobe.

Features of the auditory channel In similar way as eye-sight, no direct contact is necessary to the origin of the stimulus. In comparison with vision, it is more difficult to perceive several sound sources simultaneously. Audition is better at processing information successively, in a deferred order which is important for speech as well as music [84].

The ear of a young and skilled individual can hear sound in a frequency range of 20 to 20 000 Hz; even so, we can still distinguish between two tones that only have a frequency difference of 0.3%. The human ear can detect differences in intensity from sound of only 0.1 to 0.5 dB, while the range of audible intensities covers 12 orders of magnitude (1012), from barely audible to noise limits of such intensity that it generates pain. The hearing of the human being is optimum to sound intensities of 0 to 80 dB. Audition is also well adapted for perceiving distances, as the perceived loudness decreases with increasing distance. The sound source can be localized using the three values azimuth, elevation and range [36]. The movement of objects can be recognized through Doppler effects, i.e. changes of frequency [158]. Furthermore, objects can be identified based on the specific sound they emit [69]. Finally, audition has good alerting functions as we automatically react to unexpected sound [36].

Regarding its features, sense of audition is best adapted for temporal stimuli perceptions such as length, rhythm and speech [84].

Conjointly, the auditory channel presents some perceptual restraints [36, 69, 216]:

- Audio signals are subject to interference, especially in urban areas, inclusively if it is possible to filter out relevant information from noise.
- It is not possible to recognize precise object properties such as shape, size, color, texture or material.
- Spatial acuity is quite poor. As for other senses, illusions exist. Reflections can trick the perception of direction. If the temporal delay between the original sound and the reflection is big, we perceive it as echo.

- It is possible that sound cues are missing; every object has visible features but not every object emits sound.

There is evidence of some auditory perceptual features associated with the condition of visual impairment [36, 207, 216]:

- Subjects with visual impairments may have greater ability to perceive ultra-fast synthetic speech and pseudo speech that is impossible to understand for sighted people.
- Subjects with visual impairments have showed an improved memory for auditory and verbal information as well as an improved serial memory. This improvement of memory appears to depend on an improved stimulus processing and encoding.
- Some people with visual impairments are able to develop echolocation, which demands a subtle processing of sound. Echolocation is based on sounds created by the listener, for instance clicking noises with the tongue, which are reflected from objects. This phenomenon can even serve as an additional sense of orientation.

Speech perception Speech is a powerful means of communication that has similar properties to written text [26]. Humans can perceive speech under a wide variety of conditions, including the presence of various background noises, sloppy pronunciation, speakers with different dialects and accents, and the often chaotic give-and-take that routinely occurs when people talk with one another. Different approaches were taken to develop computer systems that mirror the impressive human ability of speech perception and recognition, yet noise cancellation, accent and dialect detection, and sound quality are challenges facing this approach. Our speech perception system is able to identify what we hear through the categorical perception process. Through this process humans are able to categorize sounds from a wide range of acoustic signals. There are multiple factors that help us do that, for example the temporal spacing between words, the context of the speech, the word's meaning, and the lip reading ability. All of these factors combined help us identify the speech we hear [74]. According to multiple studies the average speed of delivery in the English language is 160-190 wpm. In other studies the average rate lies within 130-220 wpm [211].

2.5 User Centered Design as Part of the Methodological Framework

The development of solutions dedicated to users with *functional diversities* [167, 172] is marked by the central requirement to take into account such diversity. It is a relevant challenge to be able to adequately define the level of affectation that the functional diversity has on the main process that entails the implementation of the proposed solution [3].

Designing solutions focused on the technical characteristics of the medium that contains the solution, or focusing on the characteristics of the situation that the solution aims to resolve, presents the problem of obviating the people who would use the proposed solution generating a series of shortcomings related to the interaction of users with the solution, its mean and its functionality. This raises the need to focus the design of applications and solutions on the user, so that the design, development and implementation process remain central to the user's specific needs [160, 173].

Hence, the concept of user centered design (UCD) [89, 160] is considered. This concept can be defined as a design philosophy that aims to create products that meet the specific needs of its end users, achieving the highest satisfaction and best possible use experience with minimal effort on their part. It takes shape as a process in which a series of multi disciplinary techniques are used and where each decision taken must be based on the needs, objectives, expectations, motivations and capabilities of the users.

2.5.1 Systems design focused on users with functional diversities

Returning to the concept of designing solutions for users with functional diversities, it is very important to consider details that may seem obvious or redundant, however they must be taken into account throughout the development process of a dedicated system [3, 199, 240].

- The designer must focus on what the user is capable of doing, but not on what, because of the disability, he or she cannot achieve,or can only do so with effort.

- It is necessary to evaluate the convenience between designing from scratch or adapting an existing system in order to cover the requirements resulting from functional diversities.
- The role of the designer is to facilitate the task to the user to ensure that the user is able to make use of the product with minimal effort to learn how to use it.
- User-Centered Design asks user-related questions about their tasks and goals, then takes the findings and makes design decisions about them.

As mentioned above, the design of systems focused on users with functional diversity is seen as a systematic process which makes use of specific techniques which involve the following stages [3, 132, 160]:

1. Knowing the end users thoroughly, usually using qualitative research or quantitative research.
2. Designing a product that meets users' needs and fits their capabilities, expectations and motivations.
3. Testing the design, usually with a user test.

The aforementioned stages can be synthesized in a series of specific questions which are key elements in the process of knowing the user subjects of the process and their capabilities, needs and expectations [89, 173, 242]:

(a) Who are the users?

(b) What are their tasks and goals?

(c) What level of experience do they have?

(d) What functions are needed?

(e) What information do users need and in what way?

(f) How is it expected to work?

(g) What are the most adverse cases?

(h) Will several tasks be done at once?

The parameters with which the designed system has to be tested can vary in direct or indirect relation with the particularities of the users themselves and their observed requirements; however the core of the design process offers four basic suggestions of what a design must be [132, 89]:

- It must make it easy to determine what actions are possible at any time.
- It must make the elements of the system visible, including the conceptual model of the system, the alternative actions and their results.
- It must make it easy to evaluate the current state of the system.
- It must follow natural assignments between the intentions and the required actions; between the actions and the resulting effect and between the information that is visible and the interpretation of the state of the system.

2.5.2 Design of a user experience

One of the most valuable contributions that we hope to obtain from this work is the definition of a methodological space which delimits an environment of interaction for users with visual impairment when accessing digital textual contents with the support of tactile sheets and auditory feedback. This space should cover both concrete elements as physical devices and elements of method, which involve the operation of accessing the mentioned contents.

This methodological space fits with the definition of the concept of UX [72], which according to the international standard on ergonomics of human system interaction, ISO 9241-210[1] is *a person's perceptions and responses that result from the use or anticipated use of a product, system or service*. According to the ISO definition, user experience includes all the users' emotions, beliefs, preferences, perceptions, physical and psychological responses, behaviors and accomplishments that occur before, during and after use. The ISO also lists three factors that influence user experience: *system, user, and the context of use*.

In this way the various factors that make up this UX can be manipulated in a design process UX design ([22, 154]) which aims to enhance user satisfaction through the improvement of usability, the accessibility and pleasure provided in the interaction with the proposed scheme [42]. Considering these elements, we aim to define an experience of use that can serve as a reference for the development of similar assistive approaches like that detailed in this research.

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[1] https://www.iso.org/standard/16882.html

The process of User Experience Design

The UX design process encompasses traditional HCI design, and extends it by addressing all aspects of a product or service as perceived by users [68]. In a generic way the UX design process involves an array of operative components which embody the concrete aspect of UX [22, 42, 68]:

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

Interaction design The goal of interaction design is to create a product that produces an efficient and delightful end-user experience by enabling users to achieve their objectives in the best way possible. It is well recognized that the component of interaction design is an essential part of UX design, centering on the interaction between users and products.

User interface design Also commonly known as visual design, graphic design, communication design, and visual communication, User Interface Design represents the aesthetics or look-and-feel of the front end of any user interface.

Information architecture This is the art and science of structuring and organizing the information in products and services to support usability and findability.

Usability This is the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.

Accessibility Accessibility of a system describes its ease of reach, use and understanding. In terms of user experience design, it can also be related to the overall comprehensibility of the information and features. It helps shorten the learning curve associated with the system. Accessibility in many contexts can be related to the ease of use for people with disabilities and comes under usability.

The user experience design maintains a classic structure within the user-centered design concept, opting for an iterative sequence of information gathering stages, preparation of proposals based on the information collected and a subsequent testing stage of those proposals. Morville [154] identifies four stages specifically for the UX design process. Those stages are defined in concrete sections of this work:

Investigation In which you gather all the possible information of the project, users and product to be designed. The information collection tasks for this thesis are carried out in this chapter 2 and in the next 3. The requirements gathering is detailed in chapter 4.

Organization In which all the information is processed to turn it into a product. This stage is fully described in chapter 5.

Design in which the design of the product is shaped according to the organized information. Chapter 5 continues detailing this stage.

Tests In which the quality of the proposed design is verified. Chapter 6 gives a thorough description of our testing methodologies, their basis, results and interpretations.

With the UCD a particular juncture is generated, since by having the user as the center of the design process the elements defined as Stages, activities, techniques and tools must be adaptable to the generalities and particularities of the determining factors in the *UX* (the system, the users and the context of use). Hence, within the domain of UX design there is nothing absolute; the most accurate design decisions vary depending on the context, content and users. That is why it is difficult to define rigid guidelines or methodologies for its carrying out, and it is essential that designers flexibly address each specific project [68, 22].

UX design in the context of users with visual impairments User experience design most frequently defines a sequence of interactions between a user (individual person) and a system, virtual or physical, designed to meet or support user needs and goals while also satisfying systems requirements and organizational objectives. Regarding this key feature we use UX design as a theoretical and methodological framework to approach the development of this research.

The adaptability granted by the UX design process eases the definition of activities, techniques and tools within its stages.

The investigation and organization stages require to be conducted with techniques and tools which guarantee the accessibility for the visually impaired inquired users. The information gathered should consider the main characteristic of visual impairment of the group of users. The design stage most be concerned about the particular interaction features of users with visual impairments, once again taking into consideration the mantra "focus on the things users can do, not on those things they can not".

The testing stage needs to consider the evaluation of Usability, and this parameter should be objectively assessed. Quantitative tools are required to aquire concrete measurements, and qualitative assessment techniques provide the source of data considering the UX as a factual outcome of this research.

2.6 Conclusive Ideas

As a core part of this research we have had to acquire a detailed perspective on referential and conceptual frameworks which have been milestones in the route towards defining the topic to be investigated, its generalities and details, and the methods and paradigms with which the subject has been addressed.

We define concrete elements of visual disability and its general effects on those who suffer from it. This has allowed us to establish a framework referring to the group of people who are the object of our research. We observed how the condition of visual impairment affects the perception of the world and access to surrounding information. Next, we analyze a series of concepts that are part of our referential and thematic framework. The sequence in which the various topics have been developed is discussed progressively in relation to a deductive scheme, going from the most general elements to more specific components.

Thus, we propose the juncture of space navigation for people with visual impairments. Based on the characteristics of the aforementioned situation, a parallelism has been defined with the exploration of text documents. The cognitive structures necessary for people with visual impairment to be mobilized were assessed and applied to to the analogy with the exploration of documents, and we depict a development guideline based on existing assistive technologies to support navigation.

Adaptation of the contents has been studied according to their nature and functionality. We emphasized the adaptation of written media, obtaining a deep perspective of the Braille reading and writing system. Next, the adaptation of computerized media was studied, again deepening our understanding of text documents in electronic formats.

We observed the characteristics of the group of people who are a central part of our research, which led us to the implementation of multimodal solutions as a development methodology. We define multimodality and its main features within the context of human-computer interaction, and as an alternative to design interactions within the framework of users with functional diversities. It depends on the nature of the channels or modalities based on touch and hearing to cover the interaction with users who are visually impaired and to provide access to digital text content.

The above mentioned thematic components arise from the consideration of the user as the unequivocal center of the design process and development of interaction. The user-centered design has been the guiding thread with which the milestones of the route have come together as a scientific research process within the framework of human-computer interaction. The central definitions of the technique itself, its basis and the core of its method have been exposed, considering the UCD as an appropriate paradigm to develop the practical approach of this investigation.

This theoretical framework provides the referential and conceptual foundation of this work. It is important to note that these components are accompanied by a tangible framework of previous research that is thematically related to the work presented here. The theoretical framework, seen in this chapter, and the related previous work, discussed in the next section, represent the support from which this research begins to then raise its methodologies and conclusions.

Chapter 3

Related Work and State of Art

3.1 Access to Digital Reading Material

As has been seen in the second chapter, the work to grant access to reading for people with visual impairments has had around two centuries of progress [41, 97, 145, 196]. While it is true that readers who read aloud the contents for people with visual disabilities have been the most widespread method to provide access to written texts, this method requires extensive dependence on the part of the visually impaired on others such as the reader assistants employed at specialized schools.

At present the assistive technologies available to the public that provide access to reading to those with visual disabilities can be divided into two main areas [61, 193]:

Based on reading aloud This category integrates those methods where a pre-recorded or synthetically produced voice performs the reading of a given content. This modality can be accompanied by other acoustic cues to provide more functionality. This category includes screen readers with spoken response, text to speech converters, and media with pre-recorded messages such as audiobooks. Usually the systems that use this modality have multimedia hardware which provides audio output. There are external voice synthesizer devices which may be required in case the system does not have audio outputs.

Based on Braille text This category includes the dynamic conversion of digital text to Braille format. These methods always require an additional piece of hardware component which displays the Braille text in a touchable modality.

It is important to note that in both cases a layer of software is required which captures, organizes and processes the textual information that has to be transformed to auditory signals or refreshable Braille. This layer is called screen reader software. The exception to this is pre-recorded audio methods. Embossed static Braille also requires translation software to adapt regular characters and provide format to the text to be embossed.

3.1.1 Auditory screen reader software

A screen reader is a software application that tries to identify and interpret what is displayed on the screen. This interpretation is then represented to the user by means of text-to-speech synthesizers, sound icons, or a Braille output [27, 61, 202, 245]. This software application is often combined with other assistive technologies such as screen magnifiers. Although screen readers can be installed externally in an operating system, they are increasingly integrated by default in the distributions of operating systems: "Narrator" in the case of Microsoft Windows; VoiceOver in Apple Mac OS X. The GNOME desktop environment has been developing since 2006 the Orca free software screen reader that works on Unix-like systems such as GNU / Linux, OpenBSD or Solaris. The default integration also occurs on mobile devices, such as TalkBack on Android terminals or VoiceOver on devices with iOS such as iPhone or iPad.

Screen readers are a potentially useful form of assistive technology for people with visual impairments or learning disabilities.

Some options of speech-based screen readers, also called talking browsers, and used by people with some degree of visual impairment are: NonVisual Desktop Access (NVDA), Jaws for Windows, Voice Over, PwWebSpeak, Orca, Home Page Reader and Braille terminals. These screen readers allow the user with visual disabilities to scroll through all the areas that appear on the screen and access computer applications only with the use of the keyboard, using different commands, or in the case of touch screen devices, by dedicated interaction gestures [246, 202, 138].

Command line interface

In older operating systems such as MS-DOS, which used a CLI, the screen consisted of characters directly mapped into a memory buffer and a cursor position. The input modality was keyboard based.

In the 1980s, the Research Center for the Education of the Visually Handicapped at the University of Birmingham developed a screen reader for the BBC Micro and the NEC notebook [27]. Nowadays, the different options of screen readers offer access to the CLI of the different operating systems, from the command prompt in the Microsoft systems to the pure CLI environments of Linux distributions. Examples of this type of ASRS are Jaws for DOS[2], Speak up[3], and Fenrir[4].

Graphical user interfaces

A graphical user interface (GUI) is a piece of software which operates as a user interface, using a set of images and graphic objects to represent the information and actions available in the interface. Its main use is to provide a *simple visual environment* to allow communication with the operating system of a device [64].

With the arrival of the GUI the access of the screen readers has become complicated. A graphical interface has characters and graphics arranged on the screen in specific positions, and therefore there is no purely textual representation of the graphic contents of the screen. Screen readers are therefore forced to use various low-level techniques to retrieve messages from the operating system and use them to construct a representation of the screen, in which the necessary text, dimensions, attributes and functions of the graphic objects which make up the interface are stored. This representation is called *off-screen model.*

Off-screen model Representation of the visual environment obtained on the screen, where the content, dimensions, attributes and functions of the graphic objects that make up the interface are stored and organized [27, 202, 138, 10, 61].

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[2] https://www.freedomscientific.com/Products/Blindness/JAWS

[3] http://www.linux-speakup.org/

[4] https://linux-a11y.org/index.php?page=fenrir-screenreader

This off-screen model is built from the capture of messages sent by the operating system. For example, the operating system sends messages to draw a button with its text. These messages are intercepted and used to build that model. The user can switch between the controls (such as buttons) available on the screen, and the labels and the contents of the controls can be accessed by the screen reader so that these attributes are read by a text to speech engine or shown in a Braille display. Likewise, the off-screen model allows screen readers to communicate information about menus, controls, and other visual constructions that allow users with visual impairments to interact with these constructions.

Accessibility APIs Creating the off-screen model is a considerable technical challenge. The screen reader application must collect a large amount of information which can vary frequently over the time the user interacts with the interface. The Accessibility attribute of a GUI would be given by its ability to allow a screen reader application to access and collect enough information to generate a functional off-screen model [193, 10, 27]. The designers of operating systems and applications have tried to attack the problem of the generation of the off-screen model by providing access to the contents without having to maintain an off-screen model. This implies the provision of an alternative access to what is shown on the screen through an API. Among the APIs of current use we can mention:

- Apple Accessibility API[5]
- AT-SPI[6]
- IAccessible2[7]
- Microsoft Active Accessibility (MSAA)[8]
- Microsoft UI Automation[9]
- Java Access Bridge[10]

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[5] https://www.apple.com/accessibility/

[6] https://wiki.linuxfoundation.org/accessibility/atk/at-spi/start

[7] https://accessibility.linuxfoundation.org/a11yspecs/ia2/docs/html/

[8] https://docs.microsoft.com/en-us/windows/desktop/winauto/microsoft-active-accessibility

[9] https://docs.microsoft.com/en-us/windows/desktop/winauto/entry-uiauto-win32

[10] https://www.oracle.com/technetwork/java/javase/tech/index-jsp-136191.html

Self-voiced applications

Some programs include mechanisms to generate sound events that can help blind people or people who cannot see the screen. These programs can be another form of assistive technology if they are designed to eliminate the need to use screen readers [82, 193].

Web-based readers

A relatively new development field is web-based applications such as Talklets that use JavaScript to add text-to-speech functionality to web content. The main audience for this type of application is those users with reading difficulties due to learning impairments or language barriers. Although functionality is limited compared to desktop applications, the greatest benefit is the increased accessibility of such sites when they are displayed on public computers where users do not have permission to install their own software, giving people greater freedom [82, 208, 193].

3.1.2 Digital Braille

As we have seen previously in section 2.3.1 where we study the methods to produce Braille, digital textual content can be translated into Braille via software and then printed by specialized Braille embossers. However, as can be assumed, this Braille text is static. A *Refreshable Braille display* is necessary to produce Braille that can really function as a dynamic output of a computer system.

A refreshable Braille display or Braille terminal is an electro-mechanical device for displaying Braille characters, usually by means of round-tipped pins raised through holes in a flat surface [210]. Visually impaired computer users who cannot use a computer monitor can use it to read text output. Deafblind computer users may also use refreshable Braille displays. These type of specialized peripherals are regularly handled by a *screen reader software [10]* which gathers text information on interfaces to translate it.

A Braille display operates on either electromagnetic or piezoelectric principles [229]. When currents or voltages are applied to points in each six-pin array, various combinations of elevated and retracted pins produce the effect of raised dots or dot-absences in paper Braille. Some alternatives to produce the effect of raised dots have been pneumatic actuators, nevertheless electromagnetic and piezoelectric devices have become predominant [2].

- In the electromagnetic Braille display, each pin is surrounded by a cylindrical casing that contains a coil. The pin is attached to a spring, and also to an iron rod passing through the casing. This forms a miniature solenoid. When a current passes through the coil, the pin is pulled inward. Thus when there is no current, the pin is elevated, corresponding to a raised dot in Braille; when there is current in the coil, the pin retracts, corresponding to the absence of a dot.
- In the piezoelectric display, each pin is mounted above a piezoelectric crystal with metal attached to one side. If a sufficient voltage is applied to the crystal, it becomes slightly shorter. This causes the metal to bow upwards, raising the pin. Thus when there is no voltage, the pin is retracted, corresponding to the absence of a dot in Braille; when there is voltage across the crystal, the pin is elevated, corresponding to a dot.

Nowadays refreshable Braille displays can work with GUIs and CLIs offering identification for graphical controls, haptic feedback through vibration, and connectivity to personal computers, tablets and even to smartphones. These devices can display Braille in its standard version or its compressed *Grade 2* mode. Together with this functionality refreshable Braille displays present Braille text in its two per eight dots mode already explained in section 2.3.1. In this way, digital Braille is presented as an alternative accessibility for textual content. It is common for users who prefer Braille to comment on their advantages regarding the possibility of perceiving the correct spelling of written texts, being able to read words and phrases in a segmented way, and the less invasive nature of Braille with respect to ASRS. However, as we mentioned previously, of the population of people with visual disabilities, most either do not use Braille or give it very limited use.

3.1.3 From printed to digital text

Even though in this section we comment on the methods to make digital text accessible to people with visual disabilities, in many cases the digital text comes from a more traditional source. The digitization of text shall be a step in the process that makes textual content accessible.

Text digitization tools are part of the platform of assistive technologies useful to make different types of content accessible. One of the first attempts of automatic transduction of texts to sounds was *The Optophone [45, 46]*, conceived in 1913 by Dr. Edmund Fournier d'Albe of the University of Birmingham. The apparatus consisted of a "proto-scanner" of printed texts, using photosensitive selenium sensors that were responsible for recording the black borders of the typeface, generating electrical vibrations that were then transformed into variable chords. One of the possible uses of this device according to Dr. Fournier d'Albe was that blind people would be able to interpret these sounds and translate them into the words of a piece of text. This approach presented several usability difficulties, the most outstanding being the interpretation of the tones corresponding to the processed texts preventing the test subjects from obtaining a functional reading speed. Despite these drawbacks, the device represented the beginning of OCR technology.

Only from the development of computerized technologies have more functional approaches been produced. A system of spoken text was created in the Electrotechnical Laboratories in Japan [220], demonstrated at the 6th Acoustics Congress in Tokyo in 1968. In 1971 the first commercial tactual reader, the Optacon [153], was launched. This was a device comprising a very small camera that transmitted to 144 phototransistors of 24 rows by 6 columns that in turn presented it in a tactile matrix at 240 vibrations per second, allowing a person with visual impairment to detect by touch any image or text. Five years later, the Kurzweil blind reading machine [122] was developed, based on a digital electronic system for optical character recognition. This device was capable of scanning and reading aloud printed materials using one of the first computerized speech synthesizers.

Gradually OCR technology has become more ubiquitous, being incorporated into home computing environments and together with the diffusion of scanners as commonly used peripherals, people with visual disabilities can access the digitization of texts, which together with the use of screen readers represents a milestone in access to textual content. Portability has been the next step in the spread of OCR technologies dedicated to accessibility. The use of mobile phones with a larger computing capability has allowed the implementation of OCR applications to be used by those with visual disabilities.

As an additional comment, we can mention that for many centuries people with visual impairments have trusted in human assistants to read printed text. Nowadays crowd sourcing photographical and video assistance services have reinvented this concept; when users of services like *VizWiz [25]* or *Be My Eyes [1, 14]* are inquired about regarding their use of those applications, reading texts is one of the more frequent answers.

Wearable optical character recognition approaches

The development of dedicated, portable and accessible technologies for digitizing, processing and reading texts has been the object of research. The OrCam[11] [156] is a wearable camera that uses computer vision to identify objects in which a user points to and reads aloud information about that object. The OrCam device can read aloud texts, and recognize faces, places and objects.

Nanayakkara [157] and Shilkrot [200] have worked on a wearable ring provided with a camera which works in a local-sequential manner for scanning text. This enables reading single lines or blocks of text, or exploring the text for important sections while providing real-time auditory and tactile feedback.

Kane et al. developed *Access Lens* [109], a way for people who are blind or low vision to access documents. This system uses a camera connected to a computer to read aloud the text on documents. Users can point to any element on the document to hear the associated information. This system brings promise to the accessibility of printed documents.

3.1.4 Accessibility restraints of current available approaches

The resources currently available for readers with visual impairment to access digital text content are predominantly of the ASRS type or oriented to text-to-speech feedback or Braille output. As we have seen in previous sections, Braille text presents limitations depending on its production and its ability to show the structure of the textual content. To show details of format and layout definition in a Braille print job is a challenge for the translation from ordinary text to Braille text, as Braille displays in their commonly used presentations (a single line of characters), have technical limitations to show such details. Furthermore, the Braille displays of multiple lines continue to be unaffordable for the vast majority of readers with visual disabilities.

At the same time, digital text formats have evolved in the context of their accessibility. Different tagging methodologies allow screen reading software to identify specific elements within an environment made up of text, images and explanatory elements. HTML can identify elements in its structure with different levels of detail.

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[11] https://www.orcam.com/es/

However, other formats of joint presentation of text, images and explanatory elements have not been adequately adapted. Even when ASRS allows navigation within a document through the non-linear identification of certain elements of its structure, the structure itself remains transparent for readers with visual impairment. In the works of Power et al. [179], Bargi et al. [19], Barry, et al. [20], and Machulla et al. [144] we have been able to observe how key elements for reading are not accessible in widely disseminated formats such as PDF, and in turn, those formats with a structure more suitable for accessibility have not had the expected acceptance in the communities of content producers.

As part of the investigatory development of this research, an inquiry was conducted on multiple users of digital documents about their perceptions of accessibility of commonly used digital document formats. The description of the method and the results of the mentioned inquiry are presented in chapter 4, section 4.2.1. This query gave us an accessibility scale of document formats resulting in the PDF as the least accessible format of the presented options. The query in question allows us to observe the accessibility gap that exists between the most widespread document formats and the assistive technologies that should allow access to these formats for users with visual impairments.

3.2 Tactile Illustrations

Touch provides information about irregularities in the surfaces, being able to perceive differences of fractions of millimeters in a given area. This allows the definition of textures as varied as the trunk of a tree or a polished mirror, and for recognition of concrete representations such as reading in Braille or visualization of tactile symbols [114, 241, 117, 133, 36]. This provides the ability to activate cognitive processes proper to the interpretation of visual information through tactile stimuli. The exploitation of the ability to recognize figures in a tactual way conforms with part of a state of art of tactile illustrations which aim to assist users, readers or students with visual impairments to explore elements that are usually depicted as visual images [36, 84, 66, 79, 67].

3.2.1 What is a tactile sheet?

The ability to perceive stimuli usually attributed to the sense of sight through the sense of touch opens the possibility for assistive tools with which blind people can access drawings, representations and other graphic elements through the representation of forms and textures on a surface [241, 175, 186].

Tactile sheet This is a medium where, with the use of shapes and textures distributed on a surface, recognizable elements are represented in a way to be noticed by the sense of touch. Although the tactile sheets usually include readable content (Braille), their content is predominantly graphic and symbolic [67, 66, 182, 12].

3.2.2 General background of tactile sheets

Sheets with reliefs have been used as a means for blind people to appreciate diverse graphic elements through touch such as different types of drawings, mathematical and statistics graphs, maps, and even building blueprints. The implementation of these sheets can be traced to the first artistic manifestations of low and high reliefs, especially those made on easier materials to carve such as wood, leather and plastered or waxed surfaces, which could be appreciated by people deprived of vision[12]. However, it was not until the development of specific didactic techniques dedicated to the blind that the tactile sheets became relevant as an assistive and teaching method [41, 175, 36]. Carving and embossing used to be the usual method of producing tactile sheets. Later the advent of materials such as plastics introduced the possibility of molding the sheets.

Evolution of tactile sheets

Although materials such as wood or plaster can be used to produce tactile sheets, laminated polymers and paper are currently the most widely used. Both materials require adequate methods to capture the graphics on them. Below we will list methods of current use with which tactile sheets are produced. Even when these methods vary between manual techniques practically handcrafted, and sophisticated techniques with automated devices, all the mentioned techniques are currently in common use to produce the sheets [51, 67].

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[12] In sculptural art relief is known as the representation of pictorial elements by carving them on a surface displaying only a fraction of the three-dimensionality of the representations. When the relief protrudes from the surface it is called a high relief and when the relief caves in from the surface, it is called low relief. [97, 41]

Manual methods

Sewell pad This is a raised line drawing pad which provides a "quick and dirty" method of making tactile pictures. One places thin sheets of a special mylar polyester film on a rubberized pad and sketches pictures using a stylus with a rounded tip or a ball-point pen to leave a more visible image. The sketched lines pop up, and a permanent image is obtained. The height of image's line is slight, but this pad is a useful means of instant graphic communication with blind people.

Tracing wheel A hand-held tracing wheel is used to press a line or other image into paper mounted on a firm rubber mat. Since the picture is drawn onto the paper from the back, it must be drawn in mirror image. This is a common method to emboss excellent quality images into Braille paper.

Squirted material drawings Intricate patterns of raised lines and tactile images can be traced using elements like heavy acrylic paint or fabric puff paint laid on with a squeeze bottle applicator. A standard hot glue gun can also be used to make raised line drawings on paper, plastic, fabric and wooden surfaces.

Swell paper These are heat-reactive sheets of paper with implanted microcapsules of alcohol. The microcapsules fracture when the paper is exposed to heat and make the surface of the paper inflate. Placing black ink on the paper prior to a heat process provides control over the raised surface areas. This property allows one to make regular drawings on this paper and the darker outlines will turn into raised lines recognizable by touch. Drawings can be done by hand, copied onto the swell paper using a photocopier, or printed with a standard computer printer, then the sheet needs to be heated with a lamp to produce the swelling.

Mechanical and computerized methods

Thermoforming This method requires a Thermoform Duplicator; a heated press that takes the mold and a piece of Braillon sheet. When the press is closed a partial vacuum pulls the heated Braillon sheet around the mold making a faithful copy of the original. This process involves creating a mold, usually made of soft aluminum sheets.

Embossing plates This is a press which squeezes Braille paper between heavy metal embossing plates. The male/female embossing plate pairs are made by a human-controlled machine and require a skilled operator to achieve reasonable quality. A printing press method that utilizes a single embossing plate has been developed where paper is pressed between this embossing plate and a rubber material, however the images are not as crisp as those produced by good quality embossing plate pairs.

Braille embossers Most Braille printers may be switched into a mode for printing graphic images in the form of Braille dots. Many of them have high resolution modes that print dots on a grid with dot-to-dot spacing of order 0.03 centimeters or less. Images printed with small dot spacing feel markedly smoother than those with the standard Braille dot spacing.

Nowadays Braille embossers are computerized devices controlled by a tactile graphics design software where a touchable drawing can be digitally made from scratch or adapted from standard graphics files.

Laser engraving A laser cutter or engraver is a computer controlled device which uses a laser beam to carve or cut different materials. The process of engraving can be done on Braille paper or cardboard, producing touchable patterns in low or high reliefs. In this way very detailed and defined tactile graphics can be engraved on the substrate surface.

Automated tracing devices More recently CNC devices like robotic arms and plotters are being used to trace touchable graphics on Braille paper, sheets of mylar polyester films, or plastic sheets. A computer converts the design produced by CAD software, into numbers. The numbers can be considered to be the coordinates of a graph and they control the movement of the head of the device on the substrate surface. The head of the device might have a tracing tip, a squirted material applicator, or even a laser engraver. In this way tactile sheets can be produced using some of the manual methods, but controlled by a design software.

3D printed sheets One of the most recent technologies in the creation of tactile sheets is 3D printing. Using a CNC device multiple layers of molten polymer material are arranged on the basis of a digital design, resulting in a physical object with the measurements and geometric attributes of the original digital design. In this way it is possible to produce tactile sheets of great durability and in a simpler way than with manual and mechanical methods. Likewise, the level of detail and definition of 3D prints may exceed that of those methods.

Refreshable touchable displays A sheet of cardboard or plastic provided with tactile drawings or graphics is a static medium. Sometimes squirted material might be removed from the substrate surface to redraw tactile images on the same sheet, but in the cases of thermoforming, embossing, engraving or tracing, the drawing is permanent and not refreshable.

In order to increase the ability to read information directly from the computer and interpret graphics, individuals with visual impairments have expressed much interest in the development of full-page refreshable touchable displays. Even though these devices are not considered sheets, they are currently the most sophisticated means to present drawings and tactile graphics in a refreshing and interactive way. However, their diffusion is currently reduced due to the high cost of these devices.

Several projects have used technical alternatives to generate patterns readable to the touch. Elements such as vibrotactile actuators, arrays of vibratory motors or surfaces of deformable materials by thermoelectric elements have been proposed for a touchable refreshable display, however the technology already used by the Braille line displays has become the most accepted and feasible technological option. A full-page refreshable touchable display based on Braille line devices is a multi-line version of standard Braille displays like those already seen in section 3.1.2.

Here we can list the most recent development devices to the date of writing of this work. It is important to note that several of these devices are still experimental projects. Even when they can be acquired, their availability to the public will be, in the best of cases, limited.

- HyperBraille a development of Metec AG[13]
- Graphiti a device produced together by the American Printing House for the Blind (APH) and Orbit Research[14]
- Dotpad from Dot Incorporated[15]

3.2.3 Tactile graphics

To recapitulate, a tactile sheet is a physical medium where a touchable pictorial composition is represented 3.2.1. Those pictorial compositions are the embodi-

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[13] http://www.hyperBraille.de/

[14] https://www.aph.org/graphiti/

[15] https://dotincorp.com/product/dot-pad/

ment of abstract or concrete conceptualizations sketched as a graphical depiction. Synopsizing, a tactile sheet is the physical media and the method to display, and the tactile graphic is the abstract information displayed.

Tactile graphic This is the representation of pictorial elements by means of raised surfaces which make up shapes and textures distributed on an area. A person with a visual impairment can notice by the sense of touch these raised lines and surfaces to acquire a parsed interpretation of the information that sighted people get through looking at pictures or other visual images [67, 56, 66, 182, 163].

According to Presley [182] and Gardner [66], tactile graphics can be seen as a subset of accessible images. Images can be made accessible to the visually impaired in various ways, such as verbal description, sound, or haptic feedback.

In summary, tactile graphic images are used by people with visual impairments to interpret information that sighted people get from looking at graphical contents. For example, students learning geography would be lost without maps of regions being studied. In the same way, tactile graphics are used to represent an extensive variety of pictorial elements, from a sketch of the human skeleton to a complex circuit diagram [12].

From the visual to tactile

When we studied tactual modalities and channels it was portrayed how tactual perception is much less detailed than visual perception. Tactile graphics are not a straight reproduction of the print graphic; for example they do not include color or any other visual additions. It is difficult to make tactile pictures that are very detailed without simultaneously making them confusing to blind readers, so the adaptation from a fully visual pictorial element to a usable tactile image requires careful consideration of what key aspects to depict for the users with visual impairments and tactual channel [182, 163, 58, 56, 67].

- As previously mentioned, tactual channels offers much less resolution than visual ones, consequently they require bigger elements to represent details.
- It is important to recognize that most people with visual impairment have little experience in reading tactile pictures.
- Tactile graphics are not automatically meaningful to users with visual impairments.

- To understand a tactile picture requires that the reader develop an abstract concept about the "real" thing.
- Tactile graphics need to be simple graphics that clearly represent an idea that must be represented in a spatial context.
- A user's ability to comprehend *symbolic representation* is the best indicator of his or her ability to understand tactile graphics.
- The more complex and detailed the graphic is the larger the tactile representation must be to convey the information.

When tactile graphics are introduced to a user who is visually impaired or blind, it is important to recognize the level of development of the reader. A reader will have greater success if they have demonstrated the following skills [56, 247, 133]:

- Concepts of orientation to the environment
- Basic tactual perceptual skills
- Awareness of different views of an object
- Perspective and distance
- Imaginary lines use in 3D drawing

It is important to note that some information can be conveyed through description, and images may be omitted if they do not communicate additional information. Before creating a tactile graphic, one must first decide whether to make it at all, taking into consideration the resources required to produce a tactile sheet and for the reader to process the visual contents [247, 12, 182].

The process to generate a tactile graphic Unlike in the production of tactile sheets, the production of tactile graphics is not a process of manufacture or craftsmanship. The production of tactile graphics involves the analysis and filtering of visual information to be correctly understood through tactile exploration. This analysis and filtering process starts with the identification and classification of all the visual information displayed. The sorting function screens into concrete categories [56, 66]:

(a) Visual information which does not offer relevant data and which can be ripped out.

(b) Visual information which offers data; however, its tactual adaptation represents difficulties for the current available resources, and therefore should be ripped out.

(c) Visual information which offers data, requires to be adapted, and the tactual adaptation is feasible in the current context.

(d) Visual information which offers data and can be tactually represented with very little or no adaptation.

(e) Visual information which offers data, nevertheless its tactual adaptation represents difficulties for the current available resources, although it can be adapted as textual descriptions or through another modality.

The analysis and filtering process is followed by the adaptation stage. Here all the content susceptible to be adapted should be translated to a tactually recognizable format. This stage can include a set of adequacies as follows [163, 56, 66, 182, 67]:

Resizing Adaptable elements might require to be enlarged to optimize their tactual perceptibility. As well, other elements might require to be shrunk to fit them on the tactile layout or to highlight other tactually adapted elements.

Reshaping Some adaptable elements on a picture might require adjustments in their shape to make them more perceptible by touch or to differentiate similar elements which might be confused.

Texturization As on a tactile graphic, colors are not used as a differentiation factor; the deployment of texture patterns becomes a highlighting, differentiation and categorization method. This step might be complex regarding the process of texture patterns assignment to the sets and subsets of adaptable elements.

Relocation The position adjustment of some adaptable elements in a picture might be required to fit in with other steps like resizing and reshaping. It is very important to adjust element locations in a way which keeps the same structure and composition as the source image.

