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Interactive Audio-Tactile Maps for Visually Impaired People

Anke Brock and Christophe Jouffrais

Interactive maps have the potential to provide a broad spectrum of the population with spatial knowledge, irrespective of age, impairment, skill level, or other factors.

In the first article Anke Brock and Christophe Jouffrais give an overview of their research on making geographic maps accessible to visually impaired users. They developed an accessible interactive map prototype composed of a raised-line overlay, an interactive tabletop, and speech output. Their work is currently being used in some classrooms in France for teaching geography to visually impaired children.

Characterizing and Visualizing Physical World Accessibility at Scale using Crowdsourcing, Computer Vision, and Machine Learning

Kotaro Hara and Jon E. Froehlich

Imagine a mobile phone application that allows users to indicate their ambulatory ability (e.g., motorized wheelchair, walker) and then receive personalized, interactive accessible route recommendations to their destination.

In the following article, Kotaro Hara and Jon Froehlich talk about their research work aimed at developing scalable data collection methods for remotely acquiring street-level accessibility information and novel mobile navigation and map tools.

Accessibility Layers: Levelling the Field for Blind People in Mobile Social Contexts

Tiago Guerreiro

With the emergence of new technologies it is relevant to keep in mind that enabling physical access is not enough as social aspects, and other layers, need to be guaranteed.

Finally, Tiago Guerreiro writes an article about the shortcomings of current mobile devices, particularly in the social domain. He then presents his on-going research in areas such as security and privacy, inconspicuous interaction, and social context awareness.

Hugo Nicolau
Newsletter editor

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INTERACTIVE AUDIO-TACTILE MAPS FOR VISUALLY IMPAIRED PEOPLE

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Introduction

Visually impaired people face important challenges related to orientation and mobility. Indeed, 56% of visually impaired people in France declared having problems concerning autonomous mobility [10]. These problems often mean that visually impaired people travel less, which influences their personal and professional life and can lead to exclusion from society [28]. Therefore this issue presents a social challenge as well as an important research area. Accessible geographic maps are helpful for acquiring knowledge about a city's or neighborhood's configuration, as well as selecting a route to reach a destination. Traditionally, raised-line paper maps with braille text have been used. These maps have proved to be efficient for the acquisition of spatial knowledge by visually impaired people. Yet, these maps possess significant limitations [37]. For instance, due to the specificities of the tactile sense only a limited amount of information can be displayed on a single map, which dramatically increases the number of maps that are needed. For the same reason, it is difficult to represent specific information such as distances. Finally, braille labels are used for textual descriptions but only a small percentage of the visually impaired population reads braille. In France 15% of blind people are braille readers and only 10% can read and write [10]. In the United States, fewer than 10% of the legally blind people are braille readers and only 10% of blind children actually learn braille [24].

Figure 1: A visually impaired person reading a tactile map

Recent technological advances have enabled the design of interactive maps with the aim to overcome these limitations. Indeed, interactive maps have the potential to provide a broad spectrum of the population with spatial knowledge, irrespective of age, impairment, skill level, or other factors [25]. To this regard, they might be an efficient means for providing visually impaired people with access to geospatial information. In this paper we give an overview of our research on making geographic maps accessible to visually impaired people.

Related Work

In order to classify existing accessible interactive maps, we performed an exhaustive search through scientific databases (ACM Digital Library, SpringerLink, IEEE Explorer, and Google Scholar). We found 43 articles that were published between 1988 and 2013 that matched our inclusion criteria. First, we only considered interactive maps (and not navigation systems) and only those maps that were specifically designed for visually impaired people. Second, we only included publications in journals or peer-reviewed conferences. Third, for identic prototypes we only considered one publication. We presented the classification of this map corpus in [4,5] in detail.

To sum up, the design of accessible interactive maps varied in different aspects, such as content, devices, or input and output interaction techniques. We observed that most accessible interactive map prototypes rely on touch input, and some systems use both touch and audio (speech recognition) input [1,12,15,16,36]. All systems rely on audio output, except [20] which was entirely based on the tactile modality. In Figure 2 we propose a classification according to the devices used in the prototype. We classified the devices in four categories: haptic devices, tactile actuator devices, touch-sensitive devices and other.