Relief adjustment An additional highlighting, differentiation or categorization method might be the adjustment of adapted elements' height with respect to the plane of the surface of the sheet. This provides a relief which adds

> an extra dimension to convey information in a tactual channel on a tactile graphic. This adaptation is only feasible through production methods which allow the sheet's material deformation or deposition of material on the surface, which is doable for example in thermoforming, 3D-printing or squirted material drawings.

In a hand-made or fully human-operated context these processes rely on the assessment of a designer who evaluates and adapts the visual elements to be translated into a tactile graphic. Jointly, the analysis and filtering process has been studied aiming to generate an automated model capable to do the tactile graphics production process assisted by computerized vision, artificial intelligence, image vectorization applications, and tactile sheet makers like Braille embossers or 3D-printers. Figure 3.1 depicts a flowchart which represents the analysis and filtering process.

Most work on the automation of tactile graphics has been concerned primarily with image processing, especially with forms of edge detection and image segmentation [90, 43, 230].

Ladner and Jayant developed the TGA [123, 100], a platform which supports both batch translation of entire books of figures and translation of individual graphics into tactile formats. TGA is capable of automated label placement, using machine learning to recognize text characters in images, and deal with angled text.

Crombie et al. [43] worked on the G2T, which uses a semiautomatic image processing tool in conjunction with existing drawing tools to produce tactile pictures.

In the work reported by Krufka [119], work is done on automating information extraction from vector graphics images. However, this is limited because many source images are not yet in this format, and image vectorization is a separate process. Pather et al. [171] have deployed a vector-based design software to automate the production of raised-line tactile graphics.

Bornschein et al. [29, 30] have studied the use of collaborative methods between sighted designers and users with visual impairments aiming to obtain effectively understandable tactile graphics in an empirical real time environment. This real time simultaneous design and look over experience is possible implementing a refreshable tactile display.

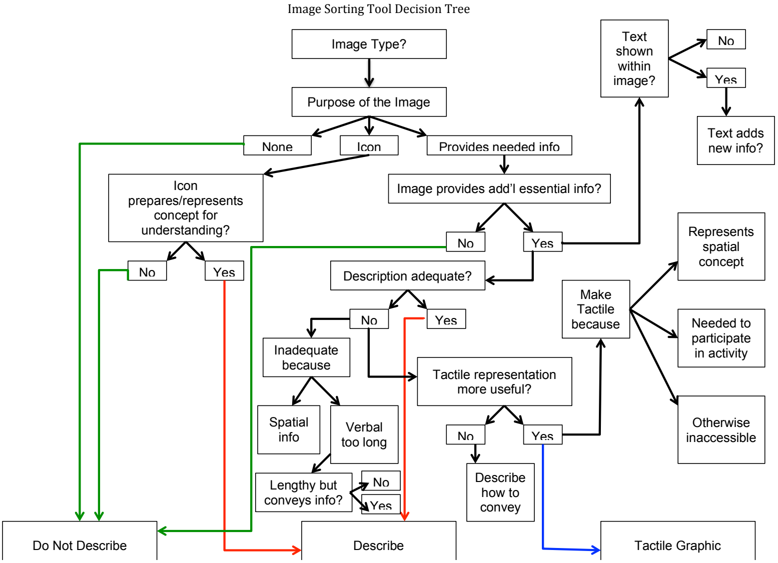

Figure 3.1: This flowchart is designed to help determine the purpose of the image, and whether it can be omitted or described, or whether a tactile graphic should be created [12].

A classification of tactile graphics

Tactile graphics as a whole share a series of characteristics and attributes, however they can be differentiated into subsets which should facilitate their study and development. The establishment of a taxonomy that classifies the tactile means of accessibility for users with visual disabilities must be done based on functional and defined characteristics.

Gardner [67, 66] has proposed in his compilations a classification based on the use of the three-dimensional axis in the preparation and design of tactile graphics. In this way we have *variable height tactile graphics* and *tactile graphs of Uniform height*. This differentiation is fundamentally based on the amount of information conveyed by the tactile representation. In compiling and studying the current technical possibilities it is necessary to introduce a third classification equally based on the inclusion of transmittable information. The tactile graphics endowed with interactivity offer a functional aspect which, together with the spatial dimensions, confer the temporal dimension with reactivity during the exploration period of the tactile graphic.

Variable height tactile images These are tactile graphics where the variation of heights in their representations embodies relevant characteristics of the displayed concept. The variations in height are not uniform and are part of one of the steps of the process of adapting the components of a source image to its tactile format.

Variable tactile pictures are very useful for conveying three-dimensional shape information such as topographic maps, images of animals, shapes of various objects, and other quasi-three-dimensional pictures. This type of graphic is feasible through production methods which allow a sheet's material deformation or deposition of material on the surface, which is doable for example in thermoforming, 3D-printing or squirted material drawings. More recently, some models of refreshable touch screens have been able to generate graphics with adjustable mobility actuators.

UNIFORM height images Uniform height tactile pictures are the tactile equivalent of visual line drawings and convey only two-dimensional information. The lines and patterns in relief maintain a regular height, therefore they generate figures in a single plane. Gardner [66] has designated this type of graphic as *2D tactile pictures*. With tactile pictures, designs such as diagrams, sketches, blueprints and charts can be represented easily. This does not mean that more complex images cannot be depicted, but in such cases the analysis and filtering of source images requires more abstraction. Another advantage of this type of tactile graphic is that because it is easier to generate the relief of uniform height, it can be made by almost all the previously discussed sheet production methods.

Dynamic tactile graphics This category is proposed out of observing the gradual development of means of presenting tactile graphics, which can be refreshed and used as peripherals in a computer system. It is important to emphasize that the medium where this type of graphic is presented is not a sheet; it would be a device. An interactive tactile graphic can contain information in two, and with the latest developments to date, three. The main characteristic of this type of graphics is that information can be updated according to input provided by the user, and the graphic's changes and updates would be the output. This ability to be modified throughout the period of use adds a time dimension its information display capability, and as previously mentioned, such graphics can be generated with refreshable tactile displays like HyperBraille or Grafity seen on page 59.

Classification based on the displayed information A natural way to classify tactile graphics is given by the type of information they present. This classification allows classification of the graphics according to their use. Thus, for example, a representation of the digestive system would be part of a basic biology class, and a tactile map of a town would be used to facilitate the navigation of pedestrians with visual impairment. Likewise, the production method of these graphs would be determined by their category within this classification.

Mathematical charts A mathematical tactile graph is any representation which displays data, usually numerical, using resources such as lines, vectors, surfaces or symbols to observe the mathematical relationship that they keep with each other. It also refers to the representation of the set of values expressed in a coordinate system and serves to analyze the behavior of a process or a set of elements or signs that allows the interpretation of a phenomenon. Within this classification we can include graphics such as pie or bar charts, graphical descriptions of functions and equations, probabilistic distributions, and vector representations. [49, 12, 182]

Maps and Layouts A map is a simplified graphic representation of the territory with metric properties on a two-dimensional surface, which can be flat, spherical, or even polyhedral. The metric properties of the map depend on the projection used, and make it possible to take measurements of distances, angles or surfaces on it and their relationship with reality, in some cases applying known coefficients for correcting the measurements. On the other hand, layouts or blueprints differ from maps in that the representation is constrained to an architectural space, and the mean of display is almost exclusively two-dimensional.

On tactile maps and layouts for people with visual impairments information is presented through reliefs or raised lines with the help of different lines, symbols and textures. Braille is used to add textual information. Examples of this type of tactile graphics are all kinds of maps; geographical, topographical, political or navigational; tactile layouts provided in airplanes to show rows of seats, emergency exits and restrooms; and building blueprints adapted to a tactile format. [182, 12, 31, 38]

Diagrams and Sketches In educational and professional environments, different types of illustrations are used which use diverse geometric resources to present an obtained proposition for a problem, the relations between different parts or elements of a set or system, numerical data tabulated and interpreted in some type of information scheme, or the regularity in the variation of a phenomenon. The tactile adaptation of these diagrams and schemes has a particular utility since they are widespread communication tools. That students and professionals with visual disabilities can access this type of representations provides a powerful means of understanding concepts and methodologies.

The diagrams and tactile schemes are similar to maps which use the surface distribution of their components as an informative parameter, but differ in that their diagrams represent abstract concepts that do not exist as such in reality. As examples of these we can mention the Block Diagram, Use Case Diagram, Class Diagram, Flow charts, or Pareto Diagram. On the other hand, the schemes simplify existing elements for better understanding and analysis. In this set we can point to the schematics of electrical and electronic circuits, schemas of mechanical components, or exploded schemes of assembly.

The production of these tactile graphics can be executed with the methods previously seen in section 3.2.2, however, given their communicative nature and what is usually required as ephemeral resources, fast and affordable methods are preferred for their elaboration. [237, 236, 238]

General object illustrations Within this category are the greatest number of possibilities of tactile representations. We can include various types of illustrations for educational purposes such as anatomical illustrations (skeleton, respiratory, circulatory, digestive), illustrations of animals and plants, representations of pictorial works, and other types of tactile figures that aim to convey the form and other certain features of objects, living beings or abstract concepts such as numbers or musical notations. Regarding the detail required within this category, it is common to use production methods that allow the generation of tactile graphics with variable height, in order to give the representations a deeper sensation of volume and three-dimensionality. [247, 51, 182]

Recognizable tactile patterns Within the representations and tactile graphics there is a subset of elements that do not represent concepts per se and are limited to differentiating themselves from other similar representations. The implementation of tactile patterns based on the production of textures is not an extended practice because of the diverse functional limitations that the personalized production of this type of figures entails. The texture patterns are used as taggers which, in the absence of the use of colors or other visual indicators, make use of tactile indicators such as the aforementioned textures. These patterns can be produced by means of the previously described methods, however, the use of easily achievable methods and substrates is preferred. [182, 181]

3.3 From Tactile Sheets to Tactile Overlays

Tactile sheets are a medium that provides considerable support to the perception of people with visual disabilities. Through them, people who cannot see are able to perceive elements that in the first instance belong to the visual field. However, even considering the manual or automated methods to produce the tactile graphics and the level of detail that can be achieved in a tactile illustration, these are primarily static elements. In the same way, in the absence of vision the referent of the tactile graphic itself, for example a complex geometry environment, may not be understood in a way compatible with comprehending sighted conventions. In other words, without the understanding of the "bird's eye view" convention, and the fact that a graphic uses space to represent space, the information carried by different kinds of tactile illustrations may forever be incomplete.

Therefore, it is necessary to provide a more functional capability for tactile graphics to grant more information modes, and a way to achieve this is through interactivity. The interactive means given by the refreshable touch displays supplies a functional dynamic element, however the technology available at the time of writing this work offers a resolution well below the resolution readable by the sense of touch. This keeps traditional tactile sheets and illustrations contained in them as a more trustworthy and appropriate assist for now, providing elements of detailed information about shapes, textures and dimensions. It should also be remembered that refreshable tactile displays continue to be devices of prohibitive cost for the majority of individuals with visual disabilities, even for organizations of the blind, so traditional methods will still be required until this barrier is overcome.

Thus, the work to provide interactivity and dynamism to the medium of tactile sheets has encompassed a series of developments that make up the state of the art in this field. Certainly the concepts studied so far directly influence the method developed to provide interactivity to the sheets, and maps and illustrations are subject to different adaptations in direct relation with the primary objective of the graphic in question. We will list the most relevant developments to turn tactile graphics into a dynamic medium as a starting point to delve into the concept of *overlays* which together with tactile interactive peripherals can produce a functional interface environment.

3.3.1 Enriching the tactile graphic experience

The concept of using computers to facilitate access to 2D tactile graphics by users with visual impairments was pioneered by Dr. Donald Parkes, University of Newcastle, Australia, with the Nomad tablet [168]. When connected to a computer, NOMAD promised to enhance the tactile experience by allowing a user to view pictures, graphs, and diagrams, and then to add various features to hear descriptions, labels and other explanatory audio material. The Nomad is a touch-sensitive digitizing pad with a built-in voice synthesizer. It is attached to a computer through a standard serial port connection. A tactile picture is mounted on the Nomad pad, and information about various portions of the picture is contained in an electronic file in the computer. A user presses on some part of the picture, and information about that region is sent from the computer to be spoken by the speech synthesizer on the Nomad. Further, the NOMAD aspired to offer the kind of multi-media, interactive experiences that have exploded on the scene in visual computing [169].

The *interaction model* used by Dr. Parkes has been a reference for the development of other platforms which aim to add auditory and verbal feedback triggered through tactual gestures made directly on the tactile sheet. Touch Graphics Inc., for example, has developed the *Talking Tactile Tablet*[16] [127] or T3 which is a graphic tablet with a touch-sensitive surface that can be used as an input device that uses swell paper to create 3D overlays and connects audio files to parts of the overlays. The device is connected to a computer and run with a programme CD, and has a tactile surface which produces touchable icons that provide audio feedback when they are pressed. It can be used to help visually impaired users to interpret diagrams, charts and maps by producing a tactile, touchable image, and audio feedback [130, 128].

More recently, Baker et al. have been working on *Tactile Graphics with a Voice (TGV) [17, 18]*; a framework to grant tactile graphics with an auditory response. A set of *QR codes* is deployed on key elements of the tactile sheet, the codes interact with a software application running in a smartphone, the device's camera reads the codes, and the application recognizes them. Each code is associated

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[16] http://touchgraphics.com/portfolio/ttt/

with an audio description and the user activates the description through finger pointing on the QR-coded desired element [18].

The use of computer vision systems which can interpret the tactile images and gestures done on them grants more possibilities for a set of faster platforms. This can be seen in works like Fusco et al. [63] TGH, where a camera is mounted above the tactile graphic which tracks the finger of the user to provide additional audio information about the tactile graphic. Similarly, Reichinger et al. [188] present a gesture-controlled interactive audio guide (IAG) based on depth cameras that operate directly on relief surfaces, providing tactile accessibility to 2.5D spatial information based on interactively explorable, location-dependent verbal descriptions.

Pointing assistive devices

Developments like *Nomad and 3T* share the feature of a computerized platform which works as a reading stand. It also detects and processes the tactual input. On the other hand, the TGH separates the tactual input detection and processing in an independent device. In both cases the device provides the auditory and verbal feedback, and the triggering tactual gesture is finger pointing.

An additional evolution of those approaches is the implementation of dedicated devices which combine the action of the tactual input and the processing and feedback. Their main feature relies on the fact that the tactual input must be done using the device instead of on the device.

Within this subset of approaches we can mention the works of Nanayakkara [157], Shilkrot [200] and Kane et al [109] about wearable reading devices previously described on page 54, which have been used to a lesser extent to scan labels and annotations deployed on tactile graphics.

An embodiment of devices that enable the recognition of marks arranged for the subsequent reading aloud of associated verbal labels is smart-pen use-based interfaces [166]. Van Schaack [223] has studied the positive impact on learning through the use of smart-pens currently available to the general public.

Touch Graphics Inc. created the TTP [126, 129], which allows blind users to access information on custom tactile graphics tagged with a proprietary code. The pen contains a small camera used to photograph the proprietary codes. When the pen contacts a tagged area, it reads aloud the corresponding file stored on the pen. Likewise, the Ravensburger's Tiptoy pen[17], and the *Talking PEN*[18], even when they are not dedicated developments of assistive technologies, are used to read verbal labels on tactile graphics.

Interacting with interactive tactile graphics

The tactile interactive sheets as an interface have required the definition of interaction methods during their development as assistive technology. This development has produced concrete guidelines on how to manage input and output in these types of modalities. In this way we have the auditory and verbal feedback as an output method, while the gestures directly on the tactile graphic are shown as the most accepted input.

Output Previously, we have commented that despite the importance of the Braille text for the education of people with visual impairments, a majority of users with visual disabilities do not know the use of Braille or use it in a limited way [114, 201, 196]. Likewise, the deployment of Braille labels or dimensions on the tactile sheets requires considerable space, so the implementation of Braille as an output method for tactile sheets would be limited.

Auditory modality comes up as an intuitive alternative to give a functional feedback. Vasquez et al. [22] were interested in learning what type of auditory feedback was preferred among users with visual impairments during the use of assistive devices. They considered speech, tone, and no feedback, and found that their subjects strongly preferred speech feedback and found it easier to use than either silent or tone feedback. Similarly, Baker et al. [17] found evidence of cognitive overload when using haptic feedback like vibration in the study of their platform *Tactile Graphics with a Voice*.

Input Direct interaction on the sheet and the graphic arranged on it have been shown as the most accepted input channel. Approaches previously mentioned such as those of Nanayakkara [157], Shilkrot [200], Kane et al [109], and others seen in section 3.1.3, support the use of gestures, giving preponderance to pointing with the finger to the desired element. Even though the perception of the tactile graphics keeps the hands of the reader occupied and the attention of the readers is on the graph, Baker et al. [17] have shown that the use of gestures such as pointing with the finger is preferred by those who read tactile graphics. It is appropriate to mention, though, that when using sensitive media to the touch or

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[17] https://www.ravensburger.de/entdecken/ravensburger-marken/tiptoi/index.html

[18] http://www.talkingpen.co.uk/

computer vision, it is necessary to define a series of concrete gestures to properly execute the input tasks avoiding situations like the *Midas touch effect [235]*.

3.3.2 Touch sensitive media

Every time we see an object that catches our attention, our mind asks us to try to touch it, as if it were a way of corroborating that it really exists. It seems that we have an inherent need to interact with what surrounds us through the sense of touch. This is particularly true of people with visual impairment for whom the sense of touch is the most reliable channel to perceive object attributes like position in the space, size, volume, shape, and other properties of physical elements [107, 23, 241, 74].

This behavioral characteristic has been exploited within the context of the development of interaction methodologies seeking a more natural way to interact with devices and gadgets. In this way the development of output peripherals (displays) which could simultaneously receive commands and encompass in a single medium the components of the menu and pointer interaction model, emerges as very close to the diffusion of the widespread use of computing devices.

First developments of touch sensitive displays

Historians attribute the first touch screen to the British E.A. Johnson [101, 102], who developed a capacitive touch screen around the years 1965 and 1967. The inventor described his work in a paper published in 1965 and then detailed it in the following years, with the idea of using this technology in air traffic control.

In the seventies, Dr. Sam Hurst (founder of the company Elographics) made the next great breakthrough. Hurst created a "touch" sensor in 1971 while a professor at the University of Kentucky. This sensor was called Elograph and was patented by the research foundation of the university itself [94]. The Elograph was not a transparent touch screen like the ones we know now; it was rather coarser. Hurst's idea was to use the system to read information more easily. After several years of research and development, in 1977 he and his company finally patented the first touch resistive screen based on five-wire resistive technology; the most commonly used touch screen technology of the day[93].

In 1983, Hewlett-Packard launched one of the first touch-screen computers for commercial use. The HP-150 worked with infrared transmitters and receivers mounted around a Sony CRT 9" screen, which detected the position of any non-transparent object on the screen. However, the sensors often became dirty with dust, which required constant cleaning for proper operation.

The vast majority of significant touch screen technologies were patented during the 1970s and 1980s and the patents have now expired. This has allowed subsequent design of products and components using these technologies to proceed without being subject to royalties, thus enabling the touch devices to spread more easily.

Main types of touch screens

Resistive Basically, a resistive touch screen is composed of two layers of very thin and transparent conductive plastic film located on the screen itself, which allows you to measure the change in resistance produced by the electrical connection that occurs when you press them with the finger or the stylus.

Resistive touch screens are much cheaper to manufacture than the others, but they do not offer the possibility of multitouch; so if we press with more than one finger the device will capture the position of only one of them. In addition, these degrade with the passage of time and it is necessary to recalibrate them.

Capacitive Based on capacitive sensors, these consist of a layer of electrical insulation, such as glass, covered with a transparent conductor such as the ITO (tin-doped indium oxide). As the human body is also an electrical conductor, contact with the surface of the screen generates a distortion of the electrostatic field of the screen, which is measured by the change in capacitance (electrical capacity). Different technologies can be used to determine in which position of the screen the touch was made, and the position is sent to the controller for processing. In this type of screen the image has a higher quality than a resistive screen, the response is better, and some allow the use of several fingers at once (multitouch). However, they are more expensive and must be used with a specialized pointer.

Surface acoustic wave Surface wave technology uses ultrasonic waves that pass over the touch screen panel. When the panel is touched, a part of the wave is absorbed. This change in ultrasonic waves registers the position of the tactile event and sends this information to the controller for processing. The surface wave touch screen panel is the most advanced of the three types, but can be damaged by external elements.

Infrared touch screens Infrared technology bases its operation on the use of infrared emitters and receivers installed along the X and Y axes. This generates a matrix of infrared light on the entire surface of the touch screen, so that when a point is touched the infrared beam is interrupted on both axes, the controller detecting the coordinate where the touch occurs. Among the advantages of this is that you can touch in addition to your finger, with any other object or with gloves. They are also multitouch. However, they also have clear disadvantages; they are expensive and bulky, as well as very sensitive to dirt.

Functional constraints of touch screen for non-visual interaction

At this point we must make categorical observations regarding the fundamental characteristics of touch screens within the context of their use by people who cannot see. Touch screen technology is in principle largely inaccessible to users with visual impairments, as it was designed mainly for a visual identification of the interface to conduct input tasks through tactual gestures, but with no tactual feedback [120, 164]. Unlike the controls on a standard mobile telephone or public access terminal, that can easily be felt through touch, touchscreen technologies do not provide any tactile distinction between controls and display space. Although a visually impaired person can learn the locations and functions of tactile control panels on current mobile telephones and public access terminals, attempting to do the same with touchscreen based devices is much harder due to the lack of tactile distinction between virtual buttons and surrounding surfaces [150, 176].

In all cases the visual touchscreen interface would need to be adapted to accommodate the needs of a user with visual impairments. With the spread of touch screens as the main method of interaction in everyday devices such as smartphones and tablets, making touch screens accessible for users with visual disabilities has been a design requirement.

As mentioned in section 3.1.1, screen reader alternatives are now available both text-to-speech and Braille for commercial touch-screen devices. Primarily the interaction with these assistive elements reverses the action scheme; when a sighted user visualizes the tactile interface and locates the control with which it has to interact, then it proceeds to execute a touch gesture as an input. Alternatives currently available for users with visual impairment involve a primary exploration of the graphical interface shown on the display by means of a *hand sweep*. This action offers auditory and verbal feedback locating the elements of the aforementioned interface. This hand sweeping places a focus on each item explored in a sequential and unique way. The user locates the desired control to interact with, then proceeds to the input of touch gestures as input [52, 176, 246].

Dim et al. [52] and Kane [108, 112] have implemented gesture-based methods to increase the fluidity of the interaction of blind users on touch screen interfaces, El-Glaly et al. [57] and McGookin et al. [150] have investigated the use of touch overlays in which tactual highlights of graphic interface controls are shown with which blind users can locate these controls more quickly and interact with them. These efforts have as a central element the graphic interface shown on the touch screen and are intended to provide access to blind users to the functions of the touch display environment.

Even though touch screens are means that present limiting characteristics for users who cannot interact visually with the contents shown in them, their characteristic of being able to react to tactile events makes these peripherals fundamental to the design of interactions based on touch contact. Thus, the approaches seen in section 3.3.1 can use means such as touch screens to recognize tactile events made on the tactile sheets placed on one of those touch displays, and in this way use all their features like touch gestures and contact detection.

This concept of positioning a sheet on a tactual sensitive medium that encompasses processing, input and output in a compact format, provides an opening to talking about *tactile overlays* as a core element within an interaction concept.

3.3.3 Tactile overlays

As we have seen in section 3.3.1 it is possible to combine tactile graphics with interactive media. With this combination it is possible to obtain a multimodal medium that creates an environment that transmits information in a complementary manner using different channels and modalities. Likewise, as discussed previously in section 3.3.2 we have commented on the potential usefulness of touch screen devices given their wide dissemination and affordability. In this way, the match up of tactile sheets and touch screens has been the subject of research and development within the environment of assistive technologies.

Tactile overlay This is a type of tactile sheet as defined in section 3.2.1, which is positioned on an interactive and sensitive to touch mean, so the tactual elements of the overlay guide the user in the exploration of the environment produced jointly by the sheet and the sensitive mean.

Within the context of this definition it is important to note that the sheets described by Baker et al. [17, 18] or Fusco et al. [63] are not positioned on a sensitive medium; the sensor is separated from the sheet, even in a position above, so that these examples would not enter the *overlay* category.

McGookin et al. [150] have investigated the deployment of a raised paper overlay touchscreen-based interface for an MP3 player, aiming to overcome touchscreen accessibility problems. El-Glaly [57] propose to use a physical overlay on the top of the touch screen. The physical overlay should have a tactile pattern that can guide users with visual impairments to interact efficiently and effectively with the touch device.

Guo et al. [81] have introduced *Facade* a crowd-sourced fabrication pipeline to make physical interfaces accessible by adding a 3D printed augmentation of tactile buttons overlaying the original control panel of home appliances. Blind users capture a photo of an inaccessible interface with a standard marker for absolute measurements using perspective transformation. Then this image is sent to multiple crowd workers, who work in parallel to quickly label and describe elements of the interface. These labels are then used to generate 3D models for a layer of tactile and pressable buttons that fit over the original controls. Users can customize the shape and labels of the buttons using a web interface. Finally, a consumer-grade 3D printer fabricates the layer, which is then attached to the interface using adhesives.

Kane et al. explore methods to access spatial layouts on unmodified multi-touch screens through overlays implemented as semi-transparent windows that reside above a standard application. They propose accessible interaction techniques that improve touch screen usability while preserving an application's original spatial layout. That approach is entirely software-based, and does not require alterations to the underlying touch screen hardware. *Access overlays [110]* is a set of three software-based overlays *(Edge projection, Neighborhood browsing, and Touch-and-speak)* intended to improve the accessibility of large touch screen interfaces, specifically interactive tabletops. *Touchplate [111]* is an arrangement of a passive tactile sheet, a visual tag, and associated software for interpreting touches on, in, or around the touchplate, whatever its placement. The visual tag enables an imaging touch screen to track the touchplate's location and orientation. Finger touches may be tracked around the touchplate's perimeter. Some touchplates have holes cut into their bodies so that touches may be detected inside the touchplate, while others may be made of transparent materials such as clear acrylic plastic, so that touches on the plate can also be detected. Touchplates may contain various tactile landmarks such as edges, grooves, holes, and ridged areas. By convention, the visual tag is typically placed in the top left corner, where it can be felt, in order to help a blind user orientate it.

He et al. [85] introduced TacTILE, a toolchain to support the creation of audio-annotated 3D printed tactile overlays for touchscreens. This approach combines auditory feedback and 3D printed tactile overlays to enhance the accessibility of touchscreens, particularly for graphical data. Overlays are composed of three parts: the name of the overlay in Braille, the 3D printed tactile elements representing the underlying graphic, and the audio-encoded cutouts. Together it employs a custom iOS app. Within the app, the blind user can use the tactile overlay with the app at any time by placing and aligning it at the top of the touchscreen and dictating the name (based on the Braille). Interaction involves exploring the tactile overlay by touch and activating the pre-encoded audio annotations by tapping touchscreen areas exposed by the cutouts.

Brock [31], Chatain [38] and Brulé [33] have studied the implementation of tactile maps deployed as an overlay on a capacitive touch screen. These investigations have demonstrated how the interactivity of the maps granted by the matching up of the overlay and the touch screen, has improved the usability of geographic maps.

Taylor et al. [212] presented a system that uses 3D printing to make tactile maps more affordable to produce, allowing visually impaired individuals to independently design and customize maps, and provide interactivity using widely available mobile devices. The system consists of three parts: a web interface, a modeling algorithm, and an interactive touchscreen application. The web interface allows visually impaired individuals to create maps of any location on the globe. The interactive application uses an approach to 3D printing tactile maps using a conductive filament to provide touchscreen overlays that allow users to dynamically interact with the maps on standard mobile devices. Götzelmann [77] has also implemented 3D-printed maps which are overlaid on a standard touch screen device. Those overlays become interactive through a capacitive 3D printable identification and on-screen tracking for tangible interaction named *CapCodes [78].*

Classification of overlays

By carefully studying the examples shown here, we can observe two basic types of tactile overlays according to their specific function: *Enhanced overlays and Contextualizing overlays.*

Enhancing overlays These are overlays whose function is to highlight in a tactile way elements displayed in the graphical user interface. Generally this type of overlay adapts interface screens with specific elements. Among this type of overlay are those for virtual keyboards, those seen in *Touchplates [111]*, overlays for multimedia playback interfaces, and overlays for home appliance screens such as those presented by McGookin et al. [150] or in *Facade [81]*.

Contextualizing Overlays These are the overlays which show a tactile environment, and this environment is what defines the interactive elements contained in a graphical user interface which is a subjacent element of the entire interactive context. Here we can mention the overlays used to show tactile graphics like *Talking Tactile Tablet [127]*, the Nomad tablet [168], or interactive tactile maps studied by Brock [31] and Götzelmann [77].

3.4 Summary

In this chapter we have been able to observe in detail the various developments within assistive technologies which aim to facilitate access to predominantly visual content for people with visual disabilities. Access to digital content through screen reader software via text to speech or Braille displays represents a milestone in the ability of users with visual impairments to access tools such as web browsing and various educational and entertainment resources.

We have defined the fundamental operative elements of screen reader software, and identified their characteristics and the way they work in the most current interfaces. We also studied the output in Braille as a form of concrete interaction.

We described tactile sheets and graphics, their production methods and their features. We delineated their categories and how they have implemented different technologies to give them interactivity from predominantly static and individual media to an interactive element within a dynamic system to display images through the sense of touch.

We delved into the concept of tactile overlays and the various uses given to this approach. We have seen how the use of current touch screen devices has aided the implementation of tactile overlays in educational activities.

The various approaches and aspects seen in this section make up the state of the art of the research reported in this dissertation. Together with chapter 2 are the theoretical and practical foundations of the development of the proposal of this work. The features, generalities and limitations of assistive technologies, tactile sheets and graphics, and their combination with touch screens as overlays are configured as the starting point for the work of defining an own concept of interaction. In the next section we will describe the process based on the observations detailed in chapter 1, where we defined in detail the functional and non-functional requirements based on careful observation of the needs of people with visual impairments who wish to access digital textual content.

Chapter 4

Requirements

In chapter 2 we defined the main characteristics of the target group of users for this approached system, and delineated how visual impairment characterizes the process of accessing digital content in different modalities including textual content mixed with pictorial and graphical material. In chapter 3 we undertook a comprehensive revision of the state of art related to the already concretized approaches to assist users with visual impairments to access different types of digital textual contents. Thus, to support readers with visual impairments, the proposed approach should incorporate the different characteristics of the process of reading digital contents by users with visual impairments aided by assistive technologies. We should observe and define processes, features and functions which depict in detail how readers with visual impairments access the content within digital textual documents.

We have opted for implementing and designing an assistive system according to a *user-centered design* process as described in section 2.5. Therefore, we first schematize and identify requirements and define interaction concepts. The requirements and concepts that are introduced in this chapter are technology independent and do not rely on the underlying hardware of the assistive system. In sections 2.5.2 and 2.5.2 procedures to investigate are described, aiming to establish a *user experience* conceptualization. We used inquiry and research techniques to define flaws and shortcomings in current approaches, and users' necessities and desires related to the current available platforms to access digital textual contents. We utilized analysis tools to delineate use cases, factual requirements in functional and non-functional aspects, components, and interaction concepts. These elements provide an information core to inform the *Design* stage.

4.1 Delineating the Picture

Research-based development involves adequately defining fundamental concepts about the objectives and needs that the development covers [209, 177]. It is necessary to observe the state of art and the theoretical framework together, and ask the key questions that will help us in the proper process of defining requirements and sketching the picture in its details, nuances and colors.

Requirements frequently start with a vague statement of intent. The first problem is to establish the boundary of investigation and, among other elements, the scope of the intended system. Unfortunately, this is rarely an easy process as target groups often don't know exactly what they want, and knowledge about the intended system is vague. Scoping tends to be an iterative activity as the boundaries become clearer with increasing understanding of the domain shared by all the participants [177, 234].

Previously we have addressed different general characteristics and details already deployed to adapt computerized contents to make them accessible for users with visual impairments. However, a user-centered requirements engineering process requires a deep understanding of the users' necessities related to the particular situation to approach a proposed system. In preceding chapters 3 we defined how textual documents display relevant information implicitly coded into the visual layout elements, and illustrated how this implicit information enhances the acquisition and comprehension of contents. We initially established as part of our state of art (see section 3.1.4), how readers with visual impairments have little or no access to most of those elements defined as implicit information coded in the structures of a regular textual document.

Thus, we outline a situation or circumstance where a concrete group of users requires a process to access a set of information that can improve the experience of accessing textual digital documents. There are specific challenges related to this which need to be gathered from the target group, so following the requirement analysis process we conducted a set of queries to collect foundational elements for a user-centered proceeding.

4.2 Studying and Understanding Users with Visual Impairments

Our research work is based on a *user centered* approach, so a mandatory part of the conducted work was to query those groups of users who fit into the characteristics of readers with visual impairments. We designed a set of inquiry tools related to the activity of accessing digital textual contents.

1. We carried out an online survey (see page 83) focused on people with visual impairments where we asked about the main difficulties of exploring different formats of computerized documents and the approaches they used to conduct the exploration. We also asked about their main needs and requirements for exploring computerized text contents.
2. We conducted a comparative study of existing skim-reading strategies in sighted and visually impaired individuals (see page 87). Using a think-aloud approach, we identified key features of visual documents that allow sighted users to adopt a highly flexible and goal-oriented approach to skim-reading. We noticed first-hand how these features are mostly lost when documents are accessed in auditory form, as is commonly the case for visually impaired individuals, and how this group has to fall back on either less efficient or cognitively more demanding exploration strategies.

The information collected in these queries became a *foundational empirical core*, which together with the theoretical framework, provide the basis for the practical and factual part of this research.

4.2.1 Online survey

This survey was conducted to collect information about the process of exploration of digital documents by people with visual impairments, their main difficulties and applied strategies to access this type of computerized contents. The survey had 25 questions divided into seven parts. It was implemented in an online format using the Lime Survey platform[19]. Because the subjects were people with visual impairments the accessibility of screen readers was tested before the survey was released. Sixty nine participants completed the survey with the following results:

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[19] https://www.limesurvey.org/

Demographics In this section of the survey we took metrics of the whole group of our participants, and we found that 45 participants were male, 52 were female and 2 identified as Not Binary. The mean age was 43.3 with a standard deviation of 10.5, 53% were currently working, 16% were currently unemployed, 20% were students and 11% were retired. We gathered participants from the following countries: United States, Spain, Argentina, Romania, Costa Rica, Panama, Australia, Colombia, Venezuela, El Salvador, Dominican Republic, Guatemala, Serbia, Chile and Zimbabwe. Sixty three percent of the participants identified themselves as blind; 37% as severe low vision. Fifty six percent of the participants had their current level of visual impairment from birth or early childhood, 24% answered since my adult age, and 20% answered since my adolescence.

Reading preferences Here we inquired about the methods to access digital textual documents, thus most of our participants (97%)selected text to speech screen readers as their preferred option to access digital textual content; the remaining 3% equally divided between printed Braille and Braille displayed on Braille line displays. Regarding the most preferred text to speech screen reader application, Jaws for Windows was the most used (57%), closely followed by NVDA (41%), and Voiceover for MacOS was least used (3%). Participants were also queried about how accessible or inaccessible they perceived a selection of digital document formats (see table 4.1). Plain text and *Ritch Text Format (rtf)* formats were perceived as the most accessible formats through a *likert* scale where 1 was the least accessible and 5 the most accessible. *Microsoft Powerpoint (ppt)* and *Portable Document Format (pdf)* were perceived as the least accessible formats. Fifty eight percent of the participants commented that their study or work material is provided in MS Word format, and 65% of the participants try to read their study or work material in its original format instead of converting it into a more accessible one.

Skim reading We asked our participants about their possibilities and methods to conduct *skim-reading* on their usual reading material. We used a Likert scale to value concrete statements (see table 4.2), and according to these quantifications were able to conduct some kind of skim-reading adapted to the features of the screen reader and the concrete accessibility of the read document. Participants were asked to describe briefly how they do skim-reading: Twenty seven of the 69 participants answered this question; their comments included using marked headers to jump into sections, increasing the reading speed of the screen reader and looking for key words with a search function. Twenty eight of the participants answered to the question

"What do you think that sighted people do to skim-read a text?", with comments regarding the possibility of sighted people to follow visual markers like font styles and pictures. Regarding the use of bookmarks on the digital reading material, a majority of participants (64%) declared that they use some kind of bookmarking method: Adding a bookmark by writing key strings on the text is used frequently (44%); the use of word processor tools to add bookmarks is not so frequent (16%), and although screen readers offer bookmarking tools, their use is limited (4%).

Special text formats In this section we queried about how aware participants are of the use of highlighting text methods like bold text, italic or underlines, what they are used for and whether they can utilize them while they read digital textual documents. As before we used a Likert scale to value this aspect (see table 4.3). When we observed these values we noticed that readers with visual impairments know about text highlighting formatting, nevertheless they are poorly able to use those features.

Reading perception Here we inquired if participants are aware when a document has a particular visual layout like double columns, non-standard organization of paragraphs or if the text in a page does not occupy all the page space, and if they are able to perceive those details during a standard reading. In table 4.4 we observe how participants are actually aware of those layout particularities; however, as in the previous case, the current accessibility tools do not allow them to notice those mentioned features.

Reading methods This part of the survey asked about the ease with which participants can access their usual reading materials through desktop and laptop computers, and touch screen devices like tablets or smartphones. Table 4.5 shows the details of the Likert scale. We found that desktop and laptop computers present fewer drawbacks to read, and touch screen devices present more difficulties. The poor accessibility of some document formats (like pdf) was mentioned by 19 participants as the main issue for reading with desktop or laptop computers. Regarding touch screen devices, 25 participants commented about a lack of accessible markers to navigate documents, and the need to attach a physical keyboard. Smartphones present similar drawbacks adding the problem of the small display which creates difficulties for interaction with the touch screen.

Find function and note taking This section queried participants about their use of "Find" functions when they read digital text; a statement which participants agreed with. In a slightly lesser way participants agreed to the statement when referring to extracting notes in an additional file to make easier further readings. Details of these queries can be seen in table 4.6.

File format	M	SD
Plain text	4.49	1.05
Ritch text format (rtf)	4.17	1.12
Microsoft Word (doc)	4.07	1.09
HTML	3.86	1.03
Epub	3.29	1.29
PDF	2.81	0.99
Microsoft Powerpoint (ppt)	2.29	1.15

Table 4.1: Means (M) and Standard Deviations (SD) of the perception of the accessibility of digital documents. Participants selected from a likert scale from 1 to 5 where 1 is the less accessible format and 5 is the most accessible using text to speech screen readers

Statement	M	SD
I can do some kind of skim reading.	5.03	1.48
I have a clear idea of what Skim Reading is.	5.43	1.7
When I read a digital text document with my usual method I can easily identify and navigate through titles, sections and other marking elements.	5.65	1.36
When I read a digital text document with my usual method I can easily add bookmarks and other markers which I can use in further readings.	4.69	1.67

Table 4.2: Means (M) and Standard Deviations (SD) of the queries about statements related to skim-reading. Participants selected from a likert scale from 1 to 7 where 1 is "Totally disagree" and 7 is "Totally agree"

Statement	M	SD
I know that printed text uses format elements like bold text, italic or underlines to Highlight concrete ideas within a document.	6.09	1.71
When I read a digital text document with my usual method I can perceive format elements like bold text, italic or underlines.	3.74	2.11

Table 4.3: Means (M) and Standard Deviations (SD) of the queries about statements related to text format and layout. Participants selected from a likert scale from 1 to 7 where 1 is "Totally disagree" and 7 is "Totally agree"

Statement	M	SD
When I read a digital text document with my usual method, I can distinguish elements like paragraphs, lists or subsections.	5.59	1.56
When I read a digital text document with my usual method, I can distinguish when a document has a particular visual layout? Like double colums, non-standar organization of paragraphs or if the text in a page does not occupy all the page space.	3.68	1.98

Table 4.4: Means (M) and Standard Deviations (SD) of the queries about statements relating how participants are aware when a document has a particular visual layout. Participants selected from a likert scale from 1 to 7 where 1 is "Totally disagree" and 7 is "Totally agree"

4.2.2 Comparative study about skim-reading strategies in sighted and visually-impaired readers

We conducted a comparative study [144] of existing skim-reading strategies in sighted and visually impaired individuals. Using a think-aloud approach, we identified key features of visual documents that allow sighted users to adopt a highly flexible and goal-oriented approach to skim-reading. These features are mostly lost when documents are accessed in auditory form, as is commonly the case for visually impaired individuals.

We recruited eight sighted participants with a mean age of 26.3 years (SD = 5), of whom four were males, and eight visually impaired volunteers with a mean age of 36.8 years (SD = 11) of whom six were males. The sighted individuals reported normal or corrected-to-normal vision and no color vision deficiency. Of the visually-impaired individuals, five were early-blind with an onset before learning to read and three were late-blind with an onset after learning to read.

Statement	M	SD
I can read properly my work or study digital text material in a desktop computer.	5.82	1.36
I can read properly my work or study digital text material in a laptop computer.	5.91	1.31
I can read properly my work or study digital text material in a tablet with a touch screen.	3.21	2.18
I can read properly my work or study digital text material in a smartphone with a touch screen.	4.55	2.06

Table 4.5: Means (M) and Standard Deviations (SD) of the statements about the easiness which participants have to access their usual reading materials using devices. Participants selected from a likert scale from 1 to 7 where 1 is "Totally desagree" and 7 is "Totally agree"

Statement	M	SD
I use Find function very often to navigate in a digital text document.	5.12	1.76
When I read a digital text documents I extract notes in an additional file to make easier further readings.	4.09	2.39

Table 4.6: Means (M) and Standard Deviations (SD) regarding the usage of the "Find function" during reading and note taking. Participants selected from a likert scale from 1 to 7 where 1 is "Totally desagree" and 7 is "Totally agree"

Six of these individuals were native Spanish speakers with poor to moderate English skills and were therefore tested with Spanish reading material. All other participants were either native English speakers or had a high level of proficiency.

Skim-reading in sighted individuals

The rapid growth of digital content (and the Internet) has resulted in reading behavior that is, arguably, more fragmented and shallow [35]. Indeed, more than 80% of participants in a survey described their screen-based reading behavior as being characterized mainly by browsing and scanning, as well as non-linear [141]. Other prominent behaviors include keyword spotting (72.6%) and reading selectively (77.9%). These features of skim-reading (or skimming) allows one to move one's eyes through large amounts of text quickly, in order to locate crucial pieces of information that would convey the gist of the content without the need to read and comprehend every word [187].

Skim-reading should not be confused with reading, or even speed reading. Indeed, Evelyn Wood who popularized speed reading as a formally taught method in the late 1950s insisted that her students were not skimming but reading instead [214] although the eye-movements of formally trained speed readers suggested otherwise [215]. Skimming is not a substitute for reading; skimmers were less likely than readers to identify statements from perused text regardless of their significance [148]. Nonetheless, effective skimming techniques can enable readers to locate potentially more relevant regions of information, allowing them to establish better memories for important details [53] and to write more accurate text summaries [95]. Eye movement data suggest that effective skimming relies on a process whereby skimmers focus on important text, especially in the beginning to establish context, and then skip ahead to the next section once information gain falls below a particular threshold [54]. In addition, readers who were forced to skim demonstrated a strategic preference for less demanding text, demonstrating a cognitive savvy for maximizing information yield over reading effort [239]. There is little reason for visually impaired readers not to possess a similar capacity for such cognitive sophistication, except that non-visual reading material is unlikely to support skim-reading in the same way as visual text.

Recent years have witnessed a focus on novel tools that support overview reading in sighted individuals [7, 98, 135]. For example, semi-transparent and static overlays for presenting candidate text for skimming have been introduced so as to combat visual blur; a common inconvenience suffered by sighted individuals when scrolling through visual text during skimming [135].

Skim-reading in visually impaired individuals

Some of the features of a document that support efficient skim reading in sighted readers are lost in the transformation for visually impaired individuals. Various solutions have been proposed to mitigate this issue, usually emulating one particular aspect used by sighted individuals when reading for overview such as the ability to seek out sections with important information [4, 5] or providing access to spatial layout and graphical content [11, 194, 195]. This is typically achieved by translating the document for auditory or tactile exploration, respectively.

For reading, visually impaired individuals mostly rely on auditory presentation via screen readers. Here, users have to listen to all available content or develop ways to achieve the equivalence of skim-reading. Some screen readers offer supporting features, such as reading only the first line of each paragraph or to selectively narrate content that matches a pre-specified regular expression. It has been pointed out that such features can lead to disjointed narrations and can result in users needing to re-read content, defeating the purpose of skim-reading in the first place [4]. This has resulted in a push towards developing algorithms for automated text summarization [4, 5, 80, 147, 206] and the development of interfaces that allow seamless switching between summarized and original content [6]. It should be noted that algorithms for auto-summarization are often mechanistic and produce "gold-standard summaries". In contrast, visual skim-reading is adaptive to the current goal of individual users and might demand more than one given summary of the text details. Therefore, there remains potential for developing more diverse methods to support skim-reading for visually impaired users.

There are also various approaches to the use of tactile interfaces for document exploration. These range from emphasizing single words and phrases through tactile vibrations delivered concomitantly with the auditory content [11], to the ability to explore outlines of pictorial material [174, 195], to the facilitation of web browsing, usually by adapting the layout to the restricted size and low resolution of the interface [194, 195].

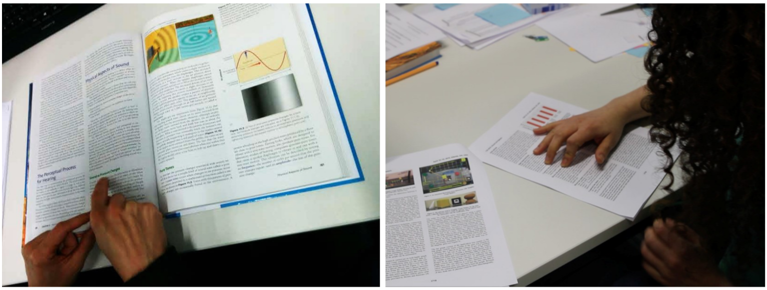


Figure 4.1: Examples of the reading material used in the comparative study: a textbook chapter (left), a scientific article (right) [144].

Method

Participants Eight sighted (mean age 26.3 years (SD = 5); 4 males) and eight visually impaired volunteers (mean age 36.8 years (SD = 11); 6 males) participated in the study. The sighted individuals reported normal or corrected-to-normal vision and no color vision deficiency. Of the visually-impaired individuals, five were early-blind with an onset before learning to read and three were late-blind with an onset after learning to read. The visually-impaired individuals were recruited from the acquaintances of the second co-author, who is a late-blind graduate researcher. Six of these individuals were native Spanish speakers with poor to moderate English skills and were therefore tested with Spanish reading material. All other participants were either native English speakers or had a high level of proficiency. All visually-impaired participants indicated a daily preference for using screen readers over Braille readers.

Study design, materials, and procedure Participants were tested individually. Each participant interacted with two non-fiction document types (see Figure 4.1). Sighted individuals were provided with printed documents. Visually-impaired individuals were presented these documents using the screen reader preferred by each individual participant. The first document was an eight-paged scientific article (for sighted individuals, we used [151], for visually-impaired native Spanish speakers [190] and for visually impaired English speakers [134]).

The articles were selected to be easy to read and comprehend even for non-experts. While we used different articles, they were similarly structured and laid out regardless of language, following the standard layout of scientific articles.

We tested participants in the language they were more fluent and confident reading technical material. Generally, there is no a priori reason to assume that skimming patterns should vary between English and Spanish. Skimming largely relies on spatial markers such as paragraphs, bullet lists etc., which are similarly applied between the two languages. Both are read from top-to-bottom, left-to-right, and use alphabets rather than pictograms.

Participants first read the title and abstract of the paper. Subsequently, all participants were instructed as follows: Take no more than five minutes to gain an overview of the structure and contents of the paper, in order to decide whether in-depth reading is necessary. The second document was a chapter from undergraduate-level textbooks that introduced either the foundations of the sense of hearing (for sighted participants we used [75]), or the concept of multiple intelligence (for visually-impaired participants, we used [65]). These reading materials require no prior knowledge of the topics covered beyond high-school diploma level. For sighted individuals, the book was placed in front of the participant, open-faced at the beginning of the selected chapter. All participants were instructed as follows: Take no more than five minutes to gain an overview of the amount and content of the chapter in order to prepare a study session for an upcoming examination.

For both scenarios, participants were instructed to use their usual approach to this type of overview reading and to "think aloud" while doing so [59]. In particular, we requested participants to verbalize what they were doing and what features of the document they were focusing on during skim-reading. If participants were silent because they were reading continuous text, we did not interrupt them. However, if our behavioral observations indicated that the person was transitioning discontinuously from one passage to the next without verbalizing their behavior, we asked them what they were doing now or encouraged them to keep talking.

Sighted individuals were tested in person. Their verbalizations and interactions with the documents were recorded using a video camera. In addition, two researchers took written notes throughout the session on observed behaviors. Visually-impaired individuals were tested remotely over a conference call by a visually-impaired researcher. Their verbalizations and interactions with the documents were recorded using an audio recorder.

Analysis For the analysis, the verbalizations of the participants were transcribed from the audio and video recordings. In addition, the researchers' notes on observed behavior during the test sessions were compared against their corresponding video recordings and recorded screenreader commands and added to the think-aloud protocols. Both the think-aloud protocols and the observational data were submitted to a thematic analysis [9]. In particular, small behavioral or verbal units were assigned codes, which in a next step were combined into larger categories spanning thematically-related codes. Codes could appear in more than one category.

Results

The results section is structured as follows: First, we describe skim reading strategies of sighted individuals. We found that sighted participants relied heavily on spatially-coded information. Strategies based on spatially-coded information could be grouped into three broad categories: use of macro and micro-structures of the document, and non-linear skimming (these terms are defined in the corresponding subsections). Typical observations from each of these categories are reported. Next, we compare and contrast each of these sighted strategies with the approach that is adopted by visually-impaired users.

We find that the majority of visually impaired individuals are aware that some document features exist that are typically associated with spatial layout in visual documents and that can benefit navigation and skimming. However, the use of these features for skimming is not efficient. This is either due to poor accessibility of these features in typically-formatted documents or due to the loss of the redundant spatial information when texts are converted from a visual to an auditory format. We find two compensation strategies; listening to the entire document linearly (at an increased speed) and cognitive filtering of information. The commonalities and differences between the two user groups are examined in depth in the subsequent discussion section.

Sighted participants

Use of macro-structures Macro-structures are defined as any feature of the document that is at least the size of a paragraph, figure, or table. Participants use macro-structures to quickly navigate through the document. In our sample, the most frequently used macro-structures at the beginning of the interaction with the document were figures ("In the beginning, I only look at the figures. If I cannot understand them I read the caption.”; "I skip this page because it does not have a figure.”) and sections ("I start by reading the beginning of the introduction.”; "I am looking at these subsections, just reading the titles." Figure 4.1 (right) shows how the participant spreads out her hand to point at the different subsections). Sections were identified by their headings and the large empty space before the heading. To gain a crude overview of a section’s content, it was common for participants to only read the beginning of every paragraph and then move on to the next ("I probably read the first sentence of every paragraph until it’s what I want", where the participant was looking for some explanatory information regarding a technical term she did not understand). This strategy mirrors a common writing practice to start paragraphs with a topic sentence, i.e. a sentence that summarizes the main idea developed within the paragraph.

Use of micro-structures Micro-structures are salient features that are embedded into the text. Participants commented that certain information "caught their eye" because it was printed in bold, italic or colored font (about a header: "That’s attractive because of the colors and the boldness of the font." ; or about a quote embedded into the paragraph: "I want to read this because it is italicized."). The text book made strong use of these types of features to structure the text. One participant commented: "I see that there is some text here that is a different color. It tells me the definition of what a pure tone is. So if I want to skim [this chapter], I would try to locate these words that are highlighted in a different color, just to get an understanding of the vocab used in this chapter."

Besides this, several participants identified and spent time reading itemized lists (i.e. bulleted and numbered items) within a block of text, which were largely ignored otherwise ("I see these bullet points here. I think these bullet points have meaningful definitions that are very concise.") Micro-structures were typically attended to at later stages of the document interaction and played a more prominent role in guiding attention in the middle, text-heavy sections of the documents.

Non-linear document exploration Most of our sighted participants (7 out of 8) adopted a non-linear browsing strategy. This included skipping sentences, sections, and entire pages, as well as return referrals to locations that were chronologically earlier in the reading order. Return referrals occurred both to sections that had already been read and sections that had previously been skipped ("I'd probably read the Methodology section last.") The eighth participant mentioned that he usually skims through reading material in a non-linear fashion (e.g. "I would usually read the conclusions first.") However, the behavioral observations revealed that he did not follow this strategy, possibly due to the unfamiliarity of the think-aloud situation. However, we would like to stress that this is the only occasion where we observed an obvious discrepancy between participants' think-aloud protocols and their actual behavior.

Skimming patterns were strongly influenced by the macro and micro-structures of the documents, as discussed in the previous two sections. These structures serve as cues for guiding attention. This happens in two ways. First, the structures provide targets for observer-initiated searches (endogenously guided attention), such as: "I keep on going to the conclusion", or "I am reading the first sentence of each paragraph until it is what I want." These types of goal-oriented searches occurred more frequently at the beginning of the interaction with the document. Second, the macro and microstructures are salient features of the document and as such attract attention involuntarily (exogenously guided attention). In other words, visually salient structures such as section headings, figures, and visually emphasized words attracted attention because they promised high information content and not necessarily because the participant was searching for them.

The skimming pattern was further influenced by the type of document and the associated scenario. Scientific papers have a highly-standardized structure, which all our participants were acquainted with. This prior knowledge facilitated very targeted skimming jumps to sections that were expected to contain valuable information. These jumps could be comparatively large, for instance, to sections of the paper that participants had not yet seen but knew were a part of a scientific paper. For example, one participant stated while reading the introduction: "I am interested in what kinds of visualizations they used. I have to look now where to find them in the paper." Then she skipped through the next pages to the procedure section, where she found a subheading 'Data representations'.

In contrast, text book chapters are more variable in their structure. Here, skimming was initially less goal-oriented and more exploratory, such as paging through the document without reading in order to gain an idea of the length of the document and the density of information from the ratio of written text to supporting illustrative elements like figures and tables ("First, I want to figure out how long the chapter is." For this the participant paged through the chapter rather than use the table of contents on the first page). To subsequently obtain a better idea of the content, participants focused on in-depth reading of the introduction section at the beginning of the chapter, the summary section at the end of the chapter and/or browsed through the document using the section headings. The majority of participants spent extended periods of time looking at figures and figure captions, one participant mentioning that she tried to relate them to the section headings. Lastly, in the textbook, micro-structures like colored text or bold text were attended to earlier in the skim reading process and more frequently, with one participant pointing out that in a good textbook such highlighting of information is to be expected for key terms. Once the defining features of such structures were identified (i.e. the color of key terms), they functioned as targets for large-scale skimming jumps through the document (One participant commented to the question how she went from one part of the document to another: "I just followed the blue words".

Visually-impaired participants

Use of features that are associated with visuospatial layout We observed that participants make use or attempt to make use of four features that are typically coded as a visuospatial structure in visual text documents: namely, TOC, pages and page numbers, section headers, and paragraphs.

Three of eight participants inspected the TOC at the beginning of the text book chapter and commented on the fact that it did not provide links to the different sections of the document, which is a common problem (". . . actually I have never encountered a PDF file with a reliably linked table-of-contents"). Links were considered to potentially provide a useful way of navigating fast throughout the document. Three participants mentioned that if page numbers are accessible, they use them to remember the location of specific information for later searches. Here, pages no longer have the function as spatial holding containers for text but are used like labels for approximately equally-sized portions of the document. However, as one participant pointed out this method had its limits for long documents. Another participant, who used a skimming strategy where he jumped from one page to the next, mentioned that he would prefer section headers to fall at the beginning of a page. This illustrates the arbitrary nature of using page numbers to structure and access documents. Lastly, pages were also used as targets for skimming jumps, as were paragraphs. This is detailed in the section on non-linear document exploration.

Several participants mentioned section headings as important indicators for extracting document structure ("Reading would be faster if I could go to each section and read a bit of each"). In particular, three participants stated that they paid attention for headings while listening to continuous reading. Only one participant used the hotkey combination to actively search for accessible headers (he commented: "To be honest, they are not so common in PDF files, but when you find them it helps a lot to navigate in the document").

Since information about visual micro-structures is typically not transferred into audio representations of the text, participants made no mention of using these, with one exception. This participant detected a bullet list and commented that the automated reading of the bullet symbols disturbs reading flow.

Non-linear document exploration While seven of the eight sighted participants employed non-linear exploration strategies, such as jumping sections of text, only four of the eight visually impaired individuals did so. Of these, two skipped from paragraph to paragraph and the other two skipped from page to page, always reading the first few sentences before moving on. Using this strategy, participants were able to skim the entire document in about 50% of the cases. There were no return referrals, though one participant started re-reading the documents: "Now that I have finished to overview page-by-page I go back to the first page and then I start to read continuously. Now I have a brief idea about what I will find in each page".

In general, while this skipping is similar to the strategy employed by sighted individuals, it is less flexible with regards to the order in which information is taken up. One older participant who lost his eyesight at age 47, and who uses a paragraph-to-paragraph skipping approach remarked: "What I do currently is just to read the whole document. When I was able to see I could use various strategies to overview a printed document. What I do now is not related so much to something like skim-reading, I just read some segments in a linear way ". In other words, though the participant performs skimming, he perceives his approach to be linear compared to how he used to browse through documents. Interestingly, all three late-blind individuals used non-linear document exploration strategies, while only one of the early-blind individuals did so. The other early-blind individuals preferred a strategy where they increased the reading speed of the screen reader. While the numbers are too few to draw definite conclusions, this observation suggests that late-blind individuals, similar to sighted users, make better use of document features that are associated with spatial markers. A likely reason for this is because they retain strategies that they acquired while still having eye-sight.

Increasing the rate of information uptake and cognitive information filtering Alternatively to skipping selected sections, four of the eight participants read the entire document. Three of these temporarily or permanently increased the speed of the screen reader. The fourth person reported typically increasing reading speed but did not do so during the observational study. Effectively, high reading speed increases the rate at which information is taken up. One participant mentioned that this strategy is a reaction to the low accessibility commonly encountered in documents, which prevents skimming-type of navigation through the document. Since the reader has little possibility to identify and target regions of the document with high information content, he or she chooses to listen to everything.

The approach has several consequences. First, it requires increased focused and sustained attention on the side of the participant ("I am very accustomed to the screen reader voice and its speed, but to increase the speed and understand it requires an extra attentional effort ... " ; "I used to read more using Braille and my concentration levels were better than when using a screen reader"). Two participants mentioned having to use earphones/background music to block out additional distractions from environmental sounds. Second, word comprehension can be diminished by higher narration rates ("I don't like to increase the reading voice speed because it is harder for me to understand texts in English").

A third difficulty of this listen-to-everything approach is that information has to be filtered for importance entirely in the reader's mind. We recorded to two coping strategies. One strategy is to allocate attention flexibly in time, i.e. pay more attention to certain sections ("This document talks about types of intelligences, but it also has a lot of accessory information. When I hear something that includes words or phrases related to the main topic, I try to pay more attention."; "I pay attention carefully, but I always miss something. I try to concentrate on key elements; at the moment, I listen for section titles with numbers"). Another strategy we observed was to slow down speed by switching from continuous reading mode of the screen reader to a self-initiated line-by-line reading of the document.

Discussion of findings

The most prominent finding of this study is the contrast between visual and auditory skimming strategies of sighted and visually impaired individuals. Both groups tried to optimize the use of their time by selective information uptake. Sighted individuals do so by relying heavily on visuospatial cues that are coupled to the logical structure of the document and thus communicate the importance of information. These cues are typically provided by the author and are embedded into the spatial layout of the document. They fall into two categories; macro- and micro-structures, which are respectively used at earlier and later stages of the document exploration process. In essence, sighted readers approach document overview reading as a visuospatial search task with the goal of identifying these structures as they are indicative of the regions with the highest information content. In addition to this filter function, the spatial layout of the macro- and micro-structures provides an interface for the (almost) simultaneous access to all information in the document. This allows for quick navigation through the document, including large, targeted jumps across sections and pages, and thus supports the easy extraction of information in non-chronological order. The non-linear exploration of documents provides the reader with control over the order and the speed with which information enters working memory.

In our sample, half of the visually-impaired individuals tried to emulate some of these strategies, such as jumping from one macro-structure to the next for skimming or looking for links in the table of contents that would allow targeted jumps. However, since participants did not have access to the spatial cues associated with the macro-structures or in some cases not even to transformations of the spatial cues (such as accessible labels for macro-structures or functional links in the table of contents), the resulting skimming strategies were suboptimal as compared to visually-guided skimming. This is evident in the use of features that have no connection to the logical structure of the document such as pages (page-to-page skipping) and in the failure to use targeted, large-scale jumps with and against the order of reading.

An alternative strategy was employed by the other half of visually impaired individuals. In particular, they set screen readers to a heightened speed and thus increased their information uptake rate. This strategy requires heightened levels of concentration and places the burden of filtering the information for importance on the side of the reader. Additionally, the linear nature of the information presentation allows little control over which information enters working memory at which point in time. Although we have only subjective reports of increased workload and decreased comprehension in the present study, it is well-established that increasing cognitive throughput taxes working memory, which can lead to increases in perceived effort, stress, and reduced information processing efficiency [233]. Reading at a heightened pace has been shown to negatively affect comprehension [187]. In sum, we observed that sighted participants had more opportunities to flexibly navigate through the document as well as be proactive in formulating goals and searching out sections of the document that contain important information; either information that helped them with getting an overview (such as summaries and introductions) or information that answered specific questions they posed to the reading material. This flexibility was largely based on the use of spatial layout features not available to visually-impaired individuals.

4.2.3 Design implications

From observations done through inquiries described in sections 4.2.1 and 4.2.2, we propose the following *design implications (DI)* to be taken into account when designing non-visual reading interfaces suitable for textual digital document accessing, skimming and exploration.

1. Clear, consistent, and accessible marking of micro and macro-structures of the text: Good writers guide the reader's attention and comprehension process by pre-structuring visual text using macro- and micro-structures. When visual documents are re-formatted for non-visual reading, many of these structures can be lost, either due to low efforts to make the document accessible or because the new format does not support the original feature. The latter is the case when spatially distributed visual text is transformed into an audio file. Here, the two-dimensional nature of the text is linearized into one dimension. Similarly, information about colored or bolded font cannot be translated 1:1 into the auditory domain. Nevertheless, these structures play a crucial role in emphasizing sections with high information content. Therefore, it is important that they be available to the reader in one form or another. For readers to effectively use the structures, they should be easily recognizable and their representation should be consistent across documents. Consequently, our results suggest that future systems targeted at visually-impaired readers should support non-visual implementations of visual micro and macro-structures.

2. Clear connection between logical document structures and structures for navigation: Non-visual features guiding the reader's attention should be connected to the logical structure of the document. Paragraphs and chapters

are good examples for self-contained logical units that have a visual counterpart and should have counterparts in other modes of feedback. In contrast, pages and double-column layouts are examples for macro-structures that carry little information about the logical structure of the text. While pages with different visual layouts can at times function as memory cues for sighted readers (e.g. "I saw that information in the upper right corner of one of the first pages of the document."), pages mostly lose this benefit when used in an auditory document. Here, they become mere labels to more or less arbitrary sections of text and are difficult to remember for long documents. Nevertheless, non-visual documents should allow on-demand access to these features, as they might facilitate the communication between the sighted and the visually impaired (e.g. "Please refer to the third paragraph on the second page.") In sum, we see a need for future systems to provide extended support for the logical structure of the text, irrespective of the visual distribution of labels in document versions for sighted users.

3. Allow for non-linear exploration: Macro-structures connected to the logical structure of the document should be easy to locate and target during navigation. Assigning each macro-structure a unique location in space will allow large jumps through the linear structure of the text to regions of high interest. Future readers for the visually impaired should offer nonlinear browsing and quick jumps between sections based on the document's logical structure. This could be achieved by distributing audio text in 3D-space around the reader or by using tactile interfaces that trace the outlines of macro-structures.

4. Orthogonal emphasis of micro-structures: Visual micro-structures such as bullet points or colored text draw the attention of the sighted reader by 'popping out' of the surrounding text passage and are particularly useful in emphasizing keywords or main ideas. Importantly, processing of the highlighting features (e.g. the bullets) and the textual information do not interfere with each other because they draw on separate processing resources [232]. In contrast, if the highlighting information is translated into a verbal label that precedes the textual information in a screen reader, the highlighting information draws on the same processing resource as the highlighted text and interrupts the continuity of the reading flow. Ideally, highlighting should be achieved by using a mode of emphasis 'orthogonal' to text comprehension and in a manner such that the emphasized unit perceptually pops out. For auditory text presentation that could be a change in pitch or the presentation of additional auditory or tactile stimuli for emphasis, such a peep tones or tactile vibrations [11, 115]. To summarize,

we suggest that future systems should explicitly highlight micro-structures in a non-interfering manner and thus allow more efficient browsing for the visually impaired.

5. Allow for flexible information uptake rate: Regardless of the feedback modality, the user should have the option to flexibly manipulate the information uptake rate-either by changing the presentation speed, as already possible in current screen readers, or distributing information in space such that the user can move through the information at his or her own pace. Another interesting option was proposed by Ahmed et al. [6], who allowed for a seamless switching between the original text and a summary of the text, effectively compressing and decompressing information density. Future systems should implement fast interaction techniques for adjusting the rate of information uptake.

6. Take into account the strengths and limitations of the feedback modality: The visual, auditory, and tactile senses are all suited for perceiving spatial and temporal detail of our environment, albeit at varying degrees. The visual sense has a very high spatial resolution and perceives large amounts of information in parallel (i.e. across the visual field). For this reason, vision is very reliable in extracting spatial relationships between objects and features. In contrast, the auditory sense is better attuned to the perception of temporal detail, such as acoustic cues that are used in speech perception. Spatial resolution for localization and determination of spatial relationships is inferior to vision under normal lighting conditions. The tactile sense falls in between vision and audition, in that it can resolve fine spatial detail, though not at the level of vision, but can also detect high-frequency vibrations, though not at the level of audition. Touch, similar to vision, can build up an inner representation of the precise spatial relationships of objects in the immediate environment, though at a slower pace than vision as less information is perceived in parallel. When designing non-visual interfaces suited for skimming, these strengths and limitations of the senses should be considered. Ideally, auditory and tactile feedback are combined as they are in some ways complementary. The user could receive information about macrostructures and their spatially layout through a tactile interface, while still retaining the possibility of speeded presentation of text through the auditory channel. Thus, users should be allowed to explore documents through different modalities, leveraging the unique capabilities of each sense.

4.2.4 Main conclusions

Over the past years, the importance of accessing digital textual documents has increased. Nevertheless, the accessibility of those contents has not been equitable for those readers with visual impairments. The proliferation of formats of documents and technological media that are not very accessible, limits the possibility of these readers to freely access the immense offering of digital documents.

We conducted two user-centered inquiries aiming to scope restraints and hindrances related to the access and exploration of digital textual documents. We administered an online survey querying about general aspects of accessing digital documents. Jointly, we proceeded with a thematic analysis on the observations of naturalistic skim-reading behavior in sighted and visually impaired individuals.

The online survey showed that text to speech screen reader applications are the preferred option to access digital contents, digital and embossed Braille is relegated to specific situations. Presentation files (PPT) and PDF documents were rated as less accessible than Plain text and RTF formats. Most of the participants get their work and study materials in digital format (MS Word) and they make efforts to read them in the original given format. Most of the participants know about the skim-reading process for a quick overview of a document, nevertheless, most demonstrated that this process presents several difficulties related to the poor accessibility of mainstream skim-reading document features with the current tools. Personal computers and laptop systems offer an easier medium to access digital documents using current tools; touch screen devices still presenting issues with accessible interaction space to explore documents. Users with visual impairments use logical and virtual structures to orientate themselves into digital documents, and if this structure is not available in first place, try to create it using bookmarks and other markers. If it is not possible to access or add a structure to the document then the navigation and exploration task becomes a high load and demanding task.

Through the skim-reading comparative study we acknowledged how technologies for efficient overview reading have been developed for sighted and, to a lesser degree, for visually-impaired individuals. These technologies provide assistance for various aspects of skim-reading, not all of which are equally well implemented for users that have access to visual reading material and those that do not. From this, we were able to identify and contrast features and strategies employed by these two user groups.

We have shown that visual reading is governed by spatial information coding the importance of certain sections of text. Spatial cues can be differentiated into macro- and micro-structures of the text, which play a role in early and late exploration respectively. Readers use these elements of the text as anchors for non-linear exploration of the document, extracting information from different sections in accordance with momentary search goals. In contrast, strategies of visually impaired readers are either less efficient or more attention demanding (or both). There are two reasons for this: a) spatially-coded information in the form of macro- and micro-structures is mostly lost when the reading material is adapted for auditory reading, either because it cannot be recoded into the linearized auditory format or because labeling for accessibility is poor. This forces the readers to skim using less-informative features such as page numbers. b) Readers attempt to compensate for the loss of spatially-coded information by leveraging the unique ability of the auditory sense to resolve fine temporal detail. For this, they increase the reading speed. However, this strategy requires higher levels of attention and concentration and induces additional mental workload. For both of these reasons, non-linear exploration is less common in the visually impaired. From this comparative analysis, we deduce a list of design implications that can be used to guide the development of assistive technologies that aim to enable efficient overview reading and skimming of documents, in order to support equal access for visually impaired individuals to today's information society.

4.3 General Requirements of the Engineering Process

Considering the elements mentioned in the previous section within the requirements engineering process, the defined requirements involve finding out what people want from a computer system, and understanding what their needs mean in terms of design. [70, 191, 136]. Requirements engineering (RE) is the process of discovering that purpose, by identifying stakeholders and their needs, and documenting these in a form that is amenable to analysis, communication, and subsequent implementation" [209, 161].

4.3.1 General analysis

The establishment of requirements is a broad process which must be well focused, otherwise there is a risk of focusing efforts inappropriately or dispersing resources, resulting in far from valuable answers [191]. According to Gause and Weinberg

[70], this process starts with conducting a series of questions which must delimit key elements in a *top-down goal decomposition* approach. Further, Maiden [146] gives hints to address a set of *goal decomposition* questions. Based on those frameworks we have raised a set of questions and defined answers:

1. What is the system purpose (goals)? - To allow readers with visual impairments to access implicit information conveyed by visual layout on textual digital textual contents.
2. What objects are involved? - A processor which adapts digital text contents, a tactile interface which incorporates the tactile representation, and interaction, an auditory platform which interacts jointly with the tactile interface.
3. Where is the system located? - It will be used as a desktop application.
4. When should things happen? - In the moment of use.
5. Why is the system necessary (goals or problems it intends to solve)? Readers with visual impairments cannot access all the information conveyed by a standard digital text document layout because current available accessibility resources grant a limited awareness of those elements.
    (a) Which information can readers with visual impairments access? They can normally access the written textual language.
    (b) Which information can readers with visual impairments not access? They cannot access contextual information given by text layout, any pictorial element, or highlighted text.
    (c) Which information can readers with visual impairments access only with difficulty? Tables of contents, and mathematical elements.

4.3.2 Use cases

After the analysis process we have obtained a set of concepts which define concrete elements to frame an arrangement of requirements and their basis abstractions.

Based in the observation of the situation and the users' feedback we can establish two main *Use Cases (U) [234, 177, 209]* related to readers with visual impairments executing the task of accessing digital textual documents using their regular assistive tools.

1. The user wants to locate a concrete element into the content: In this case the user knows one or more hints which can assist in locating a particular piece of information, a page number, some key words or a category (if the desired element is a regular paragraph, a table, etc).
2. The user must do skim-reading on the content: In this case the user needs to explore the content for its key elements, giving more attention to relevant main topics without investing too much time in details and minutiae.

4.3.3 Requirements

We define the requirements (R) for an assistive system to aid readers with VI, providing access to structural layout of digital documents as macro- and micro-structures. These are either functional requirements, which describe a function that is necessary for the assistive system to work, or non-functional requirements that cannot be measured directly but are very important for the sustaining and adequate usage of the assistive system [234, 161, 191].

Functional requirements

1. Notion of the spatial arrangement: As it was been discussed in previous approaches, the human sense of touch has a perception of location, space and contour only surpassed by eyesight. Spatial arrangements in document layouts give a set of implicit information related to the content's organization and hierarchy. To provide full access to the content to users with VI it is necessary to provide a translation of the implicit pieces of information conveyed by the spatial arrangement of a mainstream document's page.
2. A reliable method to differentiate distinct types of content elements: Information is organized in different types of structure containers (e.g. paragraphs, side-paragraphs, titles and subtitles) which grant hierarchy, categorization and attributes inside a mainstream document's organization. A method which allows a user with VI to distinguish among the different elements displayed as part of the content is required.
3. Auditory user-controlled access to the segments of content: Mainstream accessibility tools for users with VI like screen readers have established a predilection for auditory and TTS (Text To Speech) output modalities, but users with VI opt for auditory feedback over Braille text for practical reasons. Thus, a user-centered design approach points out auditory TTS

based feedback as a functional requirement to access the contents in the different segments of a document's structured layout. This auditory access should offer control in playing, pausing, stopping and resuming tasks, as well as in the levels of granularity of the auditory output.

4. Segmenting the content in an analogous way to the visual layout of the document: To take advantage of a document's visual structuration it is necessary to emulate this layout taking the key features of the structure organization in navigable and differentiable schema within a non-visual interaction space.

5. Random access to content's segments: Mainstream auditory accessibility tools like screen readers display the content in a linear scheme, nevertheless a non-linear access to the structure of a content is usually required. Users with VI should be able to jump from one segment to another regardless of the location inside the content.

6. Content refreshability and interactivity: As it has been mentioned before, media like a pin matrix device (HyperBraille or Graphiti) and fixed tactile representations (tactile maps or TacTILES) offer different functional paradigms. A fixed tactile representation requires a mechanism which allows it to refresh the displayed content. Fixed media like engraved paper foils or 3D-printed overlays cannot update their physical structure, nevertheless enabling the system to identify the individual tactile media used makes it feasible to refresh the interaction space adding a required dimension of interactivity to supply a fluid user experience.

7. Track pages: In a multi-sheet environment the user with VI requires a method to follow up the order of the different sheets. This tracking method should be independent of other components of the system and requires reliability and immediacy.

Non-functional requirements

1. Assurance and stability of the software: The interaction deploying a physical tactile layer as front-end reduces the possibility to manage configurations and settings on the regular electronic device. A sensation of fluidity in the interaction requires reliability and a stable operation of the software component.

2. Manipulability and compactness: As a tactile application the system must be robust enough to support concrete intensities of physical manipulation.

The system should tolerate a user's hand touch and handling, give the tangible sensation of integrity, and allow the user to exchange overlays keeping up the compactness.

3. Affordability of base materials and production: An important detail related to tactile representations adapted for users with VI is the obstacle of the cost of materials and production. The implementation of more economical supplies and making approaches is a key requirement for the utilization of tactile representations as a recurring assistive resource. Moreover, the implementation of commonly used electronic devices as processing platforms improves a system's affordability.

4.3.4 System components

Taking under advisement the already pointed out different requirements, we have set up a collection of interdependent components which embody a proposed assistive computerized system to aid readers with visual impairment to access digital textual documents acquiring the usually accessible textual content and also the information conveyed in micro and macro-structures displayed in the visual layout of a document. This computerized system is composed of hardware and software components; the front end is composed of the set of tactile overlays, the back end is the software which manages the access to the content's segments, and in the middle there is the GUI which literally matches the physical layouts on the overlays with the logical structure of the content.

Next we list the hardware and software components, establishing concrete relationships between a component and the functional requirements which it directly supports.

Hardware components

1. Tactual interface: As this component we identify the engraved paper overlays which display the different tactile patterns which provide spatial layout references (R1, R4), the capability to navigate and differentiate content's elements (R2, R5), and a tactile method to track distinct overlays in a sequential and non-sequential mode (R7).

2. Touch-sensitive physical media: This component provides the response to input commands in the mode of touch gestures allowing a functional tactile interaction. The component might be embodied as a standard capacitive

touch screen, a video hand-tracking platform or any other sub-system which allows a user to interact directly onto an interactive tactile surface (R1, R2).

3. Input and output processor: A computerized device which grants control functions and manages input and output elements (R1 -7).

Software components

1. Matching graphic user interface: A graphic user interface which integrates the visual layout and segments of the digital content to be represented by the system. This component can represent a single page or contain a multi-page environment.
2. Stored adapted digital content: This component includes the software elements which encloses its segments' textual descriptions. Segments are comprised of text which is processed as recognizable verbal output.
3. Feedback manager: A set of control instructions which administers functions between the stored adapted digital content and the matching graphic user interface.

In a non-visual interaction space GUIs require a set of fixed gestures on a touch screen or hotkeys to perform operations which are usually executed by visual pointer/selection tasks done with a mouse pointer or fingertips. Users with VI are perfectly able to learn and memorize a large group of those gestures or hotkeys, nevertheless this process might slow down the acquisition of proficiency in the use of those non-visual interaction spaces.

4.3.5 Interaction concepts

Tactile navigation

A *Tactile navigation interaction concept* refers to the exploration, browsing and actuation using coded touchable elements which are distributed on an area. Implicitly the layout of those elements also codes and conveys information. The tactual interface and the touch-sensitive physical media provide the interactivity features to support this concept.

Skim-reading and other methods of visual exploration on textual documents use structural elements as visual landmarks [141, 187]; likewise in Graphic

User Interfaces visual controls are the basis of a visual interaction model [64]. Correspondingly in this proposed *Tactile Interaction concept* visual structures are modelled on an engraved surface where coded micro- and macro-structures are represented by tactually patterned elements distributed on the mentioned surface. Touch exploration allows the user to recognize touchable patterns and detect the elements' spatial allocation noticing properties and attributes granted to the components of the interaction space. These functional features set up an interactive interface navigation environment based on tactile components and cues.

Refreshing contents based on self-identified overlays

One limitation of a static tactual interface to display graphical contents is that each overlay represents only a single view. Thus, for interaction with an application that supports multiple views, multiple overlays are required, and the displayed content on the touch-sensitive physical media has to be changed manually. This tends to hinder a fluid user interaction. This interaction concept is based on self-identifying overlays; an automated method for touch-screen devices to identify tactile overlays placed on the screen and to adapt the displayed content based on the applied tactile overlay. The user can set out self-identifying tactual interfaces that can request the running application on the touch-screen device to automatically change the displayed content based on the applied tactile overlay. Self-identifying overlays support visually impaired users to interact with different interfaces and enable access to dynamic contents. Static tactual interfaces become an intermediate input signal allowing a more dynamic tactile interaction.

Touchable foreground and digital background

We bring from the field of Tangible User Interfaces (TUIs) [219, 16]; a model where physical representations turn into active input and output elements in an interaction space. In this case, tactual interfaces embodied as tactile overlays represent a two-dimensional tangible component where users can identify and allocate different elements. Moreover, the remaining hardware and software components provide a set of interactive options.

Nevertheless, this interaction concept is not limited to the concrete described components. Hardware components can vary and produce analogous functions, and tactual interfaces coordinated with software components continue to support this interaction concept.

Chapter 5

Design of Representations Based in Tactile Layouts and Auditory Feedback

5.1 Introduction to the Design Process

The information collected during the phase of raising requirements has given us a definite panorama on the different elements to delineate knowledge clearly enough to provide answer to our research question (RQ 1.1) *Which is the most suitable design solution to provide a deeper access to the subtextual implicit information in digital textual documents?* seen in section 1.1.

In this chapter we will present the process and the methods through which the design cycle was executed, which resulted in the set of prototypes corresponding to each iterative stage of development. We will see how the structure of the proposal, the taxonomy and the organization schemes were generated. We will describe how the functioning of the prototypes, their corresponding screens, services and functionalities were defined. In the same way we will see the process of generation of both low and high level prototypes.

Within the methodological context of this chapter, it is relevant to mention that the conceptualization of prototypes and the design approaches were carried out by a person with visual disability of level 4 according to the classification shown in chapter 2 in section 2.1.1. Both the design methods that have considered the direct participation of users and those that raised a deeper understanding of technical aspects had to be adapted in such a way that they were functional for researchers, designers, evaluators and study subjects who presented with a visual disability. The adaptation and accessibility of the entire methodological set have been core aspects of each of the stages of this research, with special emphasis on the phases of information collection, design and evaluation.

Considering the user as a central element of the design process, in the first instance we will proceed to make an analysis of the group of users that are the focus of this investigation. This analysis aims to understand users with visual disability and their main characteristics in the context of access to digital textual content. In order to obtain a set of informative elements about the user group, we chose to generate user profiles which allowed us to manage and organize the set of information corresponding to the user group in a functional and didactic way.

User profiles were generated based on the application of the *Persona method* [40, 183, 96]. These profiles were the model to follow within the design process described here. With this tool we sought to represent all the possible structures of the contents, in correspondence with users' needs and their contexts, together with hierarchizing the themes and contents.

Next, we describe in detail the three stages of development called *Pin display stage, Fixed overlays stage, and Self-identified overlays stage*. It is important to note that each stage had internal stages of information gathering, prototyping and evaluation. The set of evaluation stages are described in chapter 6. Although the narrative structure does not faithfully reflect the iterative process of development used in each stage, we decided to present this description sequentially for a better understanding.

One of the main concerns of this research has been the generation of a comprehensive interaction environment, which, beyond a specific technical development, can be understood as a functional and efficient UX for the access of readers with visual impairments to the greatest amount of information presented in the digital textual content. Thus, we will proceed to the description of the design of the mentioned UX environment. We take as a basis the information gathered in the development stages previously described, maintaining the iterative and user-centered design scheme.

5.2 For Whom Are We Designing?

During the compilation of methodologies to carry out this research, a present element, or rather, we should say, "absent", has been a concrete method with which we could match the standard design methodologies with the fundamental characteristic that defines the users involved in this investigation.

Users with the practical inability to perceive visual elements are not subject to methodologies which focus on *design cycles* of visual components of a visual interaction environment and which ground a user experience in a visual aspect [225]. Establishing this fact forces the researchers and interaction designers to develop and use methodologies that can be adaptations of already established methods or totally original implementations which adapt to the peculiarity of the subjects, in this case the visual impairment.

The user-centered design framework provides a level of methodological openness that fits with the flexibility to investigate, adapt or create appropriate methods applicable in a design cycle focused on visually impaired users [140, 96, 37, 180].

In this way, regarding the user with visual impairment as the center of this design stage, it is necessary to obtain an understanding of the general features, particular contexts and specific aspects that can define a useful user profile as a general reference within the interaction design, prototypes and user experience.

5.2.1 Users features, their context and aspects

Despite sounding like a truism, we point out that the objective of this research is the generation of an interaction environment that provides enhanced access to users with visual impairments. Thus, the process of defining and understanding our target group starts from the shared characteristic of not being able to visually access digital textual content and the implicit information offered by the elements of the visual representation of its structure. This is the root element from which we will proceed to analyze defining components that must contribute to obtaining user profiles.

Users' features

The loss of the sense of sight generates a concrete situation where the person suffering from this loss confronts relevant modifications in their perceptual environment. The brain reorganizes itself functionally in order to adapt to the loss of visual signal reception [137, 36]; thus, the visual regions of the brain have less volume in blind people than in sighted. On the other hand, when it comes to brain regions not related to sight, the trend is just the reverse: People with visual impairments have more volume in these regions than other people. Therefore, brains of the visually impaired compensate for the reduction in the volume of the visual areas of the brain with the increase in volume of other regions. These modifications can gradually produce characteristics which we have here defined as *Auditory perceptual features, Cognitive-spatial perceptual features, and Tactual perceptual features*.

Auditory perceptual features Research has shown evidence of a number of auditory perceptual features [36, 207, 216] associated with the condition of visual impairment:

- Subjects with visual impairments have much greater perception of ultra-fast synthetic speech and pseudo speech than is generally possible in sighted people.
- Subjects with visual impairments have showed an improved memory for auditory and verbal information as well as an improved serial memory. This improvement appears to depend on an improved stimulus processing and encoding.
- Some people with visual impairments are able to develop echolocation, which demands a subtle processing of sound. Echolocation is based on sounds created by the listener, for instance clicking noises with the tongue, which are reflected from objects. This phenomenon can even serve as an additional sense of orientation.

Cognitive-spatial perceptual features Blindness does not affect the ability to process information, but it does limit the sensory data available [216, 170]. The lack of visual stimuli does not represent a lack of mental representations of concepts such as position or space as previously assumed [62]. On the contrary, the stimulation of the other senses generates alternative mental representations that provide the visually impaired person with a notion of their environment. For example, people with visual impairment, when moving through a corridor with windows, can detect the presence of these by feeling subtle changes in the ambient temperature or distinguish the existing auditory variations between the wall areas and the place where windows are located. Thus, as previously mentioned in section 2.2.1 we can see how people with visual impairment are able to generate abstract conceptions, *Mental representations of spaces and Mental maps of spaces*.

As part of section 2.2.2 we observed how with the available assistive technologies based on auditory screen reader applications the exploration of digital textual contents resembles travel through virtualized ambiances, deploying elements like *marker based navigation* and an adapted variation of *path integration*, seen in 2.2.1, where the kinesthetic feedback is used to internalize keyboard shortcuts or gestures which attempt to provide positional awareness within a digital textual content.

- The process is predominantly linear considering the available interactivity provided by auditory screen readers.
- The exploration requires markers which can be predefined or defined by the user.
- Acquired cognitive structures like mental maps provide support in the exploration.
- We have observed a segmentation of the explored content when sighted and visually impaired readers explore textual material. This segmentation maintains a nesting pattern of *micro and macro structures* [144]. These segmented structures resemble the *micro and macro navigation* processes previously described 2.2.1.
- The skim-reading process conducted by readers with visual impairments on digital textual contents presents functional commonalities with the preliminary exploration process of spaces conducted by travelers with visual impairments to gather relevant navigational information before walking through a physical environment, as we described in section 2.2.1.

Tactual perceptual features As we saw in section 2.4.2, for the visually impaired touch takes on a much more noticeable value, because thanks to it they can feel, examine, observe, and know an immense quantity of information on beings and objects [84]. Also, thanks to touch they can read and assimilate in this way all the information that is otherwise available in books. It should also be emphasized that people with visual impairments can learn to play musical instruments and write on the ordinary keyboard of any computer using only the sense of touch.

Tactual perceptual features are noticeable through Braille reading. The Braille code consists of a 6-cell, 3 x 2 rectangular matrix, with dots being present in some or all of the cells for a given character. Braille symbols are formed by raised points on the page separated from each other by 2.5 mm and 4 mm wide, the point height no less than 0.4 mm. These characteristics are slightly larger than a two-finger touch threshold at the fingertips. Experienced Braille readers can explore words almost as quickly as a sighted person can read aloud: a speed of about 100 words per minute, due to the high sensitivity of the fingertips containing a large number of mechanoreceptors, (especially small receptive fields), and also because there is more brain tissue dedicated to the sensory information coming from the tips of the fingers [241]. Conjointly, Goldreich [73] and Grant [79] have studied how tactile acuity in general is enhanced in people with visual impairments.

Users' context

Specificities and circumstances faced by people with visual impairments embody a set of functional, educational and social challenges which contribute to our users' environment *(context).* Although those context elements are affected by the condition of visual impairment, they are not directly related to the impairment's nature or circumstances.

Socioeconomic context The situation of the person with visual disability with respect to their economic capacity, purchasing power and access to services and diverse goods.

Sociocultural context The situation of the social environment with respect to the acceptance and inclusion that people with visual impairment have in different work, educational or social environments. This also refers to the perception that the immediate social group presents with respect to the visual disability and towards the people who suffer from it.

Psycho-affective context The support network of the person with visual disability, including the quantity and quality of affective links and the ability of the visually impaired individual to manage and create those links.

User aspects

This point refers to those diverse factors that are directly related to the visual disability such as the degree of blindness, its nature and the moment when it was acquired.

Nature of the condition This refers to how the affected person has acquired the disability, for example accidentally, congenitally, or due to a progressive condition. Visual impairments related to an illness or an accident which suddenly cause the condition may lead to depressive disorders [216]. On the other hand, autism and stereotyped behaviors are more likely associated with congenital blindness.

Early or late visually impaired This refers to the moment in life when the visual impairment was acquired. Researchers have not yet defined a clear parameter defining early or late blindness: Some specify the early blindness as around the first year of life, others the first three years. The proportion of life-time without visual experience has been proposed by Lebaz, Picard, and Jouffrais [133]. This value is calculated as the ratio between the life-time spent with blindness and the current age.

Psychosocial implications related to the visual impairment Visual impairment carries psychosocial implications which mark affected people's everyday lives.

- The inability to freely access diverse contents negatively affects the complete integration of individuals in collective training and education activities [106, 125, 76].
- Tasks like approaching inaccessible means or materials, mobilizing in an unfamiliar environment without support, or the continual self-perception of dependence, can become situations of great frustration, anxiety and stress for people with visual disability [139, 106, 91].
- Often people with visual impairments travel less, which influences their personal and professional life and represents a drawback for their social integration [170].

Definition of users' profiles

Beyond the condition of visual disability, our users have general characteristics that define them within a specific user segment. Elements such as age, gender, and academic level are fundamental for understanding users in a *UCD* context. Other elements such as the ability and previous experience in the management of technologies acquire relevance in the framework of a design cycle of human computer interaction oriented towards the accessibility of digital contents. It is therefore necessary to devise a methodology which allows us to place the user at the center of the design process, considering the features, contexts and aspects previously seen. Likewise, our methodology must allow us to functionally manage in the design cycle the subjects' participation by taking the greatest possible assets from the time given and the feedback that those subjects provide us.

5.2.2 Personas within the current user-centered design context

The Personas method is a tool that provides a connection at several levels between the designers and the target group of the design. Personas are *hypothetical archetypes* of actual users. They are not real people, but they represent real people during the design process [40, 183]: A persona is a fictional characterization of a user, whose purpose is to make the users seem more real, and thereby help designers keep realistic ideas of users throughout the design process. Personas have proper names that are often catchy and related to their user group name, for example using the same initial letters for the name and the role, such as Helen Rand-Smith: Human Resources Specialist, and are represented with pictures. Designers and evaluators refer to personas when considering design specifics; for example, "Would Helen know to click on that button to add a new employee?" Personas put a name, face, and characteristics on users to keep the users in the forefront of design decisions [87].

A persona includes specific characteristics, demographics, and experience levels from a user profile, for example, a specific hardware and software configuration. Additional information in personas are personal details such as behaviors, attitudes, motivations, and goals [183]. User group profiles cover a range of characteristics, and personas use specifics: *The more specific we make our personas, the more effective they are as a design tool* [40, 183]. For example, instead of saying John uses an ATM once a week, we would say John uses the ATM on his way home from work on Mondays to get cash to buy vegetables in a street market.

Personas usually range from a single paragraph to a full page, and include an image of a person, which can be a sketch, a picture cut out of a magazine, or a stock photo. Putting personas on a large poster in the design room helps keep them in the forefront during design sessions.

Including Accessibility Considerations in Personas

A persona with an impairment includes the same specific characteristics, demographics, experience level, and personal details previously mentioned. Personas that include accessibility considerations also include a description of the limiting condition (disability or situational limitation) and the adaptive strategies for using the product, such as:

- Nature of limitation (for example, blind, unable to use mouse, operating in noisy environment).
- Special tools or assistive technology used (for example, uses a magnifying glass to read text smaller than 16 point, uses screen reader software, stops machinery to hear mobile phone).
- Experience and skills with the relevant tools or assistive technologies.
- Frequency of use of relevant tools or assistive technologies.

Remembering Individual Differences People with disabilities are very different from each other. However, designers commonly fall into the trap of assuming that information from one persona with a disability applies to all people with disabilities. Ideally, designers will observe many different people with different disabilities interacting with the product to help them understand the variability. The fewer interactions designers have with people with disabilities, the more important it is to remind them of the variability among users, so including with the persona a note about the variability among people with disabilities helps avoid that trap [180].

There are key statements to keep in mind during the design cycle regarding assistive solutions and the use of personas [183]:

- People are diverse.
- All users, including users with disabilities, may use your solution in different ways: People use different interaction techniques, adaptive strategies, and assistive technology configurations.
- People have different experiences, expectations, and preferences.
- This persona is just one example of a user in the user group.

personas

Throughout the development of this research we have been able to interact with people with visual disabilities who present a variety of profiles, with different levels of experience in the use of computer technologies, and different demographics, interests and motivations. In sections 6.2 and 6.3, more detailed data is presented of the people who volunteered their time as participants in the evaluation process described in chapter 6.

By observing the diversity of people who might require a method of access and interaction to text documents such as those proposed in this investigation, the alternative is to synthesize the matter of for whom we are designing. As an option that could facilitate the design work whereby the Persona method emerges as a tool of qualitative value, and therefore has been implemented in the general development process.

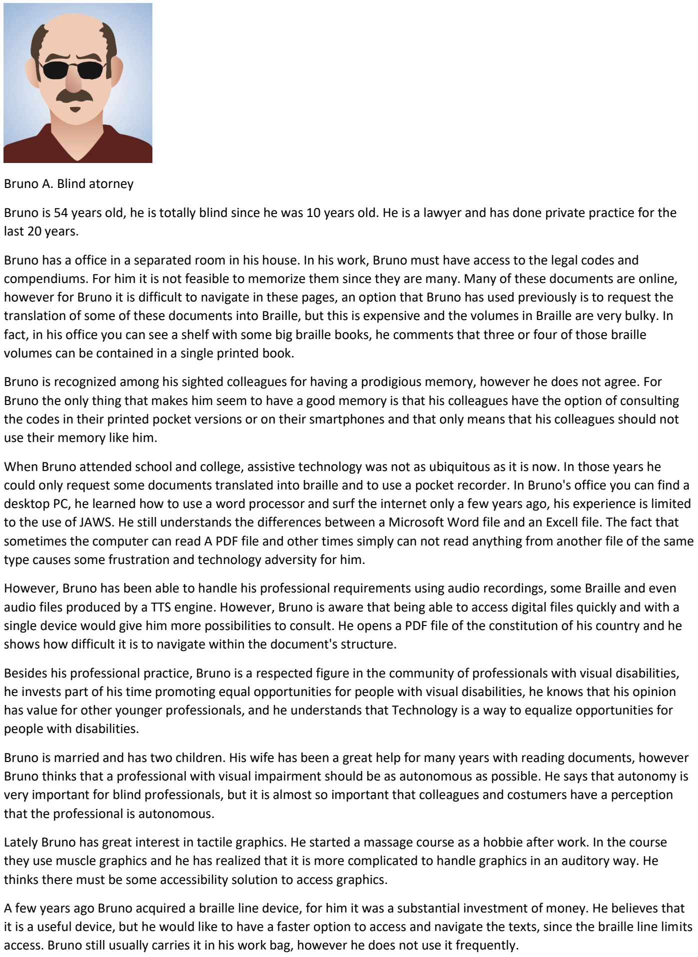
The profiles In the creation of the user profiles we followed a set of three steps recommended by Baxter and Courage [22, 42], and Granollers [96] which took us to a final specification:

Information gathering In this step, contextual analysis was used supported by questionnaires and personal interviews.

Understand the types of users In section 5.2.1 we have structured *users' features, context and aspects* based on our theoretical framework seen in chapter 2. Conjointly, we already know that the scenario and task shared by all profiles must provide access to text documents which present relevant components of implicit information through their logical and visual structure.

Profile creation For the profile sheet preparation, the following fundamental elements were considered: demographic characteristics, work, experience, level of studies, experience using interactive systems, tasks to be carried out (with the system to be designed), technology availability, personal attitudes and values

Profile sheets In the profile sheets we proceeded to construct archetypes using a narrative method, highlighting relevant elements of the profile by means of a simple structure without making use of points or sections. Drawings were used to visually represent a persona's embodiment instead of photographs in order to maintain the anonymity of the aspects and features given to each persona profile. The result of this development can be seen below:



Bruno A. Blind atorney

Bruno is 54 years old, he is totally blind since he was 10 years old. He is a lawyer and has done private practice for the last 20 years.

Bruno has a office in a separated room in his house. In his work, Bruno must have access to the legal codes and compendiums. For him it is not feasible to memorize them since they are many. Many of these documents are online, however for Bruno it is difficult to navigate in these pages, an option that Bruno has used previously is to request the translation of some of these documents into Braille, but this is expensive and the volumes in Braille are very bulky. In fact, in his office you can see a shelf with some big braille books, he comments that three or four of those braille volumes can be contained in a single printed book.

Bruno is recognized among his sighted colleagues for having a prodigious memory, however he does not agree. For Bruno the only thing that makes him seem to have a good memory is that his colleagues have the option of consulting the codes in their printed pocket versions or on their smartphones and that only means that his colleagues should not use their memory like him.

When Bruno attended school and college, assistive technology was not as ubiquitous as it is now. In those years he could only request some documents translated into braille and to use a pocket recorder. In Bruno's office you can find a desktop PC, he learned how to use a word processor and surf the internet only a few years ago, his experience is limited to the use of JAWS. He still understands the differences between a Microsoft Word file and an Excell file. The fact that sometimes the computer can read A PDF file and other times simply can not read anything from another file of the same type causes some frustration and technology adversity for him.

However, Bruno has been able to handle his professional requirements using audio recordings, some Braille and even audio files produced by a TTS engine. However, Bruno is aware that being able to access digital files quickly and with a single device would give him more possibilities to consult. He opens a PDF file of the constitution of his country and he shows how difficult it is to navigate within the document's structure.

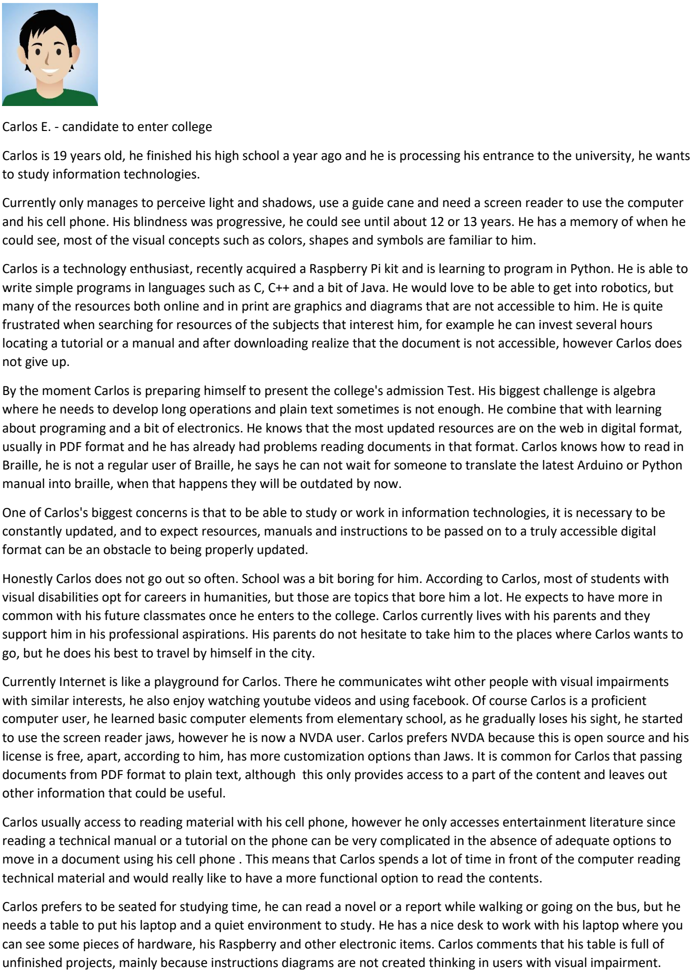
Besides his professional practice, Bruno is a respected figure in the community of professionals with visual disabilities, he invests part of his time promoting equal opportunities for people with visual disabilities, he knows that his opinion has value for other younger professionals, and he understands that Technology is a way to equalize opportunities for people with disabilities.

Bruno is married and has two children. His wife has been a great help for many years with reading documents, however Bruno thinks that a professional with visual impairment should be as autonomous as possible. He says that autonomy is very important for blind professionals, but it is almost so important that colleagues and costumers have a perception that the professional is autonomous.

Lately Bruno has great interest in tactile graphics. He started a massage course as a hobbie after work. In the course they use muscle graphics and he has realized that it is more complicated to handle graphics in an auditory way. He thinks there must be some accessibility solution to access graphics.

A few years ago Bruno acquired a braille line device, for him it was a substantial investment of money. He believes that it is a useful device, but he would like to have a faster option to access and navigate the texts, since the braille line limits access. Bruno still usually carries it in his work bag, however he does not use it frequently.

Figure 5.1: Hypothetical archetype created with the name of Bruno based on experienced senior professionals with visual disabilities.



Carlos E. - candidate to enter college

Carlos is 19 years old, he finished his high school a year ago and he is processing his entrance to the university, he wants to study information technologies.

Currently only manages to perceive light and shadows, use a guide cane and need a screen reader to use the computer and his cell phone. His blindness was progressive, he could see until about 12 or 13 years. He has a memory of when he could see, most of the visual concepts such as colors, shapes and symbols are familiar to him.

Carlos is a technology enthusiast, recently acquired a Raspberry Pi kit and is learning to program in Python. He is able to write simple programs in languages such as C, C++ and a bit of Java. He would love to be able to get into robotics, but many of the resources both online and in print are graphics and diagrams that are not accessible to him. He is quite frustrated when searching for resources of the subjects that interest him, for example he can invest several hours locating a tutorial or a manual and after downloading realize that the document is not accessible, however Carlos does not give up.

By the moment Carlos is preparing himself to present the college's admission Test. His biggest challenge is algebra where he needs to develop long operations and plain text sometimes is not enough. He combine that with learning about programing and a bit of electronics. He knows that the most updated resources are on the web in digital format, usually in PDF format and he has already had problems reading documents in that format. Carlos knows how to read in Braille, he is not a regular user of Braille, he says he can not wait for someone to translate the latest Arduino or Python manual into braille, when that happens they will be outdated by now.

One of Carlos's biggest concerns is that to be able to study or work in information technologies, it is necessary to be constantly updated, and to expect resources, manuals and instructions to be passed on to a truly accessible digital format can be an obstacle to being properly updated.

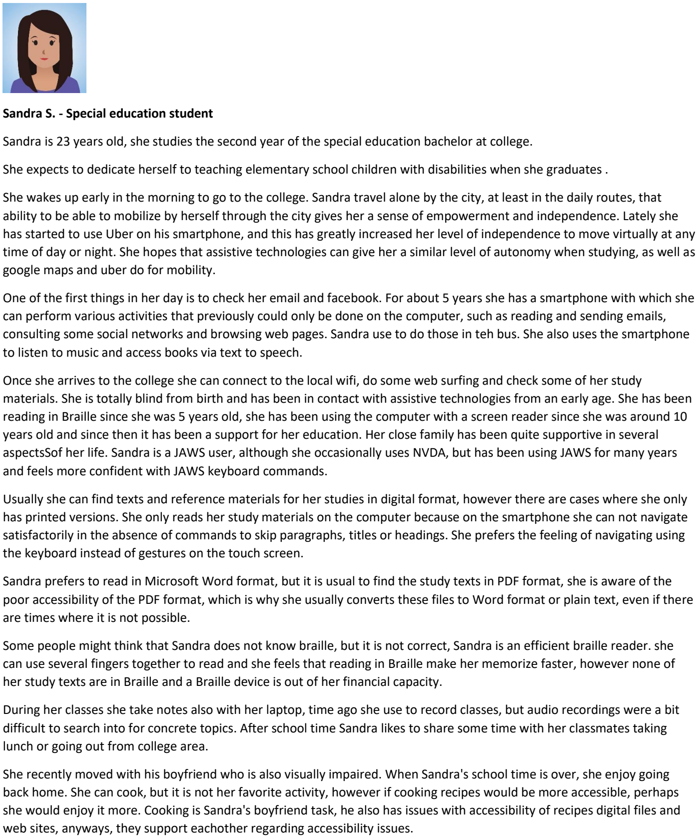
Honestly Carlos does not go out so often. School was a bit boring for him. According to Carlos, most of students with visual disabilities opt for careers in humanities, but those are topics that bore him a lot. He expects to have more in common with his future classmates once he enters to the college. Carlos currently lives with his parents and they support him in his professional aspirations. His parents do not hesitate to take him to the places where Carlos wants to go, but he does his best to travel by himself in the city.

Currently Internet is like a playground for Carlos. There he communicates wiht other people with visual impairments with similar interests, he also enjoy watching youtube videos and using facebook. Of course Carlos is a proficient computer user, he learned basic computer elements from elementary school, as he gradually loses his sight, he started to use the screen reader jaws, however he is now a NVDA user. Carlos prefers NVDA because this is open source and his license is free, apart, according to him, has more customization options than Jaws. It is common for Carlos that passing documents from PDF format to plain text, although this only provides access to a part of the content and leaves out other information that could be useful.

Carlos usually access to reading material with his cell phone, however he only accesses entertainment literature since reading a technical manual or a tutorial on the phone can be very complicated in the absence of adequate options to move in a document using his cell phone . This means that Carlos spends a lot of time in front of the computer reading technical material and would really like to have a more functional option to read the contents.

Carlos prefers to be seated for studying time, he can read a novel or a report while walking or going on the bus, but he needs a table to put his laptop and a quiet environment to study. He has a nice desk to work with his laptop where you can see some pieces of hardware, his Raspberry and other electronic items. Carlos comments that his table is full of unfinished projects, mainly because instructions diagrams are not created thinking in users with visual impairment.

Figure 5.2: Hypothetical archetype created with the name of Carlos based on young graduates from high school.



Sandra S. - Special education student

Sandra is 23 years old, she studies the second year of the special education bachelor at college.

She expects to dedicate herself to teaching elementary school children with disabilities when she graduates .

She wakes up early in the morning to go to the college. Sandra travel alone by the city, at least in the daily routes, that ability to be able to mobilize by herself through the city gives her a sense of empowerment and independence. Lately she has started to use Uber on his smartphone, and this has greatly increased her level of independence to move virtually at any time of day or night. She hopes that assistive technologies can give her a similar level of autonomy when studying, as well as google maps and uber do for mobility.

One of the first things in her day is to check her email and facebook. For about 5 years she has a smartphone with which she can perform various activities that previously could only be done on the computer, such as reading and sending emails, consulting some social networks and browsing web pages. Sandra use to do those in teh bus. She also uses the smartphone to listen to music and access books via text to speech.

Once she arrives to the college she can connect to the local wifi, do some web surfing and check some of her study materials. She is totally blind from birth and has been in contact with assistive technologies from an early age. She has been reading in Braille since she was 5 years old, she has been using the computer with a screen reader since she was around 10 years old and since then it has been a support for her education. Her close family has been quite supportive in several aspectsSof her life. Sandra is a JAWS user, although she occasionally uses NVDA, but has been using JAWS for many years and feels more confident with JAWS keyboard commands.

Usually she can find texts and reference materials for her studies in digital format, however there are cases where she only has printed versions. She only reads her study materials on the computer because on the smartphone she can not navigate satisfactorily in the absence of commands to skip paragraphs, titles or headings. She prefers the feeling of navigating using the keyboard instead of gestures on the touch screen.

Sandra prefers to read in Microsoft Word format, but it is usual to find the study texts in PDF format, she is aware of the poor accessibility of the PDF format, which is why she usually converts these files to Word format or plain text, even if there are times where it is not possible.

Some people might think that Sandra does not know braille, but it is not correct, Sandra is an efficient braille reader. she can use several fingers together to read and she feels that reading in Braille make her memorize faster, however none of her study texts are in Braille and a Braille device is out of her financial capacity.

During her classes she take notes also with her laptop, time ago she use to record classes, but audio recordings were a bit difficult to search into for concrete topics. After school time Sandra likes to share some time with her classmates taking lunch or going out from college area.

She recently moved with his boyfriend who is also visually impaired. When Sandra's school time is over, she enjoy going back home. She can cook, but it is not her favorite activity, however if cooking recipes would be more accessible, perhaps she would enjoy it more. Cooking is Sandra's boyfriend task, he also has issues with accessibility of recipes digital files and web sites, anyways, they support eachother regarding accessibility issues.

Figure 5.3: Hypothetical archetype created with the name of Sandra based on adult university students looking for a professional future.

5.3 Stages of the Concept

In chapter 3 we were able to observe a detailed description of technical methodologies used by people with visual impairments to access textual, graphic and mixed content, in printed, electronic, and combined (print + digital) media approaches. In chapter 4 we specified a series of functional requirements which must be present in an interactive system which aims to provide access to visual and graphic content to people with visual impairments, including access to the implicit information provided by the logical and visual structure of those contents.

Thus, the accessibility solutions for reading textual digital documents currently available to users with visual impairments do not offer adequate access to the different levels of information provided by the logical and visual structure within those documents. Neither tactile applications such as Braille text nor solutions based on auditory response such as screen readers or audiobooks offer a fully functional display of the structure, giving, in multiple cases, accessibility only to the text, and obviating relevant structural details such as the differentiation of paragraphs or other blocks of text.

In chapter 4, in order to define specific requirements, we conducted queries where users with visual impairments provided their feedback regarding the various methods used to access and interact with textual content in digital formats.

We carried out an online survey (see page 83) among people with visual impairments where we asked about their main difficulties to explore different formats of digital documents. The survey also inquired about their approaches to explore digital textual documents. The participants gave concrete information about their main needs and requirements related to the exploration of computerized text contents.

This survey was conducted to collect information about the process of exploration of digital documents by people with visual impairments. Sixty nine participants responded, pointing out their main difficulties and strategies to access this type of computerized contents. The survey had 25 questions divided in seven parts, and was implemented in an online format using the Lime Survey platform[20]. The subjects were people with visual impairments whose accessibility using screen readers was tested before the survey was released to them. The online survey showed that text to speech screen reader applications are the preferred option to access digital contents; digital and embossed Braille is relegated to very

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[20] https://www.limesurvey.org/

specific situations. Presentation files (PPT) and PDF documents were rated as less accessible documents than Plain text and RTF formats, which were rated as the most accessible. Most of the participants get their work and study materials in digital format (MS Word) and try to read them in the original given format. Most know about the skim-reading process of making a first glance over a document, nevertheless, most noted that this process presents several difficulties related to the poor accessibility of mainstream document features with the currently used tools. Personal computers and laptop systems offer easier media to access digital documents using current tools, but touch screen devices still present issues around accessible interaction space to explore documents. Users with visual impairments use logical and virtual structures to orientate themselves into digital documents, and if this structure is not available in the first place, try to create it using bookmarks and other markers. If it is not possible to access or add a structure to the document then the navigation and exploration task becomes a high load and demanding task.

We conducted a comparative study of existing skim-reading strategies in sighted and visually impaired individuals (see page 87). Using a think-aloud approach, we identified key features of visual documents that allow sighted users to adopt a highly flexible and goal-oriented approach to skim-reading. We noticed first-hand how these features are mostly lost when documents are accessed in auditory form, as is commonly the case for visually impaired individuals, and how this group has to fall back on either less efficient or cognitively more demanding exploration strategies.

Eight sighted (mean age 26.3 years (SD = 5); 4 males) and eight visually impaired volunteers (mean age 36.8 years (SD = 11); 6 males) participated in the study. Sighted individuals reported normal or corrected-to-normal vision and no color vision deficiency. Of the visually-impaired individuals, five were early-blind with an onset before learning to read and three were late-blind with an onset after learning to read. Visually-impaired individuals were recruited from the acquaintances of the second co-author, who is a late-blind graduate researcher. Six of these individuals were native Spanish speakers, with poor to moderate English skills and were therefore tested with Spanish reading material. All other participants were either native English speakers or had a high level of proficiency. All visually-impaired participants indicated a preference for using screen readers over Braille readers.

Through the skimming-reading comparative study we acknowledged how technologies for efficient overview reading have been developed for sighted and, to a lesser degree, for visually-impaired individuals. These technologies provide assistance for various aspects of skim-reading, not all of which are equally well implemented for users who do not have access to visual reading material. From this, we were able to identify and contrast features and strategies employed by these two user groups. We show that visual reading is governed by spatial information coding the importance of certain sections of text. Spatial cues can be differentiated into macro and micro-structures of the text, which play a role in early and late exploration respectively. Readers use these elements of the text as anchors for non-linear exploration of the document, extracting information from different sections of the document in accordance with momentary search goals. In contrast, strategies of visually impaired readers are either less efficient or more attention demanding (or both).

There are two reasons for this: a) spatially-coded information in the form of macro and micro-structures is mostly lost when the reading material is adapted for auditory reading, either because it cannot be recoded into the linearized auditory format or because labeling for accessibility is poor. This forces the readers to skim using less-informative features such as page numbers. b) Readers attempt to compensate for the loss of spatially-coded information by leveraging the unique ability of the auditory sense to resolve fine temporal detail. For this, they increase the reading speed. However, this strategy requires higher levels of attention and concentration and induces additional mental workload. For both of these reasons, non-linear exploration is less common in the visually impaired. From this comparative analysis, we deduce a list of design implications that can be used to guide the development of assistive technologies that aim to enable efficient overview reading and skimming of documents, in order to support equal access for visually impaired individuals to today's information society.

The information collected in these queries together with the *General Requirements Analysis 4.3.1*, the definition of *Use cases 4.3.2*, *Functional 4.3.3* and *Non-functional Requirements 4.3.3*, and *Interaction Concepts 4.3.5*, became a *foundational empirical core* to envision and embody a technological solution to approach the access of textual digital documents by readers with visual impairments. Conjointly, these together with UCD techniques gave us guidelines for a design strategy.

5.3.1 Prototype design strategy

The survey described in section 4.2.1, page 83, as well as the interviews that were the basis for the study seen in section 4.2.2 [144], point to the access to content related to work and school studies as a preponderant need within the problems caused by the lack of accessibility of some text content in electronic formats. Likewise, these two sources indicate PDF and PPT files as the two least accessible formats for readers with visual disabilities. Similarly, access to the implicit information of the logical and visual structures of the documents has been marked as a missing element to fully access content.

Thus, for our persona profiles (Sandra, Carlos and Bruno), a first line requirement is the possibility of improving the accessibility of the digital textual documents that make up their sources of consultation in their studies and work, facilitating their reading and increasing the amount of information that can be acquired in them. Taking this into account, our design strategy points towards content with defined characteristics that we list below:

- The content is in some electronic document format, being the *portable document format (PDF)* the most used.
- The content combines texts, graphics, and information arrangements such as tables and lists.
- The content is clearly segmented and defined in a logical and coherent sequence through graphic design elements intended to facilitate reading.
- The content is organized in relation to topics.

Following these features, we can find some document formats which match this profile. Technical manuals, scientific papers, school books and newspapers have these characteristics.

The design strategy is also delineated by the defined *Use cases 4.3.2*, the attempt to fulfil the *Functional 4.3.3* and *Non-functional Requirements 4.3.3*, and the deployment of the depicted *Interaction Concepts 4.3.5*.

These guideline elements made up a framework where the technological resources seen in chapter 3 can be considered as a base to produce suitable prototypes. Hence, the design strategy can be summarized as follows:

- Use the functional needs of person profiles as a basis for defining characteristics and functions of any prototype.
- Focus on the formats of digital text documents which present greater accessibility difficulties in their contents.

- Use the use cases and interaction concepts as user experience design references.
- Use the functional and non-functional requirements as control milestones in the practical process of prototype design.

Design strategy for content adaptation process

In chapter 2, in section 2.4.1, we revised *Multimodality* as a functional approach to convey information through alternative and *accessible* methods. As we have seen in chapter 3, tactile and auditory channels have been used with varying levels of efficiency to transduce contents into modalities that are accessible to users with visual impairments.

Previously, we established as our target content to be adapted those digital documents that contain texts and other graphical elements. As part of our design strategy we have defined a set of steps in order to analyze documents to be adapted from a graphic and visual mean to an interactive environment of auditory and tactile channels.

Analyze the documents, their macrostructures and microstructures in their logical and visual components to identify susceptible elements to be represented in a tactile or auditory way.

- Delineate which elements of the microstructure represent significant indicators.
- Define which elements of the macrostructure represent significant indicators.
- Determine which elements of the visual structure offer relevant information by means of their location.
- Determine which elements of the visual structure offer relevant information through their representation (color, font style, or size).

Designate which elements shall be represented in a tactile way and which ones in an auditory way.

- Evaluate the available technical features to produce tactile or auditory representations.

- Establish an optimal frame of reference for assigning tactile or auditory representations to each element of the document's structure.

Define appropriate auditory representations for the elements.

- Scrutinize the different components of the structure of documents in order to design auditory representations suitable for their displaying by means of sounds, either with audio icons, earcons or Text to Speech.
- Delineate the preferences of the group of users in reference to auditory feedback.
- Define a point of balance between the available technical capability to generate auditory feedback, user preferences, and the efficiency of the aforementioned auditory feedback options.

Define appropriate tactile representations for the elements.

- Revise the technical alternatives available to generate tactile representations.
- Study the tactile representations currently produced and their use, in order to establish a frame of reference.
- Delineate the preferences of the group of users with respect to the tactile representations to display information.
- Define a point of balance between the available technical capability to generate tactile representations, user preferences, and the efficiency of the mentioned options to generate tactile representations.

Determine suitable interaction functions (input / output) to display digital text documents.

- Establish a frame of reference for interaction functions through the study of existing interaction methodologies for information display systems for users with visual impairment.
- Study the users' preferences with respect to interaction methods.
- Specify interaction methods and functions based on the type of information to be displayed.

In this way, we established a series of elements to be taken into account to visualize, design and develop any prototype which has the purpose of providing alternative access to digital text documents to readers with visual impairments.

Next we will describe in detail the three stages of development of the concept with which we aim to create a multimodal platform based on auditory and tactile channels to display digital text documents, providing access to their logical and visual structures together with the implicit information these show.

5.3.2 Pin display stage

The Hyperbraille project is an initiative which has had for more than two decades the development and production of a device to generate, in a refreshing and interactive way, graphic information through reliefs. This project, in its current state, bases the generation of the reliefs on piezo-electric actuators arrays which, when controlled by a computerized system, can generate graphics that can be perceived by touch as well as Braille text.

Currently the technical capabilities of this device include the following features:

- Tactile feedback on the surface of the piezoelectric actuators which resemble a touch screen.
- Actuators with mechanisms for high-speed response to provide instant refreshing of tactile graphics .
- USB connectivity with a computer based in TCP-IP protocol.
- Directional controls based on a 9-key Perckins Braille keyboard.
- Resolution of approximately 16 dots per square centimeter using standard Braille measurement dots (approximately 2.5 millimeters of area), with a display area of at least 60 per 50 pins.
- The ability to interact with the operating system of a common computer.

The Hyperbraille is currently a development of the company *Metec AG*[21]. This company manufactures the device and produces the corresponding driver for its interconnection with Microsoft Windows systems. Likewise, *Metec AG* produces *MVBD (Metec Virtual Braille Device)*[22] is a control environment and user in-

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[21] https://web.metec-ag.de/

[22] https://download.metec-ag.de/MVBD/

terface which acts as an intermediary environment between the graphical user interface of the Windows system and the Hyperbraille device as a peripheral hardware platform.

The potential of Hyperbraille as assistive technology for people with visual disabilities has been taken into account by various research institutions within Germany. For example, the University of Stuttgart has acquired two units of the Hyperbraille, and in this way has enabled its use in research in interactive systems. To implement the Hyperbraille as an element of technical support in this research has been a logical step in the course of the development of this work.

Defining an interface with touch and auditory channels for the deployment of documents

This has been the first stage of concrete development of the concept of an interface that combines auditory and tactile channels to assist visually impaired readers to access text documents. The concepts and topics seen in chapters 2 and 3 have given the guidelines to propose methodological and technological approaches. Likewise, the conceptions seen in chapter 4 give a functional framework from which the elements described here were established.

Technical adequacies The capabilities of the Hyperbraille device to display graphical elements provided by a computerized system through touch components together with its interactive capability provided us with a convenient means to implement a tactile interface supported by auditory elements. The technological support had at this point given way to the approach of concrete elements of interaction which were defined based on the steps described in the previous section. We needed a document model to adapt and from where we would proceed to establish the conversion processes of tactile and auditory elements.

The adaptation process in this design stage presented a series of defined requirements:

- In the Persona profiles, on the part of the users, it was established that the documentation related to educational, technical and training material was the main requirement.
- The documents needed a clear segmentation and differentiation of their visual and logical structures, and to be easily able to distinguish the elements of micro and macro structures (as we defined in section 4.2.2 based in the work of Machulla et al. [144]).

- Documents needed textual as well as graphic content such as images, and organizational content such as lists, tables, and highlighted items as bold or italic text.
- The length of the documents had to be manageable for reasons of workload.
- The subject of the documents needed to be specific, in order to facilitate the analysis of their readability and comprehensibility.

Taking these factors into account, the use of scientific papers was determined as the first approach to adaptation since these types of documents comply with all the previously mentioned requirements in the first instance. With this type of digital text documents it would be possible to define elements and tactile and auditory representations to produce the desired interface.

An additional factor presented by the scientific articles is the fact that they are mostly disseminated in PDF format, and in the persona profiles this format was defined as one of the least accessible for the current assistive technologies for readers with visual impairments.

Design of tactile representations As it has been observed in sections 2.4.2, 3.2.2 and 3.2.3, the design of tactile elements is subject to different factors that influence their optimization for recognition through the sense of touch [247, 12, 182]. In an analogous way to visual and graphic design, tactile element design must ensure the easy association of symbolic elements with the meaning of the information to be transmitted [67, 56, 66, 182, 163].

We have previously noted that the sense of touch has a lower resolution to define objects than eyesight [175, 186, 21]. However, the sense of touch can define specific elements which allow a wide range of possibilities to recognize different objects, symbols, and representations. In its *epicritic and protopathic sensitivity* (see section 2.4.2), the sense of touch is able to define elements such as volume, position, textures and shapes [241].

The design of tactile elements should deploy methods which enable development of objects which are easily recognizable and can optimally transmit the information you want to reach the reader.

Development of tactile representations on the pin device Intelligible tactile representations for people with visual impairments have been developed more extensively within the field of *Tactile Graphics* [182, 66]. Elements such as maps, graphs or iconographies have provided the framework to develop tactile elements to represent diverse elements such as geographical locations, everyday objects, or samples of an educational nature [12].

The design principles provided by tactile graphics techniques which have been seen in section 3.2.3 have been combined with the technical properties of the Hyperbraille pin device which provides a resolution of 104 per 60 Braille-resembling dots, delineating the possibilities to model any tactile representation using this device.

The work of Picard et al. [175, 241] denotes as a generalized form an element called *Touch threshold* which defines minimum values of separation, volume and size for a tactual stimulus to be coherently perceived. The tactile acuity of the fingertips is explored in the Braille system. As stated earlier, Braille symbols are formed by raised points on the page separated from each other by 2.5 mm and 4 mm wide with the point height no less than 0.4 mm, which is slightly larger than the two-finger touch threshold at the fingertips. The hyperbraille is able to provide this technical requirement, however due its resolution, its ability to produce detailed and smooth shapes is limited.

Elements to be tactually represented Following the steps described in the section 5.3.1, and considering scientific papers as the model for textual documents, the following elements have been established to be defined and represented by means of tactile elements: main title, section subtitles, independent paragraph blocks, tables, and independent image blocks.

Using the process described in sections 3.2.3 and 3.1, independent tactile representations have been generated, and the surface layout of the aforementioned representations was done based on the visual layout of the document model. In this way, we obtained a composite element which has been called a tactile page.

Design of auditory representations The design of the auditory representations within the tactile reading interface has been determined by the functional features of the elements of assistive technology known as *Auditory screen reader software (ASRS)* (see section 3.1.1).

In order to simplify auditory interactivity we considered not using elements such as sound icons or earcons. Taking into account the textual nature of the elements to be represented, we decided to summarize those representations to speech translation as a strategy of continuity for interaction to maintain the model of use of screen readers. In this way, we have tried to maintain the functionality scheme without the use of foreign elements to the operation of these software applications, and the same text-to-speech scheme while retaining even the usual speech engine in the most used screen reader scheme. This is more fully described in the *interaction design*. The defined elements, titles, subtitles of sections, and independent paragraphs will keep their complete translation to text to speech. Elements such as figures and tables will use their caption text for each one. Regarding tables, taking into account their segmented feature and broad content of information, we have decided not to describe their content and use only their caption texts.

Apparatus

In our persona profiles we have been able to define common characteristics for our target users. One of the characteristics shared by our personas is the common use of screen reading applications.

If we consider that the ability to use screen reading applications is a knowledge shared by objective users, it is logical to consider this as a basis for establishing interaction methodologies based on the use of these applications (screen readers). We used as our base ASR *JAWS (Job Access With Speech)*[23], deploying its TTS engine and interaction model to navigate within textual content. This ASR option was selected considering its use is mostly extended among users with visual impairments to the date of this work[24].

Thus, an interaction methodology has been defined based primarily on the interaction conceptualizations previously seen in the interfaces of the screen reader software. Together, the technical environment of the available equipment has limitations which must be considered when defining the mentioned interaction methodologies.

Interactive possibilities of the Hyperbraille device As previously mentioned, the pin device is capable of presenting graphics and images through reliefs. Its interactive capability is limited by a processing skill dependent on an attached computerized device. The pin device is not capable of storing or processing on its own the images or graphic representations. The intermediate software between the device and the computer also produces limits in the control capability.

As we saw in the section 22, the manufacturer of the pin device purveys a software environment which includes the drivers needed to communicate the device with the computer. It also provides an intermediary environment which has some

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[23] https://www.freedomscientific.com/products/software/jaws/

[24] https://webaim.org/projects/screenreadersurvey8/

control functions, however, these functions are limited in the ability to produce tactile elements as users desire. When considering these facts, the decision was made to use an alternative software environment produced by third party researchers who developed the necessary framework to control the pin device in a sufficiently refined way to produce interfaces according to the requirements.

The *Tactile display abstraction framework* named *BrailleIO [28]* was developed with the aim of producing custom interfaces regardless of the intermediary software provided by the manufacturer. This Framework provides classes, functions, and methods necessary to control the display of information on the pin device. The Framework and its components can be integrated into the structure of a proprietary application written specifically for the pin device. These applications can operate independently of the application provided by the manufacturer, however the use of the driver it provides is still necessary [25].

The models of the pin devices available for the development of this research have the capability to display reliefs through the previously described pin structure. However, one of the required capabilities such as tactile interaction on the pins surface was still under development in the previously mentioned models. Certainly, the pin device can respond to the contact on its surface, nevertheless in the available models it is only available enough sensitivity to respond to a single point of contact on the surface. The Pin Device Framework is capable of handling several contact points; however, the device cannot process this signal effectively. In this way, there is only one contact point as an element of tactile interaction on the surface of the device.

Software modeling As part of the interaction design process we developed an intermediate application between the content and the device Hyperbraille. This application consists of three main parts: the Onscreen Interface (OSI), the Abstract Document Representation (ADR), and the General Input and Output Methodologies (GIOM) that bind with the device Hyperbraille [26].

The onscreen interface (OSI): This component of the software is the one that shows the textual segments of the documents previously adapted. These

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[25] The structures, objects and functions of the framework are described by their creators in the work related to this development [28]

[26] Note: The process of a document's adaptation is manually fulfilled. This means that the segments are transferred from the document to the ADR by a human operator, then the components are identified and labelled according to their attributes by a human operator. See in the appendix section an instruction set to create the adapted documents.

documents are segmented and stored in the ADR. The interface has functions and control methods which allow the navigation between the abstract segments of the adapted documents.

Autonomous linking between the ASR and the OSI: As previously mentioned the auditory screen reader *(JAWS)* is a fundamental part of this interface. We exploited a scripting feature of the used ASR to deploy TTS and text exploration functions from the ASR into the OSI's functional implementation. Thus, a document's segments are read aloud with the ASR's TTS engine, and text chunks can be explored with ASR's standard functions.

Display: This function loads the textual content of the document's segmented and adapted elements. These segments are not shown simultaneously, but according to the interface focus selection. An edit box displays the segment shown corresponding to paragraphs or titles of tables or images, an additional text box displays the text segments corresponding to the titles and subtitles, and another text box displays the corresponding page number.

Navigation: This function moves between the segments. Within the logical structure adapted to the textual documents are attributes including a unique identifier number which generates the ability to navigate between the segments.

Abstract Document Representation (ADR): This component stores the segments of the document previously adapted, preserving its logical and visual structure. This means that the document has been previously read and segmented. The components are sorted according to their sequential relationship within the document obtained, and this structure stores a list of individual elements (objects) which represent the segments within the digital textual document. Those segments belong to a conceptualization (class) which manages a set of attributes for each segment. The document's components, as objects of the segment class, are constructed cemented from the component classes held in the *BrailleIO framework*, so they have inherited attributes and methods from that framework.

Identifier number: This attribute refers to the order of the segmented component within the sequence of the document adapted. This attribute must maintain the sequence and the order of the components.

Page number: This attribute is independent of the number identifier and refers to the physical page where the given segment is contained.

Type of components: This attribute may be the most important. It refers to the type of the segment which is being represented: You can refer to the main title, section subtitle, block of paragraph, tables or figures. In this same way this attribute corresponds to the type of tactile representation that will be deployed in the iPad screen. See figure corresponding to the tactile representations.

Position: This attribute is the two-dimensional coordinate where the upper-left corner of the tactile representation corresponds to the component described above. Its values are confined to the physical dimensions of the surface of the device Hyperbraille.

Dimension: This attribute is the dimension in width and height corresponding to the tactile representation of component shown.

Content: This is the textual content contained in the corresponding segment. It is the text read aloud when the segment is selected, and it is also displayed in the OSI.

Segments can be the subject of a *Selection method* which sets the focus of the application on the physical representation of the segment triggering the display function seen in the OSI and a *blinking* function. This function makes the selected tactile component blink; the blinking consisting of lifting and folding in short intervals of time the pins that make up the segment.

General Input and Output Methodologies (GIOM): This component refers specifically to the methodology of interaction used to interact with those programed components mentioned above, therefore it will be closely related to the functions of the OSI and the access to the ADR's components

Numeric Keyboard Navigation: The device Hyperbraille has limitations with respect to the tactile interactivity on its surface, so for this reason it is difficult to establish direct interactions on the device. To overcome this drawback we stipulated the use of a scheme of interaction similar to that users with visual impairment implement to work with ASR applications.

The Hyperbraille device was set in portrait attempting to simulate the A4 page layout. A numeric keypad accessory was available as lateral to the device, and emulated keyboard gestures used by visually impaired users to interact with the screen reader.

The interaction model provided by *JAWS* is keyboard-based. In its basic predefined setting the numerical keypad is usually located aside the regular alphanumeric QWERTY keyboard, coming into the main navigation key-based gestures receiver. To maintain a familiar interaction environment for our users we replicated the keyboard *JAWS's* shortcuts to read and navigate our prototype within the displayed textual content. Through *JAWS's* scripting environment together with the OSI's main functions we captured a set of *JAWS's* keyboard shortcuts to trigger navigation functions in the OSI. These shortcuts, named ASR native, were named emulated gestures, and conjointly with native *JAWS's* keyboard shortcuts could be used to explore within independent segments.

Emulated gestures:

Ins + PgDn: Jumps to the next segment found in the ADR sequence

Ins + PgUp: Jumps to the previous segment found in the ADR sequence

Ins + End: Locates and reads aloud the number of the current tactile page

Ins + Home: Locates and reads aloud the main title of the document

Numpad 5: Reads aloud the content of the current selected segment

PgDn: Jumps to the next ADR's tactile page and displays all its associated segments

PgUp: Jumps to the previous ADR's tactile page and displays all its associated segments.

ASR native shortcuts

Ins + Up arrow: Reads aloud the current line of text within the selected segment

Ins + left or right arrows: Reads aloud the previous (left) or the next (right) word in the current text line, and also moves the cursor in that direction

Ins + Down arrow: Reads aloud all the text contained in the selected segment from the current position of the cursor.

Tactile interaction on the device's surface: this level of interaction has had limited development due to the Hyperbraille restrictions of the device. This scheme was limited to the selection of one component at a time through a single point of contact on the device's surface, the device being unable at that moment to recognize more than one point of contact at a time. Gestures such as the double tap or swipe were not feasible. The user selected a specific point on the surface of the device, and if the point was within the dimensions of a tactile component shown, the selection function was executed by means of a trigger key. This function located the application's focus on the chosen component and started the blinking function, and the selection function immediately displayed the component selected with its textual content, identification number, associated page and other attributes in the OSI in turn. This component was then automatically read by the screen reader associated with the OSI. The single contact point on the device's surface had to be detected alone; if the device detected a second contact point the selection process did not take place. The chosen trigger key was the */ (slash)* key on the numerical keypad; in the predefined keyboard ASR native keyboard shortcuts this key corresponded to the left click of a standard mouse.

Evaluation of this stage

Once the prototype of this stage was designed and developed, its functionality needed to be evaluated in a specific and objective environment. The evaluative section of this research stage is described in this section as it presents defining concepts which delineate the development of later stages. Chapter 6 describes the evaluation processes of the two subsequent stages; however, regarding the relevance of this first stage, we have decided to present the evaluation within this chapter.

Evaluative tests design The use cases described in section 4.3.2 demonstrate the purely exploratory nature of the application; the exploration of scientific papers was considered as the natural option taking into account the document model used to generate the prototype. However, looking at the lower consumption of this type of content by the population of visually impaired readers, the use of a secondary use case was considered to provide additional data.

Exploration of scientific papers with Tactile pages For these tests a protocol of four documents was established which maintained similarities in extension (four pages) and format, (to two columns layout and sections with numbered titles). Two of these documents were processed generating interfaces of tactile pages, and two others had to be accessed through a computer and an ASR to carry out a comparative test where the performance of the users could be measured when accessing documents in digital format by conventional means (ASR), and through the prototype of the tactile pages.

With these tests we expected to evaluate three fundamental elements:

- Document exploration execution time.
- The ability to locate specific information within the document environment.
- Appreciation of the subjective satisfaction of the use of the proposed interface compared to the use of the standard screen reader environment.

This test was conducted with four subjects; people with visual impairments recruited from the staff of the University of Stuttgart.

When executing these tests, it was determined, taking into account the execution times, that the tactile page interface requires much more time to explore than the standard screen reader interface.

The four participants provided qualitative evaluations which agreed on the determining factor which was the poor tactile interaction on the surface of the device. This interrupted the flow of the interaction, and the need to use the numeric keypad to navigate within the contents interfered with the users' ability to use the tactile page interface.

Likewise, it was observed that the test subjects maintained reading patterns similar to those described in the online survey (see section 4.2.1), opting for the reading of the entire document without resorting to navigation or exploration gestures.

The subjects agreed that if the interaction could not be carried out entirely on the surface of the Hyperbraille device, trying a tactile approach combined with keyboard interactions did not satisfy their requirements when exploring a document. Likewise, they observed how the inability of the device to process more than one contact point generated frequent errors when selecting the document segments on the tactile page.

Despite the fact that this set of tests did not yield relevant quantitative data, the qualitative data provided valuable information for the concept improvements within the investigation. It is worth mentioning that the four test subjects agreed to assess the potential utility of tactile document exploration for its visual and logical layout.

Secondary test set: Exploration and execution of cooking recipes

This test was developed as a collateral evaluation of the set of previous tests.

This test was based on the preparation of a document which shows a cooking recipe. The objective of the test was to examine the ability of users to use a document of tactile pages trying to execute a specific task with defined steps to be followed in conjunction with the implementation of the previously described interaction features of the prototype.

The recipe document consisted of a specific number of steps, and included instructions which asked the user to read items in the set of previous steps in order to force bidirectional navigation in the document. A scenario was prepared with fictitious ingredients and kitchen utensils in order for the user to proceed with the instructions shown in the recipe.

For this test, only the collaboration of two subjects could be obtained. The two subjects successfully followed the instructions and were able to navigate through the document. As in the aforementioned set of tests, the interactive limitation of the device tactile surface was a determining factor for success or failure in using the interface. In their qualitative evaluations our participants referred to the ease of finding the different elements of the document. Paragraphs and ingredient lists were easily located by using the touch page interface. Despite the limitation of tactile interaction of the surface of the device, they mentioned that by executing moving actions, locating the ingredients, carrying them, mixing them, and other actions, they were able to locate the document segments using the Touch to facilitate the task.

Conjointly, participants mentioned the staticity of the device. Taking into account the mobile nature of the task they mentioned that it would have been easier to use a mobile device such as a tablet or even a mobile phone.

General conclusions of this design stage

This stage was the concretization of the idea obtained to improve the access of the visually impaired readers to the visual and logical structure of the digital documents. The use of the Hyperbraille device as a fundamental part of the available technical environment was a logical option taking into account the nature and the primary objective of the prototype. However, given the interactive limitation of the device when presenting tactile interaction, a keyboard interaction scheme was considered in conjunction with the touch interaction.

The set of tests carried out with this prototype did not offer relevant data that indicated an objective advantage in the usability of the prototype, however, in situ observations and feedback relevant to the subsequent steps of this investigation were produced:

- The touch interaction must be executed completely on the surface of the device taking into account the user’s tactual modality.

- Designed tactile representations of the elements that compose the document are easily identifiable by the users.
- The contents used to be adapted through the interface of tactile pages (scientific papers, articles of general knowledge, cooking recipes) seem not to require a high rate of refreshment for a fluid interactivity.
- The heavy and bulky presentation of the Hyperbraille device limits the possibility of more versatile use, and additionally restricts the ability to conduct in situ tests with a large number of users.
- All test subjects convened for this evaluation stage agreed that despite the potential versatility of the touch page interface, this type of development would be far from accessible to the ordinary user, regarding the its high cost, limiting its possible extension and use in a relevant way.

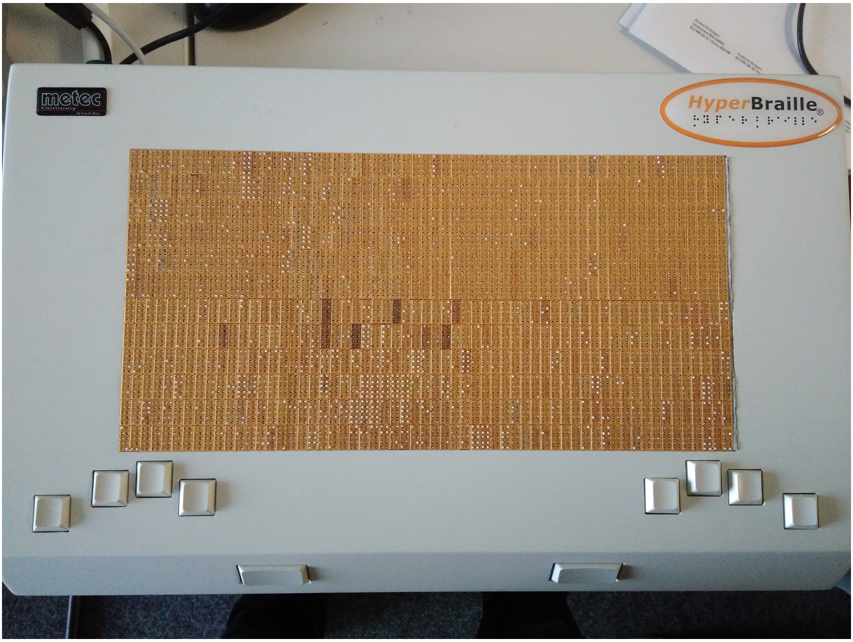

Figure 5.4: A newer model of the Hyperbraille device is now available. In the described tests, this model did not have a functional sensitive surface for tactile interaction.

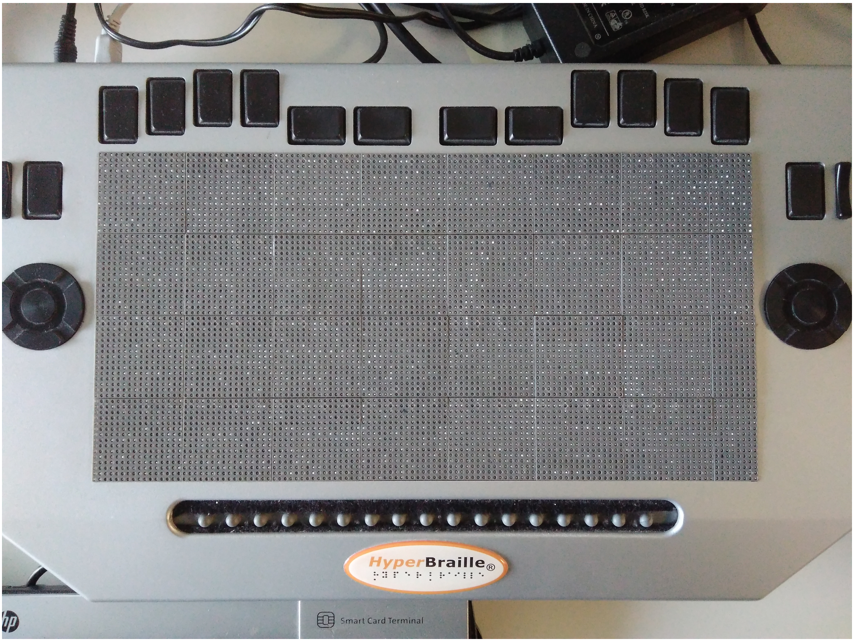

Figure 5.5: Hyperbraille device used to test the prototype interface. This model was only able to recognize a single contact point on its surface.

5.3.3 Fixed overlays stage

The previous prototype's stage left a set of key considerations related to the advantages and shortcomings of an approach to display the content of digital documents through an interface based on tactual and auditory channels. The value and potential of the proposed system were considered assets significant enough to redefine the concept in a way that can better fulfil the main goals.

To consider and assess the results of the previous stage the research work entered into a self-evaluation and introspection process. This proceeding re-evaluated the functional schemes of the prototype, and in this way we derived the following concepts:

- At the time of the development of this research the Braille device does not meet the functional and non-functional requirements described in chapter 4.

- A scheme of interaction mixing tactile interaction and interaction based on the keyboard disperses the touch-attention capability of visually impaired users.
- The OSI environment dependent on a computer connected to the Hyperbraille device presents functional limitations.
- The software environment does not offer enough stability and reliability.
- The scheme of interaction obtained in ASR desktop or laptop computer applications is based on keyboard gestures. For this reason to try to emulate such a scheme of interaction in an environment which pursues tactile interaction does not offer specific functional advantages.

Jointly, the self-evaluation process demanded that we reread the set of functional requirements (see section 4.3.3) and non-functional requirements (see section 4.3.3) as well as the interaction concepts (see section 4.3.5) that are the basis for our prototype development. In this line of thinking we delineated a series of additional guidelines to be fulfilled at this stage:

- To find an environment that offers total tactile interaction on the surface of reading
- To implement a device that offers comfort of use
- To deploy a scheme of interaction mostly based on the tactual channel leaving the auditory channel exclusively as output response.

The Hyperbraille device offers a scheme of refreshable tactile images which cannot be reproduced by other means available for this investigation at the time of this stage; however, its ability as a tactile display does not compensate for its functional limitations. Therefore, we proceeded to search for alternatives to produce tactile displays, and introduced the prototypical concept of *Tactile Sheets* [205] as a plausible approach for a multimodal support for document exploration.

Implementation of tactile overlays as tactile sheets

In Chapter 3, Section 3.2.2 we were able to observe how the development of sheets where you deploy touch perceptible graphics is a technology that has long been used to transmit certain types of visual information to people with eyesight disabilities. It is necessary to mention that the technological development of these sheets has not been comprehensive, as their means of production has until recently been only moderately mechanized, making their production cumbersome and costly. The set of manufacturing technologies known as industry 4.0 [131, 197, 143] now offers much more accessible means of production for elements such as tactile sheets made up in different materials.

Touch screen technology has had wide development over the last decades. The combination of tactile overlay technologies and touch screens has been implemented for the generation of accessible material dedicated to people with visual disabilities, however these developments have had very little diffusion being limited to the technological scheme where they were produced (see section 3.3.1). As result, this assistive technology production is expensive and non-widespread, similar to the Hyperbraille device itself.

Conjointly, current touch-screen based devices have become standard in consumer electronics. Tablets encompass touch interactivity and computing power in a single compact and portable device. The wide range of available software as operating systems, frameworks for GUIs, and multimedia displaying give versatility when choosing a development environment to produce applications that also exploit the previously mentioned touch interactivity.

The use of tablets was considered as a viable alternative to encompass the OSI, ADR and GIOM components in a single hardware component. However, the tactile ouptput component of the GIOM had to be re-evaluated and reinvented as a static option in the absence of a refreshable device such as Hyperbraille. The ADR would be contained as a logical structure in the OSI which in turn would be represented by a GUI shown on the tablet screen, and the device's tactile response capability (the general scheme of supported gestures) would act as the GIOM input tactile component. Most currently available tablets are able to handle different options of auditory output; either TTS and audio playing are supported in tablets hardware/software platforms.

Instead of displaying a tactile page, the physical distribution of the segments of the document would be displayed on a fixed sheet in which tactile patterns would be shown which would represent the mentioned segments. The preparation of this sheet raised another question. The Hyperbraille device could generate tactile representations with a resolution of approximately 16 points per square centimeter, using standard Braille measurement points (approximately 2.5 millimeters of area). The technique of making the sheets should match or exceed the resolution of the Hyperbraille to grant greater capacity to generate differentiable textures on a surface, which would allow interaction with a capacitive touch screen placed under the sheet.

Laser engraving technology was proposed as the most functional option available as it could generate engravings with a resolution of fractions of millimeters on a wide variety of materials. As options for the tactile sheets, plastic sheets for slides, standard Din A4 paper of 80 g/m^2, and Din A4 braille paper of 160 g/m^2 were examined.

Empirical tests of pattern engraving on sheet options were conducted. An Epilog laser cutter model Zing Laser Series[27] was used. The 160 g/m^2 paper was considered as the optimal option to make the tactile sheets, this because of its ease of acquisition, affordability, and its thickness that allows a deeper engraving which is easier to perceive by touch. This material also allows interaction with capacitive touch screens.

Tactile sheet: a redesign of OSI and ADR structures

Software elements like *BrailleIO framework* and desktop computer standard applications are not used anymore as development platforms to shape logical components. We exploit the GUI development framework available. This framework should allow us to produce screens which occupy and fit in the entire device's display size, and arrange a set of touch-events activatable graphic elements in customizable positions on the screen. Those activatable graphic elements should permit several possibilities of touch events (e.g. single tap, double tap, etc), and should allow resizing that might be required during the GUI design stage.

In this way we encapsulate ADR and OSI components into an instance of the GUI touch-based framework. Certainly it is required to match the tactile pattern layout made on the overlay with the layout of the touch-events' activatable graphic elements designed on the screen. The structure known as *Tactile page* from the previous stage, in this stage is a two-component entity made up by the designed screen and the tactile overlay. We denominated this entity as *Tactile sheet*.

Design of tactile patterns Despite already having design patterns implemented for the previous stage prototype, the access to a technology such as laser engraving provided a more refined capability to generate textures that facilitated the recognizability and discriminability of segments by readers with visual impairment. Thus, using as a base the previously seen patterns and the concepts on touch-perceivable elements [181, 73, 79], more complex tactile patterns were

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[27] https://www.epiloglaser.com/products/ radius- tech-specs.htm

deployed to represent the components of the documents represented in the tactual interface.

The process to adapt a page of a digital document into a tactile overlay was as follows:

1. To take a screen shot of the original document's digital file (one screen shot per page)
2. To create the tactile overlay using the screen shot of the document page as a template to arrange the segments in a vector graph program (for this case Inkscape was used[28])
3. To proceed with the manual operation of separating the individual segments and identify to which category they belonged (paragraph, title, table, image, etc.), then to assign each element its own tactile pattern using the following textures (see figure 5.13):

Main title An array of 0.5mm radius circles with 1mm of separation

Section titles Vertical lines with 1.5mm of thickness and 2mm of separation

Paragraphs blocks Horizontal lines with 1.5mm of thickness and 2mm of separation

Image block An array of 3mm by 5mm rectangles with a 0.5mm of separation.

The size of each pattern block might be adapted to adjust to the visual layout of the represented digital document, resulting in a black/white PDF file that can directly be sent to the laser cutter. The paper is then engraved with 100% speed and 45% power creating down relief on the black colored areas of the PDF file. The laser cutter takes 30 to 50 minutes to engrave one overlay, depending on the complexity of the design.

Auditory feedback The idea of implementing an ASR-resembling reading environment did not have any impact on the subjects' feedback. This conclusion drove us to implement a more simplistic approach to display the required auditory feedback in the assistive reading system. We deployed pre-recorded sound segments containing the corresponding text of each segment in the adapted document.The corresponding text content segments were transformed into MP3

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[28] https://inkscape.org/

audio files with a Text-To-Speech online service[29]. This service allowed us to produce speech in several languages and with a controlled speed rate. The audio-segments were set up with a rate of 100 words per minute, as this is considered to be an understandable baseline speech speed [74, 211]. Although there are concrete skills identified in speech listeners with visual impairments [36, 207, 216], we focus the production of those audio-segments on the content intelligibility.

Interaction design The deployment of the touch-screen device and the engraved overlay derives into an expected simplification of the interaction instance. All the input now relies on the set of interaction events within the functions and methods of the touch-activatable graphic elements arranged on the designed screen.

As in the previous stage, the core of the interaction model is summarized in the access to the auditory output through concrete input actions. Each segment is represented by a touch-activatable graphic element, and each segment has an associated unique audio-segment where the user can play, stop, and resume play. The subset of input tactual gestures is constrained to double taps on the segments to play the audio; if the audio is already being played the action pauses the playing, and a similar action (doubletap) on the same segment resumes the playing, or if the audio-segment is already ended the action will play the audio again. The double tap is selected because the visually impaired user must make a tactual exploration on the overlay's surface and a single tap scheme would generate undesired false contacts.

Prototype design

The junction of the tablet as a touch-screen based device, the tactile overlays and the involved software is denominated *Tactile Sheet*. At this stage Tactile Sheet had two prototypical implementations which shared the same components, but different hardware and software constituents were deployed.

Implementation A This deployment was embodied using overlays made up with 160 g/m^2 paper sheets with a Din A4 size, displaying the tactual patterns shown in section 5.3.3.

As our touch-screen based device we used a HANNSpad SN14T71; a tablet equipped with a screen diagonal of 33.8cm, and Android 4.2 as the

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[29] http://www.fromtexttospeech.com/

operating system. We expected that the screen size could hold the tactile overlay adequately.

As the software platform we implemented a frontend based in standard HTML controls, deploying HTML buttons as segments, and the backend based on Javascript. The backend performed the gesture input recognition and the audio-segment playing function.

The screen was displayed within an instance of a web browser, hence the screen and its tactile interactivity was circumscribed into the features of the HTML content provided by *Android* and the web browser. This conjuncture faced functionality conflict with the regular set of tactile gestures admitted by the web browser instance. Thus, the tactual exploration was required to perceive the patterns on the overlay that triggered undesired events on the front end.

Implementation B The screen's movement and resizing resulting in undesired events on the front end of the implementation A, triggered by the tactual exploration on the tablet surface, drove us to deploy a software/hardware platform which allows a deeper control on the input touch events.

We preserved the same scheme for the tactile overlays, using the same set of patterns, the same material, and the same production method. As our touch-screen based device we used an Odys Fusion tablet with a display diagonal of 29.5 cm with Windows 10 Home as the operating system, but in this case we developed the screens using WPF (abbreviation for *Windows Presentation Foundation* [30]) where each segment was a Windows Form button. The backend was developed in C#. A cross platform sound library for .NET named *Irrklang* from Ambiera'[31] library was used to manage the playing of the audio-segments. The application worked on windows tablets using the full screen mode.

The prototype described as *implementation B* was assessed with subjects with visual impairments through comparative tests to evaluate its *usability* as an assistive reading system. That evaluative process is described in chapter 6.

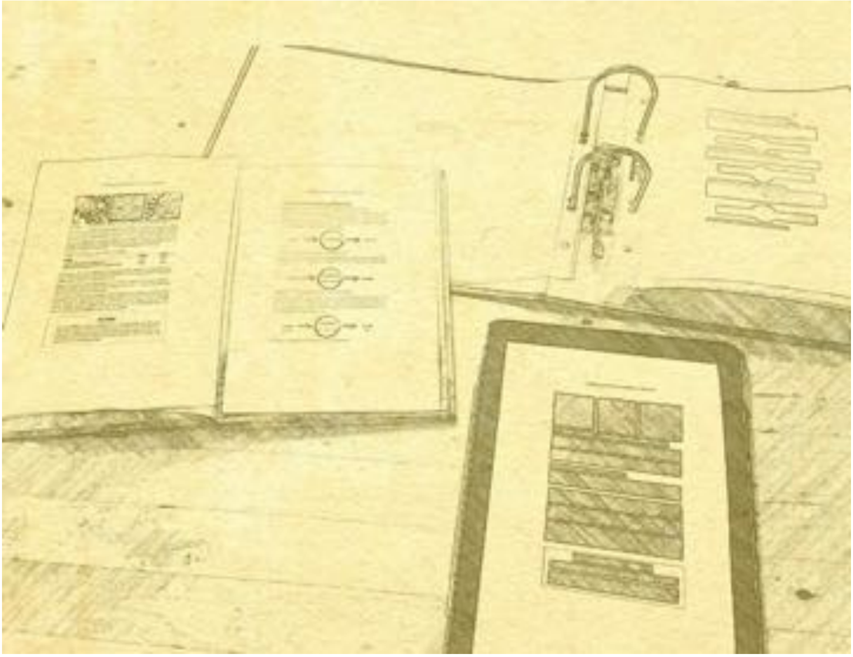

Figure 5.6: Pictorical conceptualization of Tactile Sheets [205]

5.3.4 Self-identified overlays stage

As it was previously mentioned, the Hyperbraille device offers a scheme of refreshable tactile images which cannot be reproduced by other means available for this investigation at the time of these stages, nevertheless the functionality issues encountered in the deployment of that device drove us to try out alternative mechanisms to attain a tactile display. Previously we had seen (see section 3.3.1) approaches to create interactive overlays giving the possibility to associate a concrete displayed content to a specific sheet. Those implementations rely on the capability to recognize the overlay. Those approaches established the suitability of providing an enhanced interactivity to the tactile overlays.

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[30] https://docs.microsoft.com/en-us/dotnet/framework/wpf/

[31] https://www.ambiera.com/irrklang/

Figure 5.7: By scanning this QR code it is possible to download the source code for the third design stage of Tactile sheets, it can be also accessed in the following URL: `https://github.com/MauroAvila/Interactive_Tactile_Representations_to_Support_Document_accessibility_for_People_with_Visual_Impairm`

Essentially, our goal was to make the platform as interactive as possible and be as assistive as possible, thus the deployment of a method to update the Tactile Sheets was a requisite as it was set in the functional requirements. Hence, the main effort in this stage was to give a refreshable interaction mode to a set of static overlays utilizing those components defined in the previous design iteration. The main idea was to avoid any direct interaction between the user and the software, and all the interactions to be directly with the paper, to provide the feeling of an actual book and not an electronic device behind it.

How to refresh a static sheet?

Even when this query sounds obvious, it is a core part of our prototype's design. To produce active surfaces which can alter their texture and shape is a concrete research field [227, 213] which will eventually be available to support the generation of refreshable tactile graphics. Jointly, we defined the prototype affordability as part of our *Non-functional requirements* (see section 4.3.3) seeking for an easy replicability in diversely resourced environments. Thus, we focused in the current available means to produce and handle our tactile overlays.

Documents are organized in pages, therefore we can utilize that feature to present a multiple page document deploying multiple tactile overlays. Each overlay represents a single adapted page of a selected digital textual document.

In the implementation B of the previous stage we developed two different overlays associated with two different screens for testing purposes (see section 5.3.3). To switch from one *tactile sheet* to another required switching the displayed screen on the tablet manually, then placing a new overlay. A dynamic set of *Tactile sheets* requires linking the tactile overlay in a way that the system can update the displayed screen autonomously just with the placing of a new tactile overlay on the touch-screen based device. Hence, we investigated methods to generate that association between the overlay and the displayed screen.

Overlay identification methods Pursuing the statements previously discussed, we examined some technical available options to set up a stable association between the displayed screen on the tablet, its shown represented segments, and the corresponding tactile overlay. Windows Presentation Foundation as a graphical subsystem allows one to load and display different screens in a single application GUI, and those different screens can be switched as part of an event within a list of recognizable events in the interface. A concrete and reliable identification procedure of an overlay can update the GUI to the corresponding screen. Thus, we examined options to produce reliable *Overlay Identifying System (OIS).*

QR Codes A *QR code (Quick Response code)* is a two dimensional bar code. It is a machine-readable optical label that provides certain information, which can be numeric, alphanumeric, or binary. It is created to store and retrieve data efficiently. In order to access the data of the code, a QR reader application must access the code through a camera. This is very convenient to use portable devices like smartphones or tablets provided with a camera.

The tablet used in our prototype's implementation B includes a camera. the envisioned system involves generating a QR code for each overlay that conveys the page number for that specific sheet. Unique codes are printed on each overlay, which have to be scanned by the tablet camera to activate the corresponding screen. Even so, this approach can be challenging for a visually impaired person to use. Focusing the camera or placing the code in the right positions are tasks frequently difficult for eyesight-disabled users [226]. Another downside of this method is the inadequate position of tablet's cameras, which hinder the QR code scanning procedure. These factors make this method unsuitable for this use.

Thus, regarding the observations done in previous stages, we agreed we would rather have a direct identification when the overlay is placed on the tablet touchscreen.

NFC The *Near field communication (NFC)* is a set of communication protocols that allow two devices (one being an electronic device) to communicate with each other. An NFC chip has to be connected with an electronic device that can read the NFC tags on other devices within a 4cm radius. This allows the chip to detect the tag codings and send them to the device. These chips can be programmed to perform certain other tasks such as mobile payments and sharing files.

In our system using NFC would mean placing NFC tags on each overlay that can be read by the NFC chip connected with the tablet. Similar to QR codes, each NFC tag would be coded with a certain overlay and after the chip is read the corresponding coding would be sent to the program and the interface would be automatically activated.

Using NFC chips can be much easier for blind people because the reading can happen within a certain radius, therefore the placements of the tags do not have to be accurate. However, there are downsides for this approach. Having to place new NFC tags every time new overlays are created can get costly, which neglects an important aspect of the system: *Making Tactile Sheets with affordable components which are available*. The second drawback with NFC is that not all tablets support this technology (e.g. The tablet we used for the prototype's implementation B does not support it)[32]

Conductivity As we have discussed in section 2.4.2, capacitive touch screens can be triggered using any conductive material (most metals are conductive). That means we do not have to use our fingers to activate it. We used this characteristic of capacitive touch screens to simulate touch points using conductive materials. The deployment used by Götzelmann et al [78] to provide interactivity to 3d-printed placed on a standard capacitive touch screen, adding strips of embedded conductive material within the models, extended the touch sensitivity to the 3d-printed model. This implementation was adapted to produce a similar effect of identification for each tactile sheet.

Our idea was to code different touch points for each overlay in 4-5 bit binary codes. Each binary code consists of 0 or 1 bits: 1 is the result of a touch point

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[32] **Note:** The idea of using NFC was not completely ignored; it would have been used if we had not found a better approach.

and 0 is a result of no touch point. Each of the tactile sheet pages has its own binary code that should be identified by the system once the corresponding touch positions are matched.

Conductive materials cannot produce the identification event for themselves, they require to be touched by a user. Thus, the conductive material must be in contact with the touch screen (on the inner face), and the user needs to touch the outer face of the page. This creates a design issue, that the conductive effect of a user's touch should be transferred from one side of a page to the other. We need a conductive flexible element which can keep an uninterrupted conductive track from one face of the page to the other.

We examined three different materials to deploy this approach:

- Conductive paint (see figure 5.8)
- Conductive tape (see figure 5.8)
- Conductive spray.

The third option was quickly rejected after we realized it cannot be used for creating specific coding patterns. However, it took us some investigation and trial to settle on one of the first two materials. The conductive paint we used was made out of carbon and could be applied directly from the tube or mixed with water and brushed on the paper. The tape we used was made out of aluminum, which can be found in most gardening/workshop stores. It is only a one-sided tape meaning it can stick on just one side, but could possibly be replaced with any conductive metal tape like copper or carbon for example. The tape has to be at least 3.5mm wide.

The reason we settled on the tape was the reliable identification from the screen. We could create patterns with up to seven points that were all recognized by the tablet. This was not the case with the conductive paint as we had trouble identifying more than two points.

In order to test the conductivity of the tape we created a fiber cube (see figure 5.9). We stuck the tape on top of the cube and cut it in four different pieces from the bottom. The user would have to place it on top of the tablet while touching the upper part, and the tablet should detect four touch points using our contact point detection software (see section 5.3.4). Figure 4.1 shows how we tested the automatic identification using the tape.

Figure 5.8: Left: One sided conductive aluminum tape. Right: Carbon conductive paint.

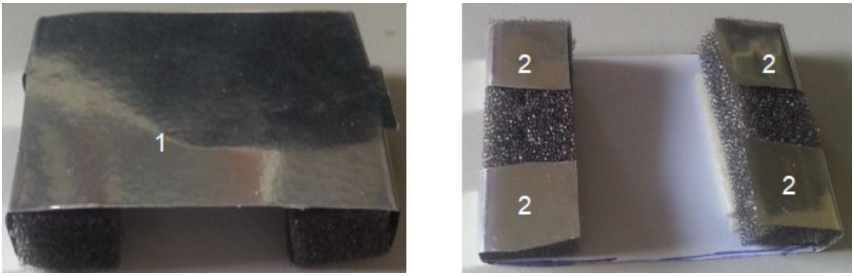

Figure 5.9: Figure of tactile representations for different components in a document. These representations are used to make up a *Tactile Page*.

Once we verified the reliability of this method we applied the tape to a sheet of paper and tested its functionality. To do that we wrapped the tape on the upper edge of the paper to have a touch point on both sides, front and back. On the back side of the paper the tape was cut into multiple parts in order to simulate multiple touch points. We then tested this approach using the same software. The tape worked appropriately during the first testing sessions. However, once the first day passed and the paper started losing its form (bending), some touch points were not recognized by the tablet because of the bending in the paper sheet. We fixed that by sticking a cardboard strip between the paper and the tape. The cardboard is more rigid than the paper and kept its shape for longer periods of time.

Touch screen contact points detector The software we created was a simple touch point counter on the screen that can tell us how many fingers are simultaneously on the tablet screen, while providing us the X- and Y coordinates of the initial starting point (figure 5.10). Once a finger is removed the initial start would also be removed. We did not track the positions after the movements of the fingers, because it was irrelevant for our system's functionality.

The reason we created this program was to enable us to detect the touch point locations for identification later on. Additionally, we added a speech synthesizer to the program, that says the number of fingers out loud after each change. Later on, we separated the screen vertically into three parts: left, middle and right, which were transferred into speech by the synthesizer that a user could hear. This software was used to test the conductivity of the materials for the identification methods. It was also created as an initial task, to get familiar with the platform and the libraries.

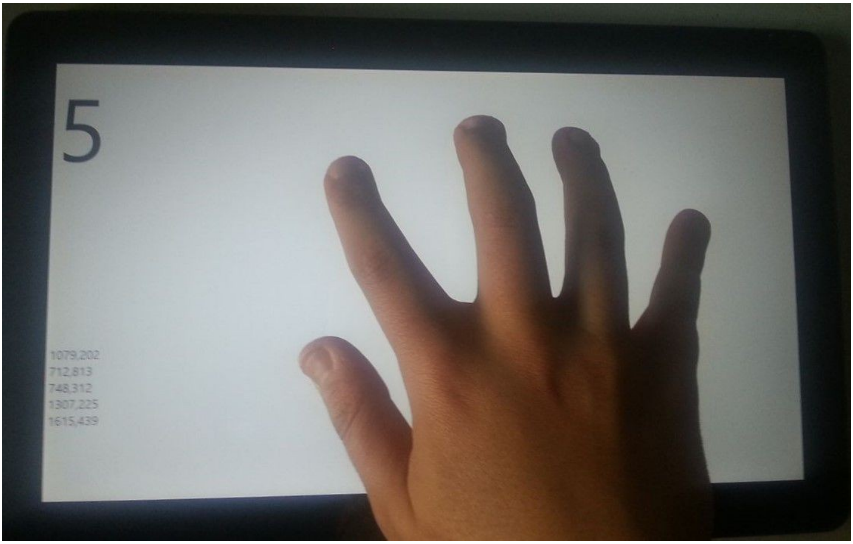

Figure 5.10: A picture of the first finger counter software. Top left corner: the number of fingers currently touching the screen. Bottom left corner: The x and y coordinates of each finger.

Self-identified overlays system?

In this section we discuss the used components to create the software platform and the interaction space. The system was developed using WPF (abbreviation for Windows Presentation Foundation) in C#. The program works on windows tablets using the full screen mode.

Here we focus on three aspects of the system. In figure 5.11 we describe the general structure of the program.

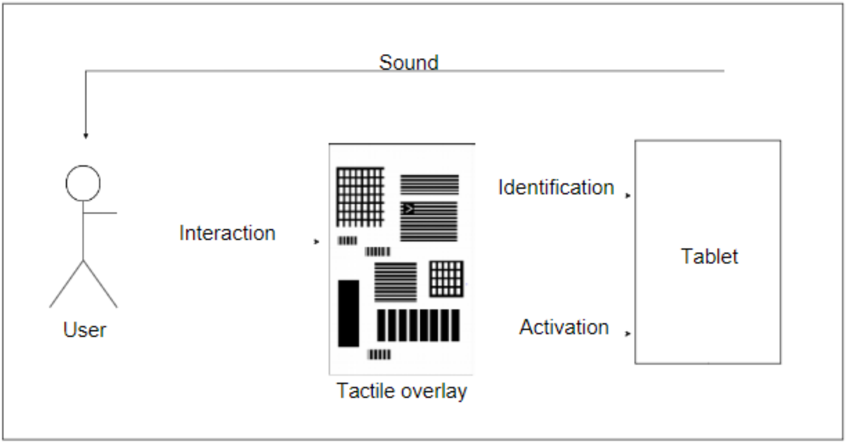

Figure 5.11: A simple diagram showing the exterior components of the system and how they interact.

Sound There are three scenarios in which sounds are utilized: page number, document elements and highlighted text. For verifying page numbers the library System.Speech.Synthesis was used. This system requires a string variable in order to synthesize it into speech. These variables were hard coded based on the binary code using a male voice. The second scenario was the individual text elements. For this scenario the Irrklang library was used, which is a cross platform sound library for .NET framework. This library requires a sound object (ISound) and a sound engine (ISoundEngine). It can play sound files in .mp3 format. In order to separate the individual sound files of the text elements we had to manually create a static sound file for each element via text to speech with a fixed speed of 100 words per minute. These individual sound files were later used for the Irrklang library. These sounds were spoken out once a user activated an element using a female voice. For the highlighted text the same library was used. However, for this scenario a male voice was used for creating the sound files.

Automatic identification For this aspect the upper part of the tablet screen was used (first 80 pixels), and separated into four parts. Each of the four parts serves as a bit in a 4-bits binary code, each set to 0 by default. Once one of them is touched the corresponding bit is switched to 1 (see figure5.12). This would not be set back to 0 once the part is not touched anymore, to compensate for the unreliability of the conductivity of the overlays. Otherwise the interface will change during the use, which will affect the usability of the system. Instead, all four bits change only once a new point is activated. The entire binary code will then change (which is all bits combined into one variable). The corresponding interface will be activated depending on the previous pre-processing in which each page was given its own binary code. All pages are stored in a WPF Tab-control. Once a page is selected (overlay is placed) the corresponding tab would be changed, and a speech synthesizer would be activated with the page number. The page switching also works using a computer keyboard, which was implemented for emergency cases during the study. The individual elements were triggered by buttons that were created manually to match the exact position and size of the paragraphs on the overlays using an XML file. For the sizes and positions to fit perfectly a screen shot of each overlay was created and added in the background of the program and the buttons dragged and adjusted accordingly. The screen shots were then removed from the program after the buttons were created.

Integrity For each session, a log file was created. The log file is in .txt format and contains the time stamp of the start of the program. After each entry (page switch, button activation, etc.) a new line is created with a new time stamp and a short description of the activity. When the program is closed the ending time stamp is also added and the file is saved. The log files were created using StreamWriters which are included in the System.IO library for C#.

Tactile representations for new type of segments The set of textures described in section 5.3.3 were complemented adding three new elements. We included new elements to represent highlights, enumerations, bullet points and side paragraphs, see figure 5.13.

Prototype interactivity

Self-identified overlays system is an iteration of the *implementation B* seen in the *fixed overlays stage* (see section 5.3.3). Therefore, the core interaction elements

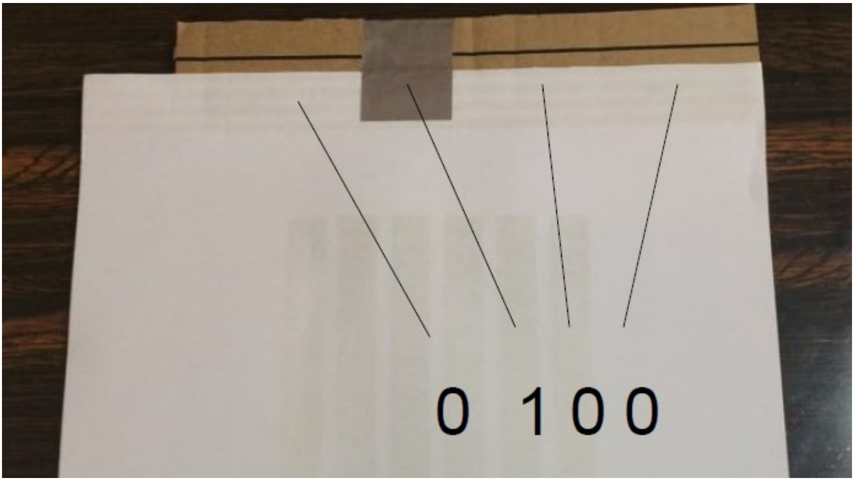

Figure 5.12: Back side of an overlay showing its binary encoding.

are an evolution of those seen in section 5.3.3. Hence, the main idea of our system is to make users interact directly with a sheet of paper and avoid any direct interaction with the tablet. Thus, the self identified overlays avoid the step of selecting a certain page on the tablet.

Here we discuss the interactivity methods of our system. The first problem that could potentially occur in such a system is referred to as the *Midas touch [178]* problem, that was identified in Eye Tracking systems. Midas touch in eye tracking occurs when gaze is used as an input modality. The software needs to distinguish if the users are making a selection with their eyes or if they are just looking around and exploring the screen. The interface of the system should also be designed so that the users have empty spaces where they can freely move their eyes without making an unintentional selection. This problem is usually avoided by implementing dwell times (fixating on the button for a certain amount of time to trigger it) or adding an activation key. We established that as a key factor in our approach, where fingers are a direct replacement for eyes so the Midas touch problem could occur. We need to be able to distinguish if the user is exploring the layout of the document or making a selection. To avoid this problem we implemented two features in our software:

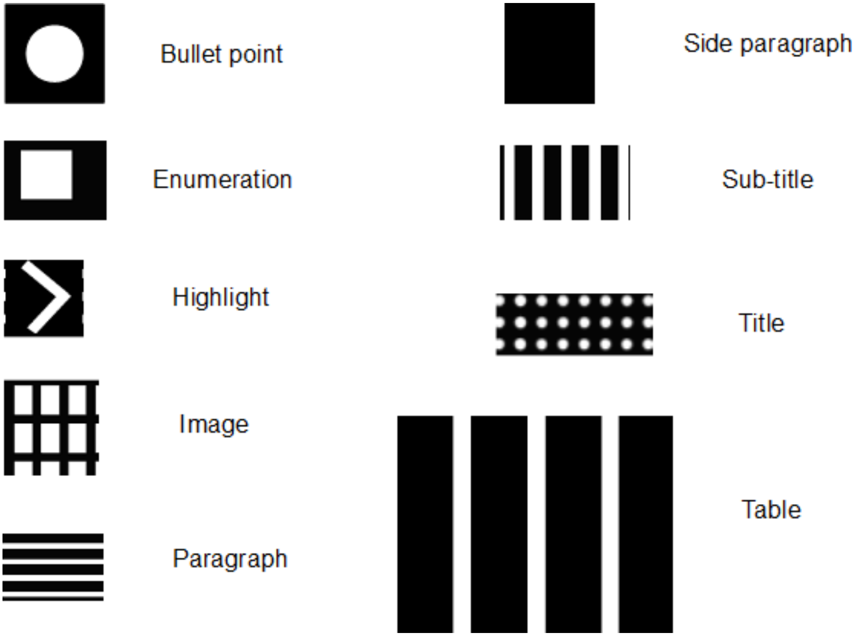

Figure 5.13: Figure of tactile representations for different components in a document. These representations are used to make up a *Tactile Page*.

1. Two sound files cannot be active at the same time. Each sound file can be paused and resumed, but if a user wants to play another sound file the first one has to end or be paused. If a sound file is active, all other sound files are blocked. This means that if a user activates an element by mistake, they would not be able to activate more elements when trying to deactivate the first one.
2. Implementation of tactual gestures that help the program identify the intention of the users. The first gesture is double tapping, which is used for playing and pausing all different elements. The second gesture is single tapping, which activates highlighted text only; usually not more than one sentence.

The system developed at this stage was a combination of our own findings regarding automatic identification of tactile overlays, and our continuation of previous work regarding tactile patterns and the usability of tactile interfaces. In the next chapter we report how we used these systems to conduct studies to validate our work.

Chapter 6

Evaluation of Interactive Tactile Representations

6.1 Introduction

The research process, through its investigative, outlining and design parts, led us to the development of conceptualizations embodied as functional prototypes. These prototypical developments and their intrinsic interaction methods needed to be tested in a controlled environment and using objective and scientific tools to validate and evaluate the usability and functionality of their interaction model.

Using outputs from the answers of research questions 1, 2 and 3, (see section 1.1) we envisioned a concrete solution to assist readers with visual impairments to access textual digital content, its logical structure and the implicit information coded in the document's layout. In this chapter we describe materials and methodologies to evaluate the impact of interactive tactile representations on the exploration of contents by subjects with visual impairments.

Taking into consideration the features and characteristics of the target user group, the information acquisition process and the proposed system, we conducted a set of experimental studies with nine participants in the *Fixed overlays stage* (section 6.2) and seventeen participants in the *self-identified overlays stage* (section 6.3). All had visual impairments. The participants compared the proposed tactile overlays designed solution with a standard auditory screen reader approach. We present and discuss the results related to efficiency in accessing information, objective assessment of the usability, and user experience of our proposed approach.

The basis and root of this assessment process is the following question: *How usable can a platform to display digital textual content comprising tactile overlays with differentiated touchable patterns and auditory feedback be?*

To have a better understanding of the usability assessment we have subdivided this research question into the following points:

1. Can a tactile interaction model supported by tactile overlays with differentiated touchable patterns based in tactual recognition and gestures offer better usability than the standard screen reader model based on keyboard shortcuts?
2. Does the implementation of differentiated touchable patterns distributed on a tactile overlay over the visual structure of a textual digital document effectively convey the logical structure of that document to readers with visual impairment?
3. Are touchable differentiated patterns more effective than standard text to speech cues offered by mainstream screen readers to locate and recognize elements in a digital textual document?

Our research addressed these questions by evaluating our model's usability using multiple factors to derive a usability assessment. We considered the users‘ satisfaction in using the Tactile Sheets approach, measured their completion time for concrete tasks, observed the cognitive load they were experiencing, and analyzed their qualitative feedback using a thematic focus.

As part of the first stages in our investigation process, we regarded the technological approach of refreshable touchable displays. This technology offers interactivity in a deeper way than a fixed engraved paper sheet, and there is previous work studying the functionality of that focus. The low spreading and affordability of that type of hardware led our focus to the use of touchable overlays which are not able to refresh their tactual content. To overcome this functional limitation we enhanced the tactile overlays providing them the technical functionality to be autonomously identified by an electronic device, bringing the capability to refresh the digital content in the function of a specific placed overlay. This concrete circumstance has led us to this utilitarian inquiry: *How can a* *non-refreshable interactive space based on self-identified tactile overlays offer a fluid display of digital textual content for users with visual impairments?*

This specific point was observed, granting the starting points for future works which aim to improve the functionality of a tactile overlay-based interface.

6.2 Evaluation of the Fixed Tactile Overlays

In the present section we report a study that investigated whether fixed tactile sheets can support the exploration of digital content. The contributions of this part of the research to the whole inquiry process have been condensed as follows:

- An implementation of the *tactile sheets* novel concept to demonstrate its technical feasibility as a means for providing low-cost access to document structure and layout to visually impaired people.
- A study with nine visually impaired users that shows the usability and value of this concept. This comparative study investigates the technical feasibility and the usability of this approach. Specifically, we compared a mainstream screen reader and two different types of tactile sheets. We achieved a similar level of usability between conditions. Additionally, the participants‘ qualitative feedback provides strong arguments for the use of tactile pattern overlays.

6.2.1 Participants

Via a local association for visually impaired people in Stuttgart (Germany[33]) we recruited nine voluntary participants (4 female; age range from 32 to 74 years with M = 51.4, SD = 11.5). Eight were completely blind and one severely visually impaired, according to the WHO classification (see table 6.1). All participants reported at least occasional use of mainstream touchscreen devices (e.g. smartphones).

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[33] https://www.bsv-wuerttemberg.de/

P	Gender	Age	Visual impairment info	Experience with touch screens	Experience with Braille
P1	f	49	10% from early childhood	Regular smartphone user	Occasional user
P2	m	57	0% from early childhood.	Regular smartphone user	Occasional user
P3	f	51	0% from early childhood.	Regular smartphone user	Occasional user
P4	m	55	0% from early adulthood	Regular smartphone user	Occasional user
P5	f	51	0% from middle adulthood	Regular smartphone user	Occasional user
P6	f	74	0% from middle adulthood	Basic smartphone user	Daily user
P7	m	32	0% from early childhood.	Regular smartphone and tablet user	Occasional user
P8	m	41	0% from early adulthood	Regular smartphone and tablet user	Occasional user
P9	m	53	0% from early childhood.	Regular smartphone user	Occasional user

Table 6.1: Participants (P) in the evaluation test for Tactile Sheets as fixed overlays. This set of volunteer participants was recruited and interviewed with the assistance of the *Blinden- und Sehbehindertenverband Wuerttemberg*

6.2.2 Stimuli, Apparatus, and Procedure

We conducted a study with three exploration conditions (C) to evaluate whether users could profit from the use of tactile sheets.

C1 This condition resembles the method of accessing touchscreen content as currently used by most visually-impaired users, namely exploration of documents using only an Auditory Screen Reader (ASR). This serves as our control condition. In our implementation, the user taps the touchscreen to activate the ASR, which reads the digital content of the document element at the tapped location. For this, documents were segmented into the elements of titles, subtitles, paragraphs and pictures. There were no additional tactile cues. Figure 6.2 (left) displays an original visual layout used in the study, Figure 6.2 (middle) the segmentation of the GUI.

C2 The second condition uses ASR and a paper overlay on top of the touchscreen, i.e. a sheet of paper with laser-cut engravings in the form of uniform rectangular depressions (see Figure 6.2 (middle)). The engraved rectangles are spatially superimposed on the document elements of the visual GUI. By tapping one of the overlay rectangles, the corresponding document element can be accessed via ASR.

C3 The third condition also uses ASR and a paper overlay with engravings. However, engravings are not uniform but textured to allow a tactile differentiation between the document elements of titles, subtitles, paragraphs and images (see Figure 6.2, right).

Figure 6.1: Hands of a participant during the evaluation test of the fixed tactile overlays

> We used the textures described in section 5.3.3 as part of the process to adapt a page of a digital document.

The technical deployment and apparatus were those described in section 5.3.3 as part of *implementation B*. The adapted documents used as stimuli were articles from websites: one was a news abstract[34], and the other a short George Orwell bibliography from Wikipedia[35]. Both sources were in the German language (audio files included) as this was the main language of all our participants.

The experiment started with a 3-minute familiarization phase on a model text document, during which participants became familiar with the speech output

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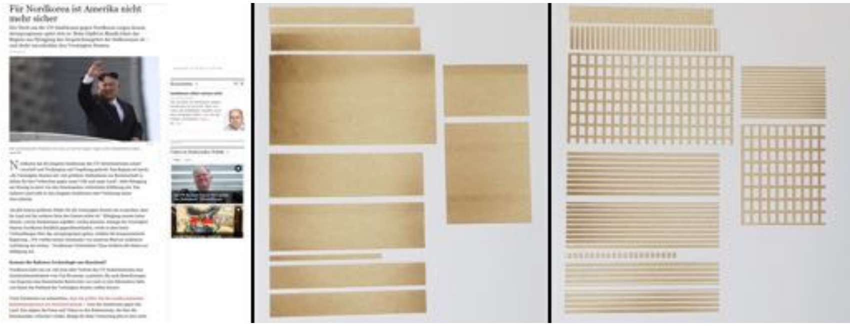
[34] http://www.faz.net/aktuell/politik/ausland/nordkorea-drohungen-gegen-die-usa-nach-un-sanktionen-15140093.html

[35] https://de.wikipedia.org/wiki/George_Orwell



Für Nordkorea ist Amerika nicht mehr sicher

Figure 6.2: Illustration of the three conditions to evaluate the Tactile Sheets (C1 at the left, C2 in the center, C3 at the right)

and acquainted to the different patterns such as the simple tap to activate the interactive elements. Then, each participant was presented with the three different exploration conditions in *pseudo-randomized* order. In each condition, the participant freely explored two documents of two pages each for an overall duration of 10 to 15 minutes, followed by a rating of the interface using the System Usability Scale (SUS) questionnaire [32]. Once a participant completed all conditions we conducted a semi-structured interview, where we encouraged them to comment on their experiences and provide a comparative evaluation of the three different interfaces.

6.2.3 Quantitative analysis

For the quantitative analysis conducted on this experiment we utilized the *System Usability Scale (SUS)* questionnaire [32]. This measuring tool provides a *quick and dirty reliable* mean for quantifying the usability.

Originally SUS was created by *John Brooke* in 1986. It consists of a 10 item questionnaire with five response options from Strongly agree to Strongly disagree, and allows experimenters to evaluate a wide variety of products and services, including hardware, software, mobile devices, websites and applications.

System Usability Scale ratings

Participants gave the prototype with the textured engravings the highest mean scores (M= 79.7, SD = 7.1), followed by the ASR-only prototype (M = 77.5, SD = 6.5), and the uniform engravings prototype (M = 75.5, SD= 6.5). Overall, this indicates good usability of all prototypes. To investigate whether the usability differed between prototypes, we conducted a repeated-measures analysis of variance on the participants‘ SUS scores. The result suggests that adding engraved overlays does not lead to a significant decrease in participant ratings compared to the state-of-the-art prototype (F(2, 16) = 1.72, p = 0.21, see figure 6.3).

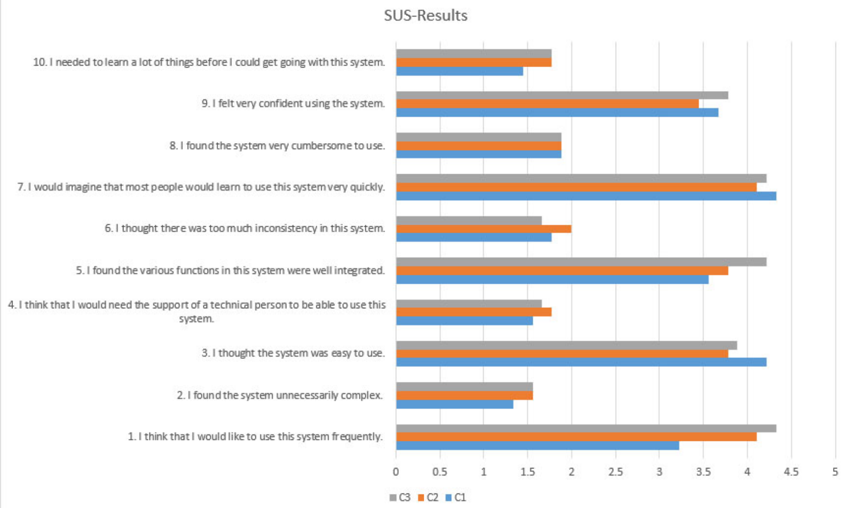


Figure 6.3: Quantitative scores attained from the System Usability Scale during the evaluation of the fixed tactile overlays.

6.2.4 Qualitative analysis

Quantitative assessment outcomes delineate and define data, and in this case also provided useful insights and personal impressions of our prototype. This kind of feedback can be processed as input data to generate qualitative evaluative information [59]. Hence, we conducted a semi-structured interview with the participants, in which we asked them for comparative evaluations of the mainstream access solution for touchscreen interfaces and the tactile approach employed in our prototypes. We also questioned them with regards to advantages and disadvantages of using texture patterns and ASR compared to normal Braille text. Lastly, they also commented about possible further applications of the approach presented.

We used a systematic, replicable technique for compressing many words of text into fewer content categories; a technique known as *content analysis [24]*, which is based on explicit rules of coding outlined by the semi-structured interview queries [159]. Using this analysis method we defined key phrases said by our participants. Those key phrases were a complementary qualitative assessment, which together with the quantitative evaluation provided us with indicators of acceptance and satisfaction [118] for our proposed system.

All participants mentioned the big improvement that additional tactile elements offered for document navigation compared to the mainstream smooth touchscreen interfaces. While some participants were aware of features that were built into their touchscreen devices, specifically those that allow access to single document elements, they also mentioned that they hardly use these features. Participants 3 and 7 commented that it is possible to determine the position of text elements on a touchscreen interface. However, they had only tried it a few times before ignoring that option *(e.g. P1: ”Finding something in particular on my cell phone screen can take me a while because I need to go item by item.” P7: ”I like tablets because they are more comfortable to explore by hand. However, mainstream screen readers just allow me to navigate in a linear way.” P2: ”In IOS you can explore the position of paragraphs on websites, but honestly I don’t use that feature because my smartphone is too small to explore comfortably”).*

While Braille provides the possibility to access documents with the tactile sense, all participants remarked that Braille typically carries little to no information about the layout of documents. For instance, P1 mentioned that *"With Braille I can read immediately, but I don’t have a good idea about the layout or organization of the things I read."*. All participants were aware that the visual layout typically reflects the logical structure of documents. Importantly, having access to the layout allows for faster and more flexible browsing of documents. P6 commented that she likes *"the possibility to read each block separately, I can read a bit of it, and if it is not interesting I stop it and I can go to the next. It is faster."*. While skimming from paragraph to paragraph is also available in ASR, tactile layout information also allows for non-linear exploration. Participants 1, 2, 3, 6 and 7 commented that the tactile patterns approach is very useful to access information in a segmented way. These same participants also remarked that it was very practical to use texture to identify different types of elements by touch only, i.e.

without using additional gestures or hotkeys. Participants 1, 4, 7 and 8 suggested that the access to content could be improved even further if the user could get an auditory summative preview of the content when the fingertip slides over the desired tactile element.

Participants made several suggestions on how tactile patterns could be employed besides document exploration. All participants were particularly enthused by the idea of using this approach to access the content of table cells (e.g. *P2: "On the phone or the computer, reading tables is very hard. I would like to have some tactile element to read tables."; P9: "Have you read a Braille table? They are big and hard to read. I really would like to have something like these tactile blocks to read cell content."*). Participants 2, 3, 4 and 7 suggested representing elements on presentation slides since these are mainly visual, and to make them accessible is still challenging.

Other popular suggestions were to use textures to indicate different elements on tactile indoor or outdoor maps (Participants 1, 2, 3, 4, 7, 8 and 9). For instance, P3 remarked that it *"...would be very interesting to have a map of the city or of a mall with tactile relief on paper which I can explore in the same way as your approach."* Lastly, several participants (P1, 5, 7 and 9) commented on the possibility to represent mathematical material through engraved textures, in particular elements which rely on spatial layout, including equations, algorithmic charts and graphics.

6.3 Evaluation of the Self-Identified Overlays

During the carrying out of this research work we have observed how challenging, frustrating and inefficient might be mainstream approaches to grant accessibility to digital textual documents for readers with visual impairments. This is because different functional constraints do not provide information about the visual layout which mirrors the logical structure of the document; simple images are not accessible in the first instance, textual content needs to be displayed in Braille, which can occupy a lot of space, and visual layout information does not translate to auditory media either with recorded voices or text to speech. Moreover, using these technologies to access digital textbooks can be troublesome to spot specific elements on a page.

Hence, to address these complications we created automatically identified paper tactile overlays for touch screens to allow the visually impaired to have access to a document's layout, differentiate between the individual elements, and navigate through the document. To assess the functionality and usability of our approach we conducted a comparative study of auditory screen readers (ASR) and our system to navigate through PDF textbooks. Seventeen participants took part in the study, providing their assessments and feedback.

In this section we describe in detail the study conducted, its methodology and results. Also, we describe the building of an apparatus to evaluate our approach with a functional prototype.

Our goal was to observe objectively if the usability increases for performing certain tasks using the tactile overlays, if providing tactile information about the document's layout is categorically beneficial, and if our prototype helps visually impaired readers in a measurable way to follow the logical structure of the document. Also, we wanted to examine how fluid is the interaction with the non-refreshable interactive space based on self-identified tactile overlays provided by our proposed system.

6.3.1 Study participants and location

The core idea to grant better accessibility for digital text documents for visually impaired readers comes from the necessity to provide more functional tools for educative content. Visually impaired students at different levels require well adapted and accessible didactic material [20, 149, 49, 66]. Thus, to gather test subjects closer to the profile of a student, we made two of the three persona generated profiles (see section 5.2.2) of young adult students. In addition, seeking a younger set of participants also closer to students‘ age range, we moved the location of the study to Panama City, where we could collaborate with *El Patronato Luz del Ciego (PLC); a non-profit organization dedicated to provide training and extracurricular education to the population of young and adult visually impaired in Panama city and its surroundings* [36]. We recruited seventeen participants from the PLC's users.

The participants were eight females and nine males, with a mean age of 26.53, and a standard deviation of 3.18. All participants had a 0% of vision level, with the exception of one participant who had 20%. The age of vision loss varied

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[36] http://www.patronatoluzdelciego.org/

considerably (from birth to adulthood) as shown in table 6.2. With the exception of two participants, all used smart-phones on a regular basis. Eleven participants were occasional Braille readers, the others were daily or regular readers. All were college students.

P	Gender	Age	Visual impairment info	Experience with touch screens	Experience with Braille
P1	f	23	0% from early adolescence	Regular smartphone user	Occasional user
P2	m	25	0% from adult age	little experience	Occasional user
P3	m	30	0% from adult age	Regular smartphone user	Occasional user
P4	f	30	0% from Early adolecence	Regular smartphone user	Occasional user
P5	m	27	0% from early childhoodd	Regular smartphone user	Daily user
P6	m	24	0% from birth	Regular smartphone user	Occasional user
P7	f	23	0% from birth	Regular smartphone user	daily user
P8	m	28	0% from adult age	Regular smartphone user	Regular user
P9	m	20	20% from early adolecence	Regular smartphone user	Occasional user
P10	f	24	0% from birth	Occasional user	daily user
P11	m	27	0% from late childhood	Regular smartphone user	daily user
P12	f	28	0% from birth	Regular smartphone user	Occasional user
P13	f	24	0% from late childhood	Regular smartphone user	Occasional user
P14	m	29	0% from late childhood	Regular smartphone user	Occasional user
P15	f	32	0% from birth	Regular smartphone user	Occasional user
P16	m	28	0% from Early adolecence	Regular smartphone user	daily user
P17	f	29	0% from late childhood	Regular smartphone user	Occasional user

Table 6.2: Participants (P) in the evaluation test for Tactile Sheets as self-identified overlays. This set of volunteers was recruited and interviewed with the assistance of the *El Patronato Luz del Ciego (PLC)*, located in Panama City.

All participants were older than the legal age of accountability according to the law in Panama (eighteen years), and they were appropriately informed about the nature of the experiment. All consented to participate in the study and signed a consent form written in their own language, which was read aloud prior to signing.

6.3.2 Experiment design and apparatus

The qualitative and quantitative data shown in the last stage seen in section 6.2 established the texture differentiated tactile patterns as suitable overlays to display the structure and layout presented in a digital text document. The deployment of the self-identification feature to the tactile sheets added a complementary dimension to the system's interaction space. Therefore, we focused this evaluation stage on objectively comparing our approach with an already available mainstream assistive solution to access digital textual documents for visually impaired readers.

Previously we have seen how the auditory screen reader (ASR) is the most preferred currently available application among readers with visual disabilities to read text documents in digital formats, even regarding the known constrains of this method. Hence, the logical choice of comparison for this stage is our self-identifying tactile sheets and an auditory screen reader accession; two well defined conditions for this comparative study.

Conditions for the comparative study

We chose a chapter (13 pages) from a geography textbook similar to those regularly used in Panama's high school system. This book section contained a lot of different document elements: titles, subtitles, paragraphs, side paragraphs, pictures, tables, and highlighted text. The document was divided into two halves: Pages 1-6 and Pages 7-13.

Here the two conditions were prepared:

C1 - auditory screen readers (ASR) The selected text book was originally available in PDF format. The chosen chapter was extracted with an online PDF edition tool[37], and with the same tool the two halves previously mentioned were separated. The chapter did not have any accessibility element available; the two documents were prepared adding the accessibility elements recommended by the PDF accessibility committee of ACM publications following the procedure indicated by this organization[38]. In this way the textual digital document was set accessible with mainstream available ASR tools.

C2 - Tactile sheets The thirteen tactile overlays corresponding to the pages of the chosen chapter were produced according to the procedure described in section 5.3.3, including all the document's elements found within the book section. Also, the screens were generated to be displayed with the identifier GUI described in section 5.3.4. In this way we achieved a fully functional self-identifying set of tactile sheets which worked with the same tablet described in section 5.3.3.

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[37] https://www.cleverpdf.com/

[38] http://www.sigaccess.org/welcome-to-sigaccess/resources/accessible-pdf-author-guide/

Test methodology

In order to conduct our comparative study, we defined nine tasks (T). These tasks sought to include those accessibility difficulties faced by readers with visual impairments when they try to access digital textual documents through mainstream assistive technologies like ASR [88, 179]. The defined tasks were focused on the acquisition of the document's structure provided by the layout. According to our theoretical framework [144, 8, 20, 19] and research bases (see section 4.2.1) this set of elements present negative effecs on the integral accessibility of those digital contents.

T1 Searching for tables and counting them.

T2 Finding tables and explaining their content.

T3 Searching for exercises in the document and being able to identify their page numbers.

T4 Continuity of reading across two pages.

T5 Finding definitions of words in side paragraphs.

T6 Large scale non continuous jumps across pages (finding a specific highlighted term in a certain page).

T7 Finding a paragraph by the first two words.

T8 Reading highlighted terms and bold text.

T9 Getting an overview of the entire page. Reading the titles and the highlighted terms.

It is important to mention that tasks T6 and T8 present a special setting because ASRs in base-line conditions are not able to detect or announce highlighted or bold text; elements which do not have a defined accessible mark readable by ASRs. This circumstance establishes T6 and T8 as primarily only doable with condition two (C2). We kept those points within the task set, and let the participants do them with the auditory condition (C1) as well to prove our point and to observe how they would approach solving these tasks. Other than this special setting, all tasks were doable with both conditions.

Procedure

The process of the study was as follows:

1. Participants sign the consent form
2. Participants answer questions about their demographics and their condition
3. Participants answer questions about their experience in Braille reading and usage of assistive technology
4. The experimenter conducts a semi structured interview about their use of text books in their school or college time
5. A time slot (5-8 minutes) is given to the participants to get familiar with the different tactile patterns and the gestures. This includes a description of each pattern, a short explanation of the content of the book and a guidance on how to place and use the overlays
6. A time slot (3-4 minutes) is given to the participants to get familiar with placing the overlays on the tablet
7. Participants are asked to perform the predefined tasks using tactile patterns or screen readers. During this part a video of their hands is being recorded (figure 6.4 and figure 6.5).
    - The order of the condition used and the adapted document's segment combination were pseudo-randomized
    - Each participant used one method (tactile sheets, ASR) for one of the halves and the other method for the other half
    - The tasks the users had to perform for each condition were predefined
    - Each task had an adapted version for each condition
    - We observed the success of each task
    - We compared the completion times for each condition
    - We asked the participants questions about the approaches and about their previous experience with assistive technology.
8. The participants filled a System Usability Scale questionnaire (SUS) and a NASA Raw Task Load Index (TLX) for each condition

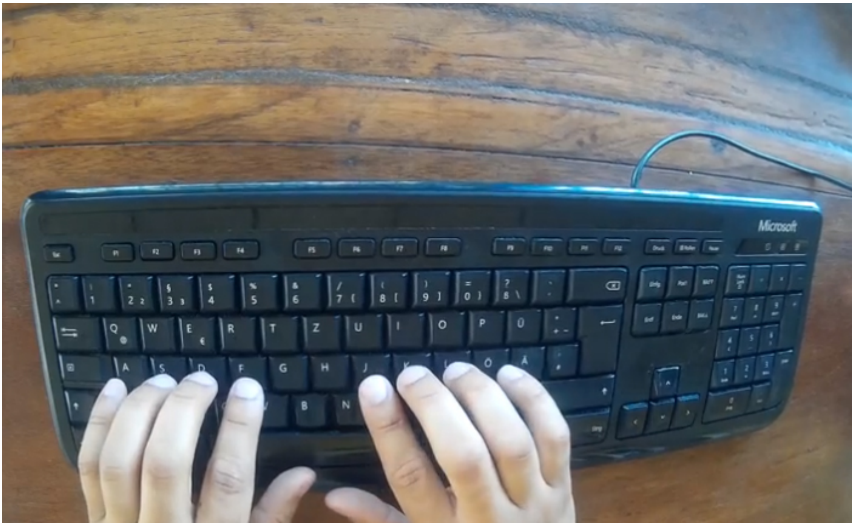

Figure 6.4: View from top of the work space during a test in ASR condition (C1)

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9. After the study the participants had a semi-structured interview, in which they gave their opinions about both conditions and their feedback about our approach.

We aimed to assess the usability of the system and the workload required to execute the set of tasks. Thus, we utilized the *System Usability Scale questionnaire (SUS)* [32] and a *NASA Raw Task Load Index (raw TLX)* [83]. Conjointly we collected and processed elements of qualitative data through semi-structured interviews, and a *thematic analysis* [9] approach was used to obtain concrete evaluative statements from the participants.

System Usability Scale (SUS) System Usability Scale - also referred to as *SUS*, is a 10-question form that evaluates the usability and the satisfaction of the users for a specific system or program. Each of the questions has five response options in a Likert scale from Strongly Agree to Strongly Disagree. Our questions covered different aspects of the system usability: retention, complexity, ease of use, robustness, functions integration, consistency, confidence and pre-knowledge.

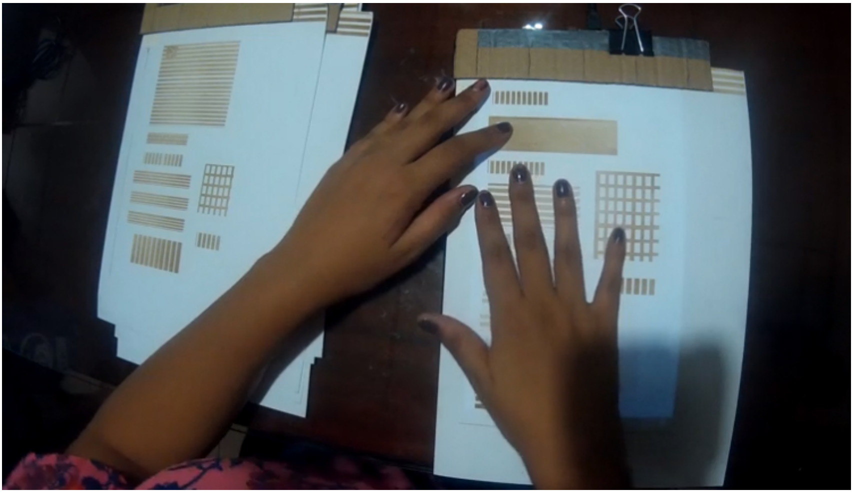

Figure 6.5: View from top of the work space during a test in the condition using tactile self-identified overlays (C2)

Brooke, et al. [32] defined a method procedure as follows. Each of the five options on the scale is given a corresponding value from strongly disagree: 1 to strongly agree: 5. The answers of the participants should then be changed accordingly. To evaluate the questions 1, 3, 5, 7 and 9 we need to subtract 1 from the participants‘ answer value. To evaluate the questions 2, 4, 6, 8 and 10 we need to subtract the answer from 5. We then get new values for each of the questions. Those new values are summed for each question per participant to obtain a resulting value for each user. This value is multiplied by 2.5 to get an individual SUS score for each user. This SUS score is the average of each individual score. The system can be considered usable or user friendly if the SUS score is 69 or higher (100 as a maximum score).

Raw TLX (Workload evaluation) Nasa-TLX is a multi-dimensional scale for researchers to acquire an approximation of the mental workload for one or more conditions [83]. The TLX has 6 sub scales: mental demand, physical demand, temporal demand, effort, performance and frustration level. Results are obtained based on the weighted average of rating for each sub scale given by the participants during or immediately after the task on a scale from 1 to 7. The TLX has proven its effectiveness in different fields of studies, and is a reliable method for researchers to estimate the mental workload of their approach on the user.

The most common modification made to NASA TLX is referred to as raw TLX, which analyzes each of the sub scales individually without the weighting process, allowing some of the sub-scales to be ignored based on their relevance. Due its simplicity and ease of use this version was used in this experimental setting, and the physical demand sub-scale was removed because of its inapplicability to the experiment. Ratings were given by the participants for each scale for each condition (C1 and C2).

Complementary questionnaire Two sessions of questions were conducted; one before the two conditions (C1 and C2) test and the other afterwards.

The first session included the following questions:

1. On a regular school day, how many of your classes (excluding sports, crafts etc.) use material from a standard textbook?
2. How is that material provided to you?
3. What is difficult about not having visual access to textbooks?
4. How often do you have to work with a textbook in college? Do you use textbooks more often in college than you did in school?

For the afterward questionnaire the following questions were prepared:

1. Which option did you prefer (screen reader or tactile sheets) and why?
2. What advantages can you highlight for your preferred option?
3. What is your feedback about the feature of self-identified overlays?
4. You have used the adaptation of a text book. If you could adapt another type of material to the tactile overlays format, what material you would like to adapt? Please prioritize your adaptations.
5. Please make general comments about your perception of the tactile overlays system (Tactile pattern recognition, audio feedback, touch interaction, possible improvements, etc).

6.3.3 Quantitative results

In order to assess our method we conducted a set of objective measurements aiming to provide a valid answer to the research questions presented in the introductory section of this chapter (see section 6.1). Those measurement methodologies were described in section 6.3.2, and their results were as follows.

SUS results

The screen reader received a SUS score of 58.38. The tactile overlays SUS score was 87.21. We used a Wilcoxon signed-rank test to determine the significance of the results and the test score with n=17 was 153. The critical value for $p<0.05$ is 41, which shows us that the tactile overlay was significantly more usable than the screen reader in our particular use case (Figure 6.6 shows the mean results for each SUS statement).

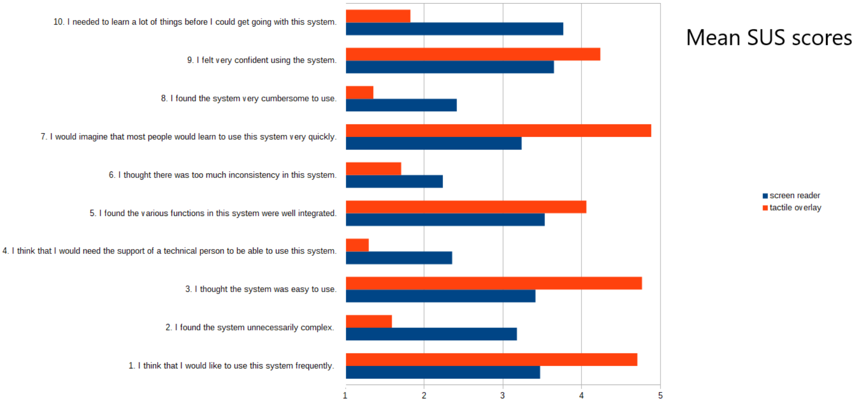

Figure 6.6: Bar chart of the mean SUS scores given by the participants for C1 and C2 (1: Strongly disagree 5: Strongly agree).

Raw TLX Results

The TLX results were evaluated for each sub scale separately. The mean rating for each category was calculated and a repeated measures t-test was done for each. Here we describe in detail the results of the t-tests (A graphical representation of the results can be seen in figures 6.7 and 6.8):

Mental demand The mental demand of the tactile overlays was significantly less than the demand required for using a screen reader, with a sum of differences=4, mean=0.235 and standard deviation=0.191. (t(16)=2.219, p=0.02).

Temporal demand The temporal demand of the tactile overlays was significantly less than the demand required for using a screen reader, with a sum of differences=5, mean=0.293 and standard deviation=0.346. (t(16)=2.062, p=0.03).

Effort level Participants required significantly less effort to use the tactile overlays than the screen reader, with a sum of differences=5, mean=0.294 and standard deviation=0.221. (t(16)=2.582, p=0.01).

Performance level Participants had significantly more success using the tactile patterns than the screen reader, with a sum of differences=27, mean=1.588 and standard deviation=0.507. (t(16)=9.194 p<0.01).

Frustration level Participants were significantly less frustrated using the tactile overlays than using the screen reader, with a sum of differences=35, mean=2.059, standard deviation=0.559. (t(16)=11.356, p<0.01).

Completion time results

In figure 6.9 we see the values for completion time means and standard deviations (SD) for both conditions. The results in the mean column are all in seconds.

For each participant we measured the completion time for each task for both conditions (C1 and C2 see section 6.3.2); the time measured using the video footage captured during the tests. For the ASR condition (T1-T5,T7,T9) the mean completion time was 56.67 seconds and the standard deviation was 2.67. For the tactile condition the mean time was 66.35 seconds and the standard deviation was 1.90. In table 6.9 you can see the mean completion time and standard deviation for both conditions per task.

As we expected, the participants were not able to complete T6 and T8 using the ASR condition (C1), therefore we omitted the results of those two tasks from our comparisons and our significance tests. Nevertheless, it is worth mentioning that the mean completion time for tasks T6 and T8 using the tactile overlays (C2) was 61.44 seconds and the standard deviation was 8.38.

We used two way ANOVA to determine if we could or could not reject the *null hypothesis* for each factor. The first factor was the modality. The null

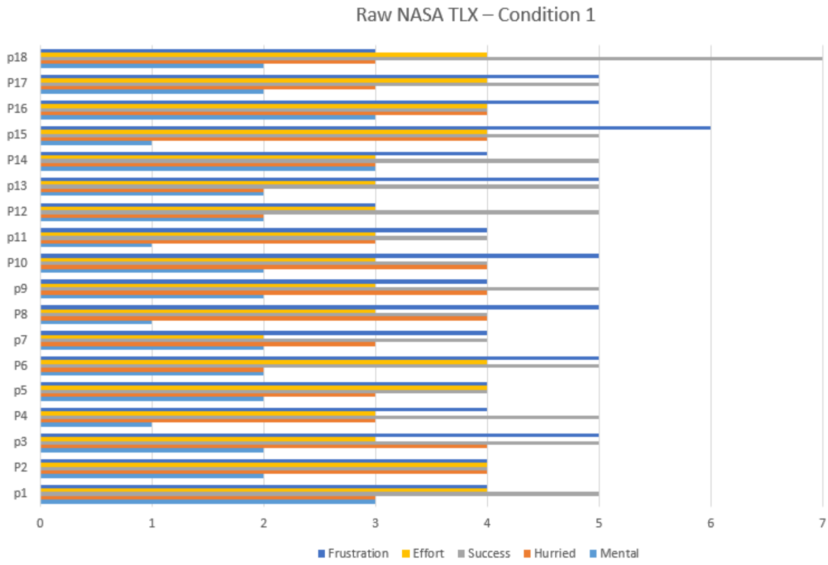

Figure 6.7: Raw-NASA TLX results in average for condition 1 (C1)

hypothesis was H0= The modality has no effect on the completion time. The second factor was the task. The null hypothesis was H0= The task has no effect on the completion time.

The results of the two way ANOVA were as follows:

- Modality: (F(1,224) = 18.779, $p<0.05$) We rejected the null hypothesis for this factor. This means that the modality does have a significant effect on the completion time, and the tactile condition requires more time than the auditory.
- Task: (F(6,224) = 3.114, $p<0.05$) We rejected the null hypothesis for this factor. This means that there is a significant difference between at least two of the tasks in completion time.
- Combination of Modality and Task: (F(6,224)=19.951, $p<0.05$) We rejected the null hypothesis.

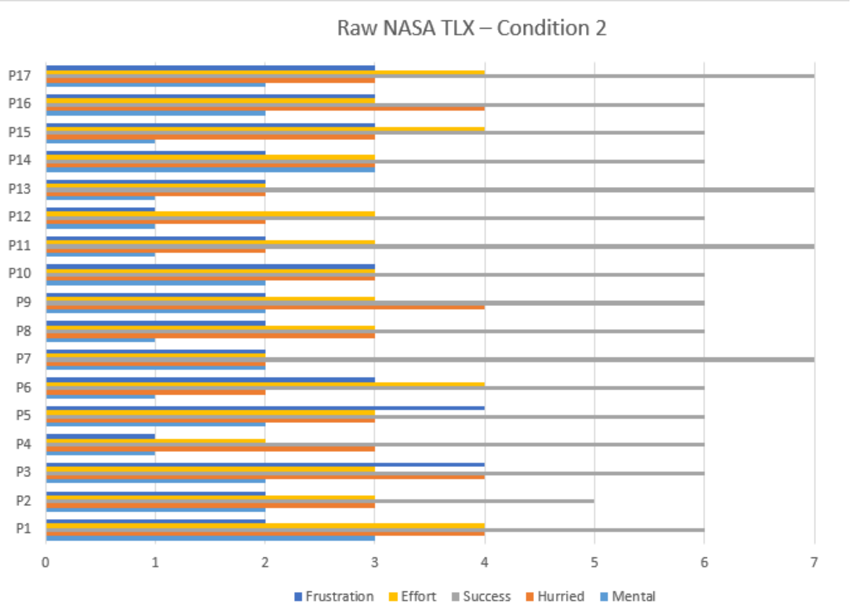

Figure 6.8: Raw-NASA TLX results in average for condition 2 (C2)

Our findings prove that the completion times of the prototypes are different from each other, but only for some of the tasks.

Success/ Failure results

The participants were able to perform all the tasks successfully on both conditions(C1 and C2). However, in T3 three participants were not successful using the ASR condition (C1).

For this point we also omitted the results of T6 and T8 from the statistical tests; however it is worth mentioning that both tasks had 0% success rate for the ASR condition and 97% success rates using the tactile overlays.

During the deployment of our prototypes different technical difficulties impeded evaluating and comparing the log data with the video footage. Nevertheless it is worth mentioning that participants did not complain about activating elements

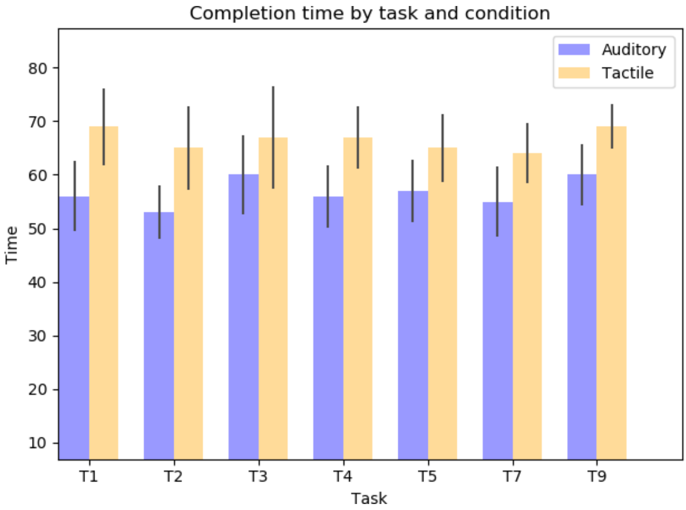

Figure 6.9: Bar chart for completion time means for each task and condition with a standard error.

unintentionally aside from two or three occasions when a participant triggered the highlighted text by accident.

6.3.4 Qualitative results

Besides quantitative measurements related to usability and task completion, in this research we consider participants‘ comments, attitudes, statements, and other qualitative feedback related to the proposed system as data entries which can indicate values of acceptance or rejection, or concrete assessments such as improvement suggestions or criticisms to the presented approach.

We conducted a pre-questionnaire before the test and a post-questionnaire afterwards, which gave us the starting framework for a semi-structured interview. As we established previously, all the participants (P) interviewed were Panamanians so we used regional vocabulary.

All the quotes (q) used in the following two sections are translated from a colloquial language (Spanish) to standard English. The statements were adapted neutrally and the meaning and context were not changed in translation.

Pre-questionnaire

Before the tests a short questionnaire (see section 6.3.2) was answered by the participants about their previous experience with textbooks and their accessibility. Here is a summary of their answers:

On a regular school day, how many of your classes (excluding sports, crafts etc.) use material from a standard textbook? All the participants required a printed textbook for all their classes during high school.

> P5: *"Teachers did not care that printed books were useless for us, they wanted all the students to have the book."*
>
> P13: *"I remember about a History of Art text book I bought. I never opened it; I sold it some time later and the cover and the pages looked new."*

How was the material provided to you? All the participants had access to books through audio tapes or digital audio files. Additionally, eight participants used OCR (Optical character recognition) to scan the books and two others had access to the books in digital text files provided by their teachers.

> P6: *"My portable CD player became my best friend, when volunteers were able to record the reading in MP3 it was a hit. Then I could have my study material available in a very small packet."*
>
> P10: *"I was not sure where, but my teacher got the PDF version of my social sciences text book. In those days I did not have a laptop, but I was able to study the lessons at home.... Those same lessons as my sighted classmates. In fact the access to that specific book helped me to decide to study Sociology in college."*

What was difficult about not having visual access to textbooks? All the participants agreed that there is always an important loss of relevant content when books are transferred to an accessible format as audio or digital text (pictures, tables, layout, graphs), because they were originally made to be visually read. Two participants mentioned that pictures and tables are the most important lost content elements.

> P5: *"I can remember a case when we were studying World War II. There was a map with information about some battles, but the information in the text had a mistake, the map was OK. I was not able to see the map with the*

right info, but all my sighted class-mates studied with the map. I failed in that exam because the textual info I got was wrong. I was not my fault nor the fault of the volunteer who recorded the book for me, however I failed the exam."

P17: *"it was not rare that during high school and even now in college my classmates can go directly to the paragraph or chunk of text they should read because that block is differentiated in the page layout, with a different color, perhaps an outlined frame, or something which the scanner cannot get, or the volunteer did not comment in the audio recording."*

How often do you have to work with a textbook in college? Do you use textbooks more often in college than you did in school? All participants agreed that they need to work with more text books now (during college) than during the high school. All participants declared that they have much more access to digital text books in college than they did during high school.

P1: *"Usually in the school, teachers assigned us, for example, to write a paper. It was common that the teacher gave the guide about what book you can find the information in. Now in college we should write a paper and we should figure out the sources for the info. It is not bad, it makes us read from several books and journals, nevertheless it makes us deal with several inaccessible sources instead of a single one."*

P13: *"During my school we got a list of text books, one book per subject, and the teacher stuck to that book for the class. Now I have a subject and it is not rare that we should use two or three different books to get information, to check for some details, or to look for data. Usually those books are in the library, almost never with a digital version available and this makes studying into a challenging task; as in the school, but multiplied by two or three."*

As previously observed, answers of the participants in the pre-questionnaire were similar, showing consensual opinions about the queries. They established a set of qualitative factors shared by our group of subjects, aspects which tally with factors previously seen in the related work 3 and in the chapter dedicated to requirements 4 in reference to the difficulties of readers with visual impairments to access standard printed contents.

Post-questionnaire

After the study a questionnaire was answered by the participants regarding their experience with both conditions (C1 and C2) and what they preferred and why. Together with concrete answers for our queries we aimed to gather deeper and more extended insights from the participants,and in this way our queries were the starting point for a semi-structured interview.

The content extracted from those consultations was analyzed with a *Thematic analizis* technique, and the outcome of that process is shown as follows:

Which option did you prefer (screen reader or tactile sheets) and why? All the participants agreed that they favored the tactile overlays over the screen reader. There were multiple reasons behind that opinion.

Some participants (p2-p17) discussed the physical sensation of handling a book.

> P3: *"It is like reading a book without a book. I think I can lie in a hammock, put the book on my belly and have a relaxing study session."*
>
> P11: *"When I read with my computer I should be at the desk; to read using my smartphone is more comfortable but I cannot navigate easily throught the content. This tablet is like a cool mix of those options; it is like a book which I can just take out from my bag and read anywhere."*

Participants (p1-p7, p10, p12) commented about the convenience to use the tactile overlays to locate and identify the content directly on the paper sheet's surface without having to rely on keyboard commands or gestures

> P5: *"I slide my hand across this page and I know what am I touching without asking the screen reader what it is, that is great! Besides, when I use my phone to read something I never have an idea about what type of element am I reading, if it is a simple paragraph or what."*
>
> P10: *"Imagine that I need to find information which is in a table or in a bullet list. I don't even need to put the pages on the tablet, I can explore by hand, look for the wanted page and find the table or text block I want, then I can use the tablet. However, the possibility to do that like this will save a lot of time and is more handy."*

Participants who were born sighted (p2, p3, p4, p8, p9, p14, p16, p17) asserted that tactile overlays allowed them to remember a regular book's layout and it aided the comprehensive reading of the content.

P4: *"The engraved pages really remind me of a printed book, magazine or newspaper; that layout is useful to make the text easier. Honestly I have been not able to find anything similar with Braille printings."*

P14: *"I feel that the possibility to see the text layout helps me to understand better the information from the book, it is like the information segmentation helps my mind to organize it better."*

What advantages can you highlight for your preferred option? About this query participants provided responses in line with the previous question.

A number of participants (p1-9, p11, p13, p17) expounded on being able to handle physical pages more easily when navigating through the content.

P5: *"If you ask me to find something on page five, I just need to do this (the participant took a set of tactile overlays and flipped the pages quickly) and I get page five. Fast and easy, with a PDF file there is a keyboard command to go to a page, honestly right now I don't remember it, but sometimes it does not work."*

P9: *"I like the feature which makes me able to jump pages with a keyboard shortcut, but to feel paper pages in my hands, and being able to flip them for me is more helpful than keyboard shortcuts."*

Other participants (p2, p4, p5, p8, p11, p12, p16) remarked on the advantage of allowing them to identify the type of each element on the pages, which is not feasible when using auditory screen readers.

P8: *"It is great that I don't need any keyboard command,and can flick or tap on a touch screen to identify the different parts in the page. I just need to touch it and quickly I know if it is a table or a regular paragraph."*

P16: *"Engravings let me know if there are paragraphs, tables or pictures in the page before I access their content. Of course it is much more practical than screen readers where in the best case I can just identify tables."*

Some participants (p1, p3, p6, p7, p8, p12, p15) said that the tactile patterns on the overlays were easier to recognize than Braille text.

P1: *"To be honest I am not so good with Braille, I am a big fan of text to speech, however your tactile engravings are much easier to identify because they are a wonderful mix of audio and touch."*

P15: *"I always will defend Braille as a reading and writing method for blind people, but I also should admit that for books and long contents it is bulky. These tactile pages offer something in between Braille and screen readers, it is faster and easier."*

What is your feedback about the feature of self-identified overlays? All participants provided positive opinions about this feature, and offered a set of quotes which proposed different improvements to the presented prototype and its functionality.

All the participants concurred with the idea that the main goal should be being able to produce the self identified overlays using some kind of printers available at home.

P7: *"It would be a hit if I could get these overlays printed out at my home with a special printer, and very important that the printer be affordable."*

P16: *"One of the biggest weaknesses of Braille printing is that a Braille printer for home is ridiculously expensive. I would buy your idea if you can make it possible to produce the overlays at home like a regular desktop printer."*

Here we include some additional feedback statements extracted from quotes shared by the participants regarding the tactile overlay system:

- It is necesary to improve the method of placing the overlays on the tablet.
- The system could be made more agile by using a smart pen and putting aside the tablet.
- Tactile representations can be better presented adjusting the layout to the needs of the visually impaired user instead of trying to show the original layout of the book.
- The reading function should allow the users to navigate through the text by character, by word or by lines.

You have used the adaptation of a text book. If you could adapt another type of material to the tactile overlays format, what material would you like to adapt? Please prioritize your required adaptations. The participants suggested more use cases for the tactile overlays other than textbooks, for example:

Didactic and navigational maps, drawings and diagrams, as well as power point designs and table contents.

Not printing overlays for an entire book, but instead adapting key elements of the content aiming for a joint interaction among auditory screen readers, tactile overlays and Braille. This was a popular suggestion given by the participants (p1, p2, p3, p5, p7, p8, p11, p12, p14) Being able to print out only important pages as overlays and read plain text with the screen reader.

P2: *"At the end, if I need to print out 1 or 2 hundred overlays for a book, and also I should carry a tablet to make them work would be as impractical as carrying a whole book printed in Braille. If you print just important pages as overlays like tables or figures, and I can read plain text with the screen reader, everything would be easier."*

P12: *"You know, you don't need to make engraved pages for all the book; just make overlays for the things you really require to see tactually, such as drawings, maps, very complex tables and so on. Make all the things work together: your overlays with the taps to read and the screen reader with the keyboard shortcuts, and then you will get an interesting reading platform for blind readers."*

Although, in general, most of the feedback we received in the qualitative interview was positive, there was also some criticism regarding some prototype aspects. The question Please give general comments about your perception of the tactile overlays system (Tactile patterns recognition, audio feedback, touch interaction, possible improvements, etc.) elicited the following:

There was some criticism regarding the placement of the sheets on the tablets. Two participants in particular commented on that.

P1: *"Putting the overlays on the tablet is very slow and it takes away the feeling of high tech."*

P11: *"Exploring each tactile sheet is very quick, but taking so much time to place the sheet on the tablet diminishes the sensation of fluent reading. "*

Another aspect commented on was the capability to read individual words and characters with ASRs.

P15: *"When I read with the screen reader I need to stop the reading to check the spelling of a specific word, but when I read in Braille I see the spelling while I read. The audio of your sheets does not let me check the spelling."*

An argument provided by two participants referred to organizing the document's page layout structure in a more abstract way that optimizes comprehensibility more than a visual layout emulation.

P10: *"I think this is the first time I can look at the layout of a page. However I might say that it would make better sense for me if the blocks were next to each other like in a chess board, using the space on the page better."*

P14: *"The representation with the tactile patterns is good and the layout is easy to understand, but perhaps if you organized the patterns in a kind of grid where each cell contains a single paragraph, picture or title you would be able to track the elements‘ positions much easier than on a random layout."*

The comments we received from the participants were very fruitful and insightful. There are however some interpretation concepts we need to discuss in order to properly understand their answers and relate them to the quantitative data. In the next section we scrutinize our results more deeply.

Chapter 7

Discussion, Conclusions and Description of Further Works

The evolution of this research was carried out in three stages; the first based on a refreshable reliefs pin display; the second based on engraved paper fixed overlays; and the third where the fixed paper engraved overlays were boosted with the possibility to be identified turning the components into a dynamic interface system. Each stage presented its own particularities and offered concrete information, used for data entry for the subsequent stages conjointly with information that showed collateral aspects related to the envisioning, designing, development and building of tactile interfaces for users with visual impairments.

In the present section we compile the concepts and ideas learned throughout this research and discuss our findings providing answers to our research questions. We then outline potential further research lines that arise from our research.

7.1 General Discussion

In this following section we will proceed to discuss the main output for each stage of this research work. We seek to provide interpretation, meaning and consequences of the most significant results. Each stage is considered separately, maintaining a comparative focus considering the iterative setting of our process (see section 1.2), where the set of findings, recommendations, and relevant resultant elements in each step become the input for the next stage.

7.1.1 Discussion about the pin display stage

As we mentioned in section 5.3.2, the *HyperBraille* device was implemented as the technical base where we started to envision the whole concept of tactile representations for textual content. The use of this technology seemed to be logical in our context, and its implementation outlined the technical deployment of this early stage.

In chapter 5, in section 5.3.2, we described a primary user test (Exploration of scientific papers with Tactile pages), in which we expected to collect concrete data related to the usability of the conceptualization of *Tactile pages*; the tactile interface prototype designed to present the visual layout of textual documents through an interactive tactual and auditory interface. In this test we compared the use of mainstream auditory screen reader software for desktop computers with our prototype, in order to explore a set of previously evaluated scientific papers. Four subjects with visual impairments participated, and in this first round of tests the participants generally showed a better performance using the standard screen reader.

We noted discrepancies between the quantitative performance and the subjective qualitative declarations given by participants; where they expressed interest in the tactile interactive presentation of the textual documents layout, nevertheless navigated more confidently and quickly through the test documents using the auditory screen reader. In later conversations to probe this further, they remarked on the interesting idea of implementing an interaction dynamic with features like a mainstream desktop computer screen reader, but how in practice that dynamic interfered with the interaction fluidity.

We designed and conducted a second experiment (Exploration and execution of cooking recipes, see section 5.3.2), in order to evaluate collaterally how users could interact with our prototype through a set of instructions to execute a fake cooking task. All the ingredients were replaced by innocuous items that resembled food and ingredients. Participants had to access, explore and read the recipe using the Tactile pages, and follow the instructions which involved taking items, moving through a few additional steps, and going back to the Tactile page interface.

This was not a comparative observation; we expected to gather objective data from a simulated daily life activity. An additional interaction interference factor was added, and the non-mobile and fully desktop physical configuration of the HyperBraille was not optimal for an in-motion use case. Two visually impaired subjects participated in the test.

Here the observations offered by these subjects were not very different from the previous experiment, in that the quantitative data gathered was not favorable for the Tactile pages prototype, however the qualitative information presented a line of thought which required to be considered. The interaction concept was interesting for the users, but the interaction design had problems which needed resolving.

Concept design main drawbacks

Despite the few participants, the uneasiness shown by our subjects evidenced a unfocused design of the user experience. The envisioning of a interaction space which resembles a standard *auditory screen reader software*, although it might looks as a reasonable approach, has presented a set of practical hindrances:

- The deployment of a secondary small keyboard added to the interaction space to resemble the keyboard interactivity of a screen reader, required users to move their hands from the tactile relief surface, taking away their ability to exploit the keyboard interactivity or the tactile relief textual document presentation properly.
- Due to the early stage of development in the interface dedicated software for the HyperBraille prototype, the interfacing between the linked ASRS and the designed Onscreen Interface (OSI) seen in section 5.3.2 was not able to create a subjective impression of fluidity in the interaction space.
- The interaction design of a regular desktop computer auditory screen reader is intended for an auditory interaction, but the addition of a new interaction channel or modality implies an unavoidable adaptation and redesign of the interaction space. A tactile interaction space requires its own interaction design.
- Although the logical structure created to represent the segments of different textual documents (see section 5.3.2) was technically functional, even resembling that used in ASRS, the interaction space was not able to convey that functionality to the casual user.

Summary of the main ideas arising from discussions with the subjects

Although the assessment of this concept and prototype offered a non-favorable evaluation, the post-experimental feedback given by the subjects provided a valuable opportunity for us to improve the whole conceptual design:

- The feedback gave us further insights and ideas for both functional and non-functional requirements for an effective system (see section 4.3.3 and section 4.3.3).
- Relevant elements such as required hardware and software system components (see section 4.3.4), as well as interaction concepts (see section 4.3.5) were also finally concretized using the experience acquired in this design stage.
- The design for the tactile representations was successful in offering an easy identification element for the textual digital documents elements.
- Participants were able to recognize and navigate in a tactual mode the tactile representation of a document's page visual layout.

We concluded that the HyperBraille device has potential, nevertheless from a user convenience perspective it presents a number of barriers to overcome:

- Their purchase price is not affordable for regular users, or even institutions.
- The interfacing software is in a very early development stage.
- The worldwide community of users is scarce.

Reconsidering the technical approach At the beginning of this stage we expected to collect concrete data related to usability and user experience, however the information we obtained has shown circumstances to consider before deciding if the initially selected technical approach (HyperBraille device) is the best alternative. These include:

- The definition of the logical structure created to represent the segments of different textual documents (see section 5.3.2), was a didactic task which allowed us to learn how work the backend of screen reader software works, nevertheless that object structure can be represented within already developed *OOP* ambits, simplifying the logical representation work.

- The technology to produce refreshable and interactive reliefs dedicated for tactile interfaces oriented to users with visual impairments is still in an experimental stage, so it is not profusely spread.
- Hardware mobility is a factor which would benefit the user experience and the user test design.
- Although it is possible to purchase *HyperBraille* and other similar devices as manufactured products, there is not an environment to develop applications in an efficient way. Solutions like MVBD (Metec Virtual Braille Device[39]) or BrailleIO [28] are at an early *Research and Development* stage, and seemingly they will stay in that status for an undefined term.

Hence, the rethinking of the technical setting requires us to consider alternative approaches to offset the loss of HyperBraille's interactive features. This add a further dimension to our research questions about providing interactivity to tactile representations .

7.1.2 Discussion about the engraved paper fixed overlays stage

After the research process entered into a self-evaluation and introspection stage, we delineated a series of guidelines to be fulfilled at this design stage:

- To find an environment that offers total tactile interaction on the surface of reading
- To implement a device that offers comfort of use
- To deploy a scheme of interaction mostly based on the tactual channel, leaving the auditory channel exclusively as output response.

The HyperBraille device offers a scheme of refreshable tactile images which cannot be reproduced by other means available for this investigation at this time. However, its ability as a tactile display does not compensate for its functional limitations. Therefore we proceeded to search for alternatives to produce tactile

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[39] https://download.metec-ag.de/MVBD/

displays, and introduced the prototypical concept of *Tactile Sheets [205]* as a plausible approach for a multimodal support for document exploration.

Instead of displaying a *Tactile page* on the HyperBraille, the physical distribution of the segments of the document would be displayed on a fixed sheet in which tactile patterns representing the document's segments would be shown. The overlay would be made of paper and the tactile representations engraved on it using a laser cutter. This procedure is described in detail in section 5.3.3

Conjointly, the use of tablets was considered as a viable alternative to encompass the OSI, ADR and GIOM components in a single hardware component. However, the tactile ouptput component of the GIOM had to be reevaluated and reinvented as a static option in the absence of a refreshable device such as HyperBraille. The ADR would be contained as a logical structure in the OSI which in turn would be represented by a GUI shown on the tablet screen, and the device's tactile response capability (the general scheme of supported gestures) would act as the GIOM input tactile component. Most currently available tablets are able to handle different options of auditory output; either TTS and audio playing are supported in tablets hardware/software platforms. Software elements like *BrailleIO framework* and desktop computer standard applications are not used anymore as development platforms to shape logical components, so we exploit the GUI development framework available. This framework should allow us to produce screens which occupy and fit in the entire device's display size, and arrange a set of touch-events activatable graphic elements in customizable positions on the screen. Those activatable graphic elements should permit several possibilities of touch events (e.g. single tap, double tap, etc.), and should allow resizing that might be required during the GUI design stage.

As auditory feedback we deployed pre-recorded sound segments containing the corresponding text of each segment in the adapted document. Thus, the details of the interaction design can be seen in section 5.3.3. The junction of the tablet as a touch-screen based device, the tactile overlays and the involved software is denominated *Tactile Sheet*.

With this reinvention of the *Tactile pages* idea, we expected and got a simplification of design, deployment and implementation elements. This reinvention and second design stage explored a novel and cost-efficient way to assist visually-impaired individuals to access the visual layout of digital documents. For this, we developed two types of engraved paper overlays that can be placed on a capacitive touch screen device so that the engravings spatially coincided with various document elements. The first consisted of uniform rectangular depressions representing major document elements and the second of differentiated tactile patterns (see section 5.3.3 and figure 6.2.2); one for each type of major document element.

In a user study with nine participants with visual impairments (see table fixed-participants), we compared these prototypes with a state-of-the-art screen reader modality where the user activates the auditory feedback without any tactile interaction. The detailed description of this evaluation can be read in section 6.2.

We collected SUS questionnaire ratings to assess the usability of each condition, and a similar level of usability between conditions was achieved. Participants gave the prototype with the textured engravings the highest mean scores (M= 79.7, SD = 7.1), followed by the ASR-only prototype (M = 77.5, SD = 6.5), and the uniform engravings prototype (M = 75.5, SD= 6.5). Overall, this indicates good usability of all prototypes. To investigate whether the usability differed between prototypes, we conducted a repeated-measures analysis of variance on participants' SUS scores. The result suggests that adding engraved overlays does not lead to a significant decrease in participant ratings compared to the state-of-the-art prototype (F(2, 16) = 1.72, p = 0.21, see figure 6.3).

In addition, we gathered qualitative feedback related to the proposed interaction model. This feedback revealed that participants reacted very positively to the possibility of having access to the spatial layout of a document's elements. They remarked that it offered them the ability to browse through documents faster and in a non-linear fashion. Differentiating elements through different tactile textures was also appreciated as it served as a mini-preview of what to expect at a certain location, helped to related those elements with their position on in the digital document and thus supported building an internal representation of the document's logical structure.

Discussion's summarized main ideas

From an objective point of view the evaluation in this design stage did not show an irrefutable user preference for the prototype of Tactile sheets. We observed a usability quantification which matched the one shown by an ASR alternative. However, although it was the first time that our participants were exposed to the Tactile sheets prototype, and the interaction scheme, was learned in situ, similar satisfaction values between the auditory screen reader and Tactile sheets approaches is evidence that supports a number of points:

- The ASR model has a strong rootedness in the users' preferences.

- The tactile scheme brought from the previous design stage to represent documents' elements layout is also functional and usable in this current stage.
- Two-dimensional arrangement of non-differentiated tactile elements offers a very limited perceptual functionality to represent a document's layout.
- Differentiated texturized tactile representations for document layout elements plus a coherent two-dimensional arrangement present a more suitable level of perceptual functionality for the users.
- Users keep interest in tactile representation of documents' usually non-accessible aspects.
- The fact that eight of the nine participants were regular users of touch-screen mobile devices affected the acceptance level of the simplified interaction scheme oriented exclusively to tactile and auditory modalities.

Collected qualitative data showed more favorable evaluations than in our previous design stage, and a number of enthusiastic suggestions were offered, confirming the need for and direction of our development:

- Profuse user suggestions about possible uses for Tactile sheets might indicate unsatisfied expectations about the current functionalities offered by the mainstream ASR interaction model. We obtained an empirical confirmation of the suitability of developing an auditory modality interface from a tactile interaction model.
- Participants showed most of their interest on the technical feature of combining the functionality of a regular touch-screen with tactile overlays. This gives us impetus to exploit that feature in additional document types like maps, charts, or presentation slides.
- Tactile sheets were granted with a qualitative higher functionality than Braille text regarding its possibility to code and convey more information in a smaller space.

As we previously mentioned (see section 7.1.1), tactile sheets left aside the possibility of HyperBraille to refresh the content as its engraved overlays are static. The following design stage should approach the problem of adding fluidity to content overlays, as discussed in the next section.

7.1.3 Discussion of the self-identified overlays design stage

Our goal was to make the platform as interactive as possible and be as assistive as possible. Hence, the core problem in this stage was to give a refreshable interaction mode to a set of static overlays utilizing those components defined in the previous design iteration. Our functional requirements were to deploy a method to update the Tactile Sheets without requiring any direct interaction between the user and the software, relying instead on interaction directly with the paper, and to provide the feeling of an actual book and not an electronic device behind it.

We explored different alternatives to exploit our currently available resources to obtain the desired effect. In section 5.3.4 we described in detail how capacitive touch screens can be triggered using any conductive material (see section 2.4.2) without having to use our fingers to activate it. We used this characteristic of capacitive touch screens to simulate touch points using conductive materials to produce a similar effect of identification for each tactile sheet. We coded different touch points for each overlay in 4-5 bit binary codes. Each binary code consisted of 0 or 1 bits: 1 being the result of a touch point and 0 the result of no touch point. Each of the tactile sheet pages had its own binary code that would be identified by the system once the corresponding touch positions were matched. In section 5.3.4 and 5.3.4 we describe this in detail.

The technical achievement of producing a reliable content refreshment effect with static engraved overlays required to be assessed in the context of user experience and tactile representations of a textual document's visual layout. Our users' evaluations are discussed below.

Discussion about self-identified overlays evaluation

The evaluation process of this design stage is described in detail in section 6.3. In this experiment seventeen visually impaired participants took part in the test (see table 6.2). We moved the location of the study to Panama City, where we could collaborate with *El Patronato Luz del Ciego (PLC); a non-profit organization dedicated to provide training and extracurricular education to the population of young and adult visually impaired in Panama city and its surroundings*[40]. The conditions for this experiment are described in section 6.3.2.

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[40] http://www.patronatoluzdelciego.org/

For each condition participants filled a System Usability Scale questionnaire (SUS 6.3.2) and a NASA Raw Task Load Index (TLX, see section 6.3.2), and in each of the nine tasks (T) we observed completion time and success/ failure. Conjointly, two sessions of questions were conducted; one before the two conditions (C1 and C2) test and the other afterwards (see section 6.3.2).

Summary of discussion main points In order to evaluate the SUS questionnaire properly we included the feedback given by the participants. Screen readers are commonly used worldwide in many different applications, establishing their proven levels of usability and user satisfaction. Screen reader condition got a 55 SUS score (less than 69 the minimum score required). This value does not mean that it is unusable, nevertheless when the use case refers to reading textbooks it reflects a high frustration level. Our subjects noted that texts in PDF format presented particular problems. A similar result was also shown in the NASA TLX questionnaire. The mental workload and frustration levels were significantly in favor of the tactile overlays.

The statistical tests we used for the completion times proved that the task, the modality, and the combination of task and modality all had a significant effect on the time required for completing a certain task. We were able to detect that the screen readers had better completion times than the tactile overlays, yet when we considered at this data along with the qualitative data and the interview arguments, we found contradictions between what the participants did and what they said. The completion times of the screen readers were significantly better than those of the same tasks using the tactile overlays, yet in both the interviews and the SUS/TLX questionnaires most feedback was in favor of the tactile patterns. We therefore determined to gather information possible reasons for this, and came up with the following possible explanations:

1. Our system could have had emotional effects on the participants as it gave them a similar experience to what a sighted reader would have had reading a similar document.

   Though people were performing their tasks more efficiently with the screen reader, their self-evaluation of success was in favor of the tactile overlays. The negative emotions they experienced and the frustration they felt when using the screen readers, in addition to failures to achieve some of the tasks may have affected their self-evaluation.

   - Regarding the success rates of performing the tasks, the participants were able to perform the tasks successfully with both conditions except for T3: finding exercise questions, T6 and T8: finding highlighted text, where multiple failures occurred using the auditory condition.

- T6 and T8 were use cases that inspired creating the tactile overlay approach. It is generally not possible to find highlighted terms or definition in a text using a screen reader.
- The 0% success rate for these two tasks using a screen reader was already predictable. T3 however, should have been able to be performed using a screen reader. The main challenge here was that the section had no heading “Exercise", so the user had to read different sentences and understand their content to make the conclusion that they are exercise questions, adding to the reading burden.
- Enumeration of the questions is not enough evidence. Hence, three participants failed to perform the task successfully.

Also related to a possible data bias based on an emotional effect is that most of our participants had lost their sight in their late childhood or later (adolescence or adulthood), and were familiar with a layout of a textbook. This might have increased the satisfaction of using the system, allowing them to remember how a textbook looks and feels.

2. The second possible explanation for that observation was described in a work by Dell, Vaidyanathan, Medhi, Cutrell and Thies et al. called *Yours is better: Participants Response Bias in HCI [48].* This article reported that participants are 2.5 times more likely to prefer a technological artifact they believe to be developed by the interviewer, even when the alternative is identical. The bias increases by up to 5 times towards the interviewer’s artifact if he/she is from a different country than the participants (if a translator is present during the study).

   Hence, these researchers concluded, the participants’ qualitative feedback should receive more attention within the Human-Computer-Interaction community, especially when designing for underprivileged populations such as impaired participants or for elders. Thus, in our evaluation for the second and third design stage, the experimenters identified themselves as the prototype developers, fulfilling one of the conditions for the bias, but in the second design stage, where evaluations were quantitatively less favorable, they identified themselves as from a different country, and the test was held in English. Later, the participants and experimenters in the third design stage evaluation shared both nationality and language, and here both the quantitative and qualitative evaluations were much more favorable to the presented prototype.

3. Finally we can mention a third possible explanation for this situation. Specifically, participants have a lot of experience with screen readers, but still needed to familiarize themselves and practice using our prototype. This will be more defully considered in the discussion of the system limitations (see section 7.1.3).

General limitations of the approach

To design usability studies like those shown in this work might present difficulties when the concept is unfamiliar for the participants. We introduced tactile patterns that represent different elements of a document's visual layout that participants were not familiar with. The lack of experience with a concept in a usability study can affect the results of the study. Participants had a time slot in which they learned and got familiar with the system, yet one could argue that this time slot was not enough. During the study we had to answer questions about the different patterns and what they represented, although this had already been covered in our introductory session. On some occasions we helped the participants with placing the overlays on the tablet. Secondly, most of our participants had had previous experience with screen readers. If a similar study was made for Braille reading with participants who had no prior Braille reading experience the results would have been more negative for Braille. However, Braille has proven to be the currently most efficient reading method for the visually impaired. The familiarity limitation was present in our study for both identifying the individual patterns and for finding and placing the overlays on the tablet. Therefore, this particularity must be carefully considered.

During the study there were also limitations with the hardware we used. Tablets running Windows 10 have multiple built-in gestures that trigger certain features of the system. We tried to avoid these by making our software run on full screen. This avoided most of the gestures, however during the study some gestures that were performed unintentionally by the participants triggered the multi-tasking feature of the tablet that caused the program to be minimized. To fix this issue we had to restart the task each time it occurred.

Another limitation we faced was the conductivity of the tape and the form of the cardboard we used. The study ran for a whole month and the participants were distributed across that month.

Another limitation point to remark is the effort and time investment which represents the production process for the overlays, the conductive arrangement, the Ghi, and the audio files. All this process was manually done, and in the section of further work 7.2 we describe an envisioned solution for this difficulty.

7.2 Conclusions

The present work has been led by concrete landmarks which have established the route map in this research process. Those landmarks are outlined in the research statement and subsequent research questions in the introductory chapter 1.1, and lead the exposition of our concluding thoughts, pointing to the main contributions of this research. In the following segments we itemize each research question and detail the gathered information to provide consistent answers to them.

7.2.1 Threshing the research questions

The following research questions are the result of a reflexive process seeking to address the particular user experience of accessing digital textual documents using accessibility computerized aids. These questions can be found in chapter 1.

RQ 1. How do readers with visual impairments access digital documentation and how much information can they acquire using the accessibility tools of regular use?

In chapter 2 we studied the adaptation of contents according to their nature and functionality. We emphasized the adaptation of written media, obtaining a deep perspective of the Braille reading and writing system. Next, the adaptation of computerized media was studied, again deepening our understanding of text documents in electronic formats. In chapter 3 we observed in detail the various developments within assistive technologies which aim to facilitate access to predominantly visual content for people with visual disabilities. Access to digital content through screen reader software via text to speech or Braille displays represents a milestone in the ability of users with visual impairments to access tools such as web browsing and various educational and entertainment resources, we studied fundamental operative elements of screen reader software, and identified their characteristics and the way they work in the most current interfaces. We also studied the output in Braille as a form of concrete interaction. We also described tactile sheets and graphics, their production methods and their features. We delineated their categories and how they have implemented different technologies to give them interactivity from a predominantly static and individual media to an interactive element within a dynamic system to display images through the sense of touch.

In chapter 4 we deepened our inquiry to concrete user groups about their needs, what can they access fluidly, what contents are partially accessible, and what simply is not accessible with their regular use accessibility computerized aids. In the survey seen in section 4.2.1 we concluded that PDF files and electronic presentation slides are the least accessible digital documents, and non-linear navigation through documents, together with accessing micro and macro structures (see section 4.2.2) are the most difficult tasks for a visually impaired reader using mainstream computerized accessibility aids.

Thus, we found out that visually impaired readers basically cannot access and use documents' visual layout and different types of text highlighting. They can only poorly access information organized in tables and other non-regular single column text layouts.

We also ascertained how Braille text, although it is a potential solution for the previously mentioned limitations, is not yet a fully functional alternative for showing document layout, tables or text highlighting.

RQ2. What is the most suitable design solution to provide a deeper access to the subtextual implicit information in digital textual documents?

As we have stated in the previous question, computerized accessibility aids for users with visual impairments are mainly based on auditory feedback, and in fact auditory screen reader software (ASRS) is the most extensive assistive technology to support visually impaired users when they access computers and mobile devices. Aids based on touch e.g. Braille, is used on a regular basis by less than 40% of readers with some visual impairment.

Auditory feedback can be managed in an easier way with solutions purely based in software not requiring any additional hardware to the computer or mobile device, however we have also established how sense of touch can convey several types of information that are cognitively more complex to process in an auditory channel. As we saw in section 2.4.2, touch can provide information about shape, position, texture or size.

Non-interactive tactual alternatives like Braille text or simple tactile graphics exploit those features of touch, nevertheless we have observed how the adding of interactivity to tactual means, as described in section 3.3.1, can be seen in the development of refreshable tactile displays as we saw in section 3.2.2, and in section 3.3.1, we saw how the inclusion of auditory channels into a tactual interface becomes a natural option to define a design alternative to convey information to users with visual impairments.

Based on the abovementioned elements within this theoretical framework, an interactive means that includes auditory feedback and tactile interactivity is established as the best design solution to provide access to the implicit information related to visual layout or content differentiation within digital textual documents.

RQ 3. What are the functional and non-functional requirements for a system to provide access for readers with visual impairments to the subtextual implicit information in digital textual documents?

Besides the theoretical framework and state of art established in chapter 2 and chapter 3, in chapter 4 we described a set of queries posed to visually impaired subjects (see sections 4.2.1, 4.2.2). With those tools we were able to define a list of requirements for the desired system (see section 4.3.3; we also defined a list of three non-functional requirements (see section 4.3.3).

The required software and hardware interdependent components are detailed here, establishing concrete relationships between a component and the functional requirements which it directly supports:

- Hardware components
    1. Tactual interface: As this component we identify the engraved paper overlays which display the different tactile patterns that provide spatial layout references (R1, R4), the capability to navigate and differentiate content's elements (R2, R5), and a tactile method to track distinct overlays in a sequential and non-sequential mode (R7).
    2. Touch-sensitive physical media: This component provides the response to input commands in the mode of touch gestures allowing a functional tactile interaction. The component might be embodied as a standard capacitive touch screen, a video hand-tracking platform or any other sub-system which allows a user to interact directly onto an interactive tactile surface (R1, R2).
    3. Input and output processor: A computerized device which grants control functions and manages input and output elements (R1 -7).

- Software components
  1. Matching graphic user interface: A graphic user interface which integrates the visual layout and segments of the digital content to be represented by the system. This component can represent a single page or contain a multi-page environment.
  2. Stored adapted digital content: This component includes the software elements which encloses its segments' textual descriptions. Segments are comprised of text which is processed as recognizable verbal output.
  3. Feedback manager: A set of control instructions which administers functions between the stored adapted digital content and the matching graphic user interface.

RQ 4. How usable can a platform to display digital textual content composed of a combination of tactile overlays with differentiated touchable patterns and auditory feedback be?

With outputs from the answers of research questions 1, 2 and 3, we envisioned a concrete solution to assist readers with visual impairments to access textual digital content. It was necessary to assess objectively the Usability of our proposed approach. We conducted a set of user tests aiming to provide an objective answer to this question.

Taking into consideration the features and characteristics of the target group, the information acquisition process, the proposed system, and the design stages described in chapter 5, we conducted a set of experimental studies with nine visually impaired participants in a first stage, and seventeen in a second stage. These participants compared the proposed tactile overlays designed solution, with a standard auditory screen reader approach. To have a better understanding of the usability assessment we have subdivided this analysis into the following points:

RQ 4.1. Can a tactile interaction model supported by tactile overlays with differentiated touchable patterns based in tactual recognition and gestures offer a better usability than the standard screen reader model based on keyboard shortcuts?

The user test conducted with the second design stage shows a similar level of objective usability between the *Tactile sheets* approach and a mainstream auditory screen reader approach. This can be seen in detail in section 6.2. Once we added a refreshing functionality to the prototype and conducted a new set of comparative tests, the *Tactile* *sheets* approach showed a significant increase in its usability values overcoming the obtained values for the screen reader. Both SUS 6.3.2 and NASA TLX 6.3.2 values indicated a higher level of usability and preference for the *Tactile sheets* prototype enhanced with the refreshing feature added. This is more fully described in section 6.3.

Based in the mentioned test values we can assert that the third design stage prototype for *Tactile sheets* described in section 5.3.4 offers a higher level of usability than mainstream auditory screen reader softwares under the conditions given for the experiments seen in section 6.3.2.

RQ 4.2. Does the implementation of differentiated touchable patterns distributed on a tactile overlay convey the spatial structure of a textual digital document effectively to readers with visual impairment?

The results of a nine tasks users tested with the third design stage of *Tactile sheets* (see section 6.3.2) affirm that readers with visual impairments are able to obtain concrete elements of visual and logic structure of digital textual documents when they use *Tactile sheets* to access these kind of contents. That acquisition is not present when users with visual impairments utilize auditory screen readers.

Conjointly, according to the qualitative data gathered during the same round of user tests and shown in section 6.3.4, *Tactile sheets* are able to convey the logic structure given in paragraphs, titles and subtitles, including segments for tables and figures.

RQ 4.3. Are touchable differentiated patterns more effective than standard text to speech cues offered by mainstream screen readers to locate and recognize elements in a digital textual document?

The nine element-recognition tasks our subjects tested in the third stage of design for *Tactile sheets* (see section 6.3.2) provided consistent evidence of a *Tactile sheet's* advantage in locating and recognizing elements in a digital textual document.

We evaluated the usability of our design by comparing user satisfaction, completion time for concrete tasks, and cognitive load with the standard auditory screen reader approach. The qualitative feedback from the participants was analyzed through a thematic focus. These combined factors granted a usability assessment.

RQ 5. How can a non-refreshable interactive space based on self-identified tactile overlays offer a fluid display of digital textual content for users with visual impairments?

In our third design stage we enhanced the *Tactile sheets* prototype providing the technical functionality to be autonomously identified by the electronic device. This feature brings the capability to refresh the digital content in function of a specific placed overlay (see section5.3.4). With this feature we turned a ream of fixed engraved overlays into a set of tactile interactive smart-sheets able to interface between a user and a complementary digital content. The refreshing feature given to *Tactile sheets* described in section 5.3.4 provided a level of interactivity circumscribed to the content of the digital textual document processed as a *Tactile sheets* modality, and made it possible to navigate randomly within the context of pages granting a two-dimensional fluidity that goes beyond the simple linear navigability of a mainstream auditory screen reader approach.

While the refreshing functionality was achieved and the conductive tags attached in the engraved sheets made it possible to update the content in the computerized version of the prototype, nevertheless some characteristics affected the test performance. The material used and the frequent manipulation of the system caused flaws in the identification of the tag, causing significant hindrances during the user tests. As we commented in section 7.1.3, sometimes the placement of the overlays on the touchscreen required supervision or aid from the experimenters to assure an adequate functioning of the refreshing feature. Despite these drawbacks, the subjective insight of the users, analyzed in section 6.3.4, confirmed a marked perception of fluidity in the use of the *Tactile sheet* prototype.

Thus, based on the qualitative data gathered from our group of participants, we can offer evidence of achieving a fluid displaying of content within the context of our user tests described in section 6.3.2. Our approach of self-identifying overlays was able to provide interactivity to the initially fixed mean of *Tactile sheets*.

7.2.2 Conclusive Ideas

Tactile sheets provide a functional approach to making digital textual documents accessible for visually impaired readers. This approach allows the users to get spatial information on the interface, and help them to perform different tasks and read textbooks.

In this research work we investigated the main difficulties faced by readers with visual impairments to access digital textual documents. We learned that the most remarked-on difficulty using current mainstream computerized accessibility tools like auditory screen readers was to access the implicit information given in documents through text layout, formatting, and content organization. This is caused by the limitation of mainstream accessibility aids to convey that information in a format accessible for visually impaired readers.

Consequently, we envisioned, designed and developed a system which has worked on conveying information about visual layout of digital textual documents. This system is based on differentiated tactile elements constructed on the surface of overlays, which are placed on a touchscreen tablet creating a tactile interface that enables users to navigate through a document, recognize its layout, acquire implicit information related to the position and classification of different document elements like titles, paragraphs, tables or highlighted text, and access its content through auditory feedback. As a design iteration we have introduced an automatic identification method which allows the user to update the digital content in relation to a concrete tactile overlay placed on the touchscreen device. This improves the usability of tactile overlays and grants an innovative level of interactivity and fluidity to the tactual pages interface system.

We conducted a set of studies with visually impaired participants who were requested to perform different tasks with our system and with auditory screen readers. Our system received positive quantitative and qualitative assessments and was preferred by most participants over the screen readers, despite functionality issues reduced their efficiency.

We were able to demonstrate the feasibility of a multimodal interface dedicated for visually impaired users; modalities based on tactual and auditory channels. We also demonstrated that this interface can convey a concrete and interactive flow of information to the users.

We also proved the possibility to generate a refreshable interface based on a means initially conceived as a fixed setting such as tactile cardboard overlays. This feature utilizes affordable resources and an easily replicable method. Thus, we consider that the automatic identified tactile overlays approach is a promising method for touch screen accessibility, that improves the usability and gives the users more control over the touch screen and provides more content on the layout structure and element types of a text document.

Hence, we appeal to the scientific evidence which has been presented in this work, from the theoretical framework to the experimental assessment, to validate the statement established in section 1.1.

7.3 Delineation of Further Research Lines

All research work is a process with a concrete set of aimed objectives, and it is a natural part of the process to identify aspects or elements which were not fully developed, and starting points for potential future research lines. During the development of *Tactile sheets* three potential future research lines came out.

7.3.1 An automated process to create user interfaces and printable tactile overlays

As it has been mentioned previously, within the context of this research work, the processing of the digital textual documents to produce the GUIs displayed on the tablet, the making up of the engraved overlays, and the attachment of the conductive tags, were done totally by hand. This represents a significant obstacle for a really functional assistive reading system for the visually impaired. Thus, within the theoretical approach of the third design stage, we envisioned and delineated a *Process automation pipeline*, which has been described in a related work [205] (see figure 7.2).

1a The text chunks, tables, and images are extracted and their bounding boxes are recorded. The granularity for text is lines.

1b The whole page is graphically rendered as an image (e.g., JPG).

2 For each chunk (text, table, image) an audio file is created. This may be done using a TTS tool or by a person reading or describing it. For each audio file the bounding box is also recorded.

3a A single HTML page is created that shows the image of the book page and has an image map associated with the picture of the book page. If the user now touches a position on the image the linked audio file is played. Buttons on the left and right allow navigation to the next and previous page.

3b The graphics of the book page are converted into a tactile sheet. This requires image processing (e.g. edge and region detection). The text, tables, and pictures are replaced with the respective textures and a page is laser cut, where the tactile textures are engraved.

On the right lower corner of each page the page number can be displayed in Braille for easier reference.

We investigated detection of text chunks and graphical rendering using image processing methods. Recent research has not explored this problem because of its irrelevance for current technologies. However, we found older material that used different approaches to detect the elements of documents that were printed using a typing machine to transfer them into a digital document. These included linguistic and spatial evidence used to detect text blocks [**?**], white space used for automating document recognition and interpretation, dividing the document into a hierarchy of logical elements [**?**], and a bottom up algorithm developed to detect the minimal spanning tree of a document [**?**].

As a theoretical approach we developed a program using Processing[41]. Processing is a Java based programming language for new media art, electronic art and visual design communities. It is mostly used for visualization and image processing tasks. The program extracts a PDF page and detects the individual elements and their positions/ sizes and creates a new PDF file with the corresponding tactile patterns. For the prototype we started off by detecting the titles and paragraphs with image processing. We did that in two phases.

The first phase was when we tried to detect the elements of the page. We followed these steps:

1. Extract the PDF page and convert it to PNG.
2. Import the PNG image to the Processing program using PImage.
3. Iterate through each pixel and round their R,B and G values to either 0 or 255. This removes all gray values and converts all pixels to either black or white.
4. Start from the top left pixel and iterate through each pixel from left to right then from top to bottom, until the first black pixel is found (first text character). Store the location of this pixel as the starting point of the rectangle.
5. From that pixel iterate through each pixel horizontally and count the white pixels until the next black pixel. If the white pixel count is more than 15, assume that the paragraph is over (horizontal). The new point is stored as the top right corner of the rectangle.
6. Go back to the top left corner of the triangle and iterate through each pixel vertically and count the white pixels. If the white count is more than 20

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[41] https://processing.org/

pixels, assume that the paragraph is over (vertical). The new point is stored as the bottom left corner of the rectangle.

7. Use the X value of the top right corner and the y value of the bottom left corner to generate the bottom right corner.
8. Draw a black rectangle with the 4 points. Make sure to make the rectangle 3-6 pixels wider in each direction in case the detected points are not accurate.
9. Do the same with the rest of the page.
10. Save the outcome as a temporary image.

The second phase was when we tried to identify the individual elements and give them a corresponding pattern. We followed these steps:

1. Import the temporary image to the Processing program.
2. Iterate through each pixel and find the first black pixel.
3. Go through the entire box vertically and count the black pixels in that box until you find the first white pixel. This count is the height of the element.
4. If the height of the box is less than 30 pixels assume that this is a title. If the white space is more than 30 pixels assume that it is a paragraph.
5. Draw the corresponding patterns on each of the elements.
6. Save the outcome as a new image that can be used as the overlay.

Due to time limitation the step of drawing the corresponding patterns was not implemented, however we were able to detect the individual elements (See figure 7.1).

Improvements

As a future work, there are multiple improvements to this approach that should be addressed. We point out the most important improvement suggestions to the algorithm as follows:

- Detect the elements with text detection libraries.

- Use a different framework for image processing (e.g. OpenCV).
- Decide the maximum white space dynamically based on the size of the elements.
- Create a sub category of titles (sub titles) based on their sizes.
- Make the algorithm work on pages with double columns.
- Carry out image detection and table detection.
- Add distance to neighboring elements as a second method to distinguish between the patterns, along with white space.
- Parse the meta data of the PDF file (e.g. font size, location etc.)
- Use gray-level histograms.
- Implement Haralickís texture features.

7.3.2 Peripheral touch

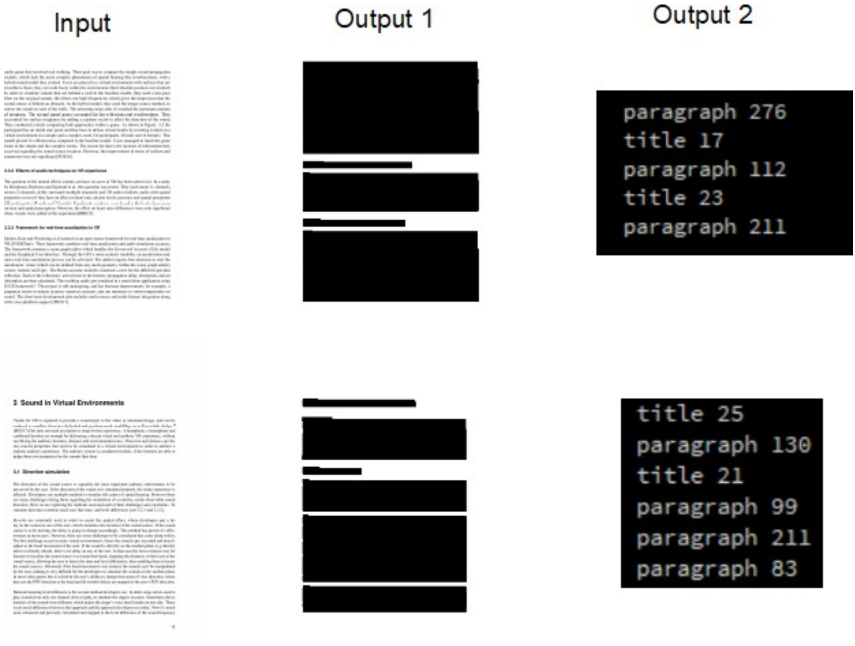
In chapter 2, in section 2.4.2 we learned about the two types of tactile sensitivity.

Protopathic sensitivity This is the most primitive and diffuse sensibility. Little or nothing is differentiated; it responds to all the painful cutaneous exciters, extreme heat and cold, and strong touch. The subject cannot accurately locate the stimulus, or discriminate between different stimuli.

Epicritic sensitivity This is sensibility that ensures a finer, localized and accurate discrimination, allows to appreciate the stimulus of little intensity, and normally exerts inhibitory influence on the protopathic system.

Hence, the epicritic sensitivity can be understood as the focused touch, and the protopathic sensitivity is a more dispersed and diffuse touch experience. It is not hard to make an analogy with the central and peripheral eye-sight.

This potential research line can be summarized as the study of those two types of touch sensitivities from an interface paradigm with the main objective to exploit this sensorial feature to enrich the possibilities for tactual stimuli. It is possible to envision a tactile interface able to display simultaneously different levels of


Input

Output 1

Output 2

```
paragraph 276
title 17
paragraph 112
title 23
paragraph 211
```

```
title 25
paragraph 130
title 21
paragraph 99
paragraph 211
paragraph 83
```

Figure 7.1: Input and output examples for the processing program.

tactual outputs which would be perceived by the epicritic and the protopathic sensors in adifferentiated way (e.g. Adding a haptic stimulus to the perception of a tactile pattern like those used in Tactile sheets).

This research line might bring new dimensions to touch based interfaces, including haptic, tactile and tangible stimuli, and adding pressure or temperature which can be processed through either the epicritic or the protopathic channel.

7.3.3 Production of tactile media

We have defined the advantages of tactile means together with other modalities to convey information to those who cannot rely on their eye-sight, however nowadays the production of elements like tactile graphics still require complex processes which among other drawbacks, are mostly inaccessible for those visually impaired users interested in any of those production methods. Even those

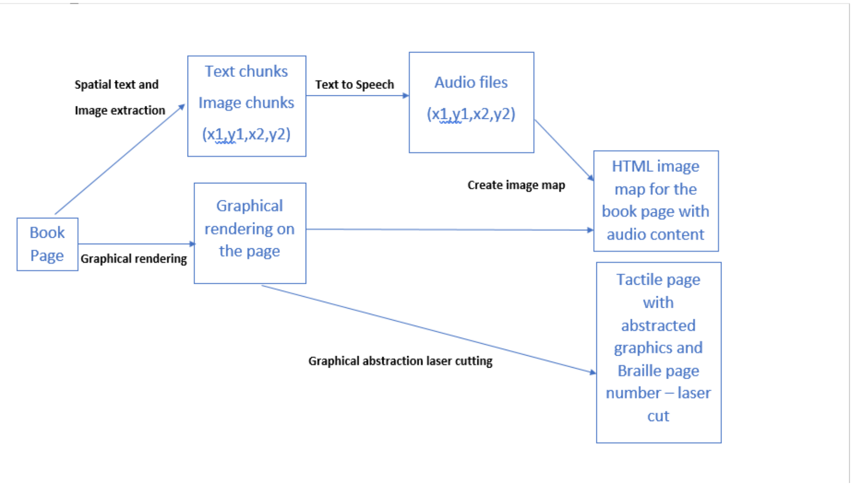


Figure 7.2: Processing pipeline.

most modern processes like 3d-printing or laser cutting are not accessible for a user who requires a screen reader. This proposed research line goes in the direction of generating operational environments which allow visually impaired users to access those technologies like 3D-printing or laser cutting in a way which might be usable and functional.

The maker culture and Industry 4.0 offer solutions to the production of elements which have a very dedicated and focused group of users; elements like tactile graphics or tangible components. The community of people with visual impairments can be extensively benefited by being enabled to produce their own tactile maps or tactile sheets using one of the currently available alternatives like low priced 3D-printers, desktop robotic arms, or desktop laser engravers.

This research line shall be focused on the study of interaction concepts and software functionalities which provide accessibility for users with visual impairments to those functions and operations useful to produce within the context of *Do it yourself* tactile elements.

We hope that the research described in this thesis provides a platform for its realization in new enabling technologies for the visually impaired, and a basis for further developments such as those envisaged above.

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