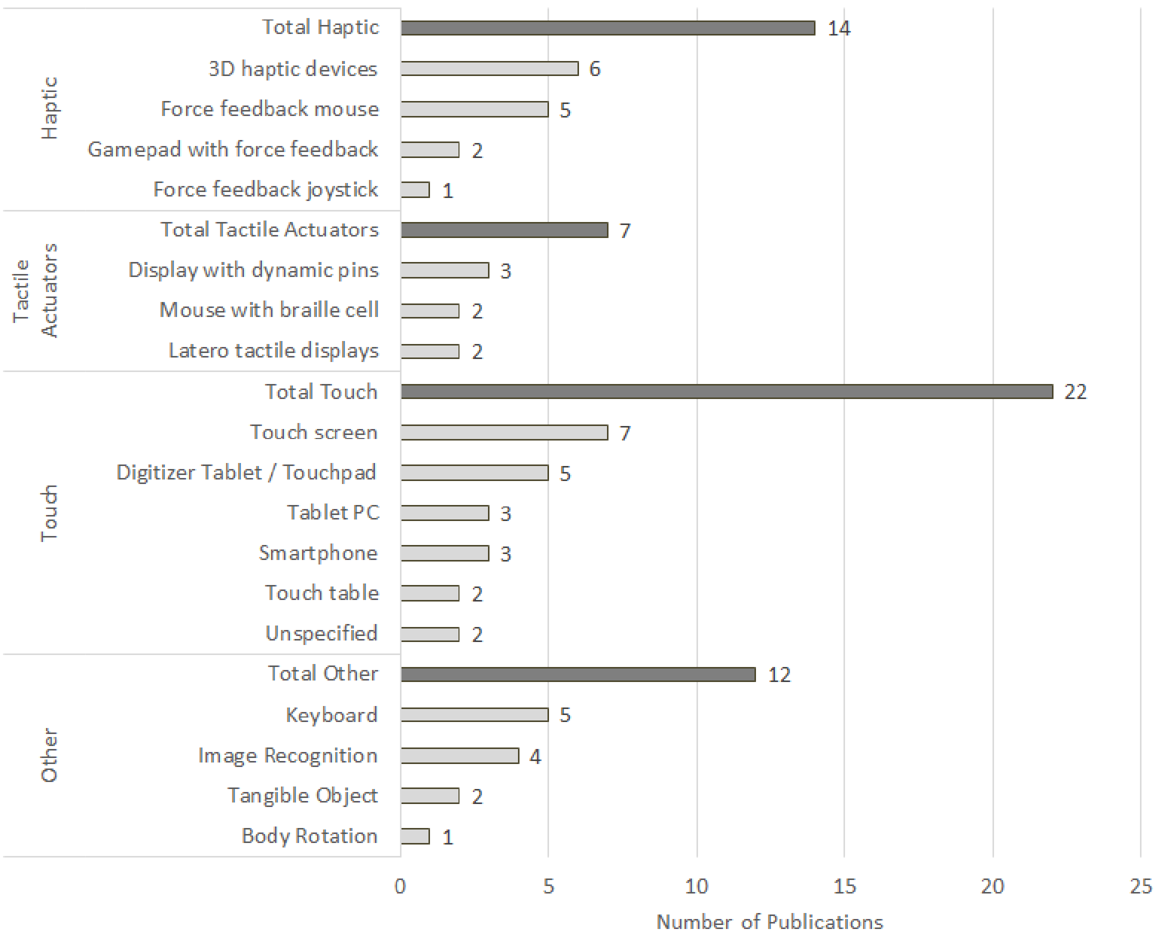

Figure 2: Classification of accessible interactive map prototypes by type of device.

Within the "haptic devices" category, we included devices that provide force feedback. This means that they mechanically produce a force that is perceived as a kinesthetic sensation by the user. Examples for prototypes using this type of technology are presented in [13,26,34,36].

"Tactile actuators" dynamically provide a cutaneous stimulation on the user's skin. Many of those systems use needles or pins that are mechanically raised. Many visually impaired people are familiar with this kind of stimulation, as they often use dynamic braille displays that are based on a similar principle [2]. A few interactive map prototypes are based on large displays with actuated pins (see for instance [41]). However, as the production of large displays is expensive, smaller displays have been used, e.g. in the size of braille cells (see [38] as an example). Another solution relies on tactile feedback, which is produced by laterally stretching the skin of the finger [29].

Within the "touch-sensitive" devices category we gathered different technologies that locate touch inputs (mono and multi-touch, using bare fingers or pens). Touch-based surfaces per se do not provide tactile feedback and thus are usually combined with audio feedback [1,16]. In some accessible map prototypes, the touch-based device was combined with a raised-line map overlay [19,22,27,39] or with vibro-tactile stimulation [33,40] in order to ease the exploration with a supplementary tactile information.

The last category includes all the prototypes with a different technology. For instance, some prototypes integrate keyboards as supplementary input device for entering textual information [1,19,26]. Other prototypes are based on image recognition (e.g. [15]) allowing to localize the hand relative to the map and provide audio feedback consequently. The user thus interacts with the map as if it was based on a touch-sensitive surface. Few projects investigated tangible interaction, i.e. interaction through physical objects [23,32]. Finally, one project [23] used the rotation of the user's own body for controlling the map orientation.

Design and evaluation of an audio-tactile map prototype

Design of an audio-tactile map prototype

Based on the survey of the related work and our own observations of visually impaired users during mobility and orientation lessons [see 14], we developed an accessible interactive map prototype. The interactive map prototype was composed of a raised-line map overlay placed over a multi-touch screen (see Figure 3), a computer connected to the screen and loudspeakers for speech output. Users could explore the raised-line map on top of the screen with both hands, i.e. ten fingers, exactly the same way that they would explore a tactile paper map. Instead of reading a braille legend, they could obtain the names of streets and buildings by double-tapping on the map elements. The development of this map prototype consisted in three processes [see 6]: 1) drawing and printing the raised-line paper maps, 2) choosing the multi-touch technology, and 3) designing and implementing non-visual interaction methods.

We chose to use microcapsule paper for printing the raised-line maps because it is the easiest production method and has been successfully used in previous audio-tactile map prototypes [22,39]. Another important argument was that this paper is slim, which is advantageous to detect touch input through the paper map. Maps were designed with the Open Source Inkscape software using SVG (Scalable Vector Graphics) format. There are no strict rules on how to design tactile maps and those maps use different symbols and textures. However different guidelines exist [3,31,37] which we respected when designing our prototype (Figure 3, [8]).

Concerning the choice of a suitable multi-touch technology we identified several criteria. The most important one was reliable touch detection through a paper overlay. After diverse tests, we chose the 3M Inc. multi-touch screen model M2256PW. The capacitive projected technology ensured preserved responsiveness through the paper overlay. Furthermore, the dimensions of the screen (slightly larger than A3 format) were well adapted for representing a city neighborhood.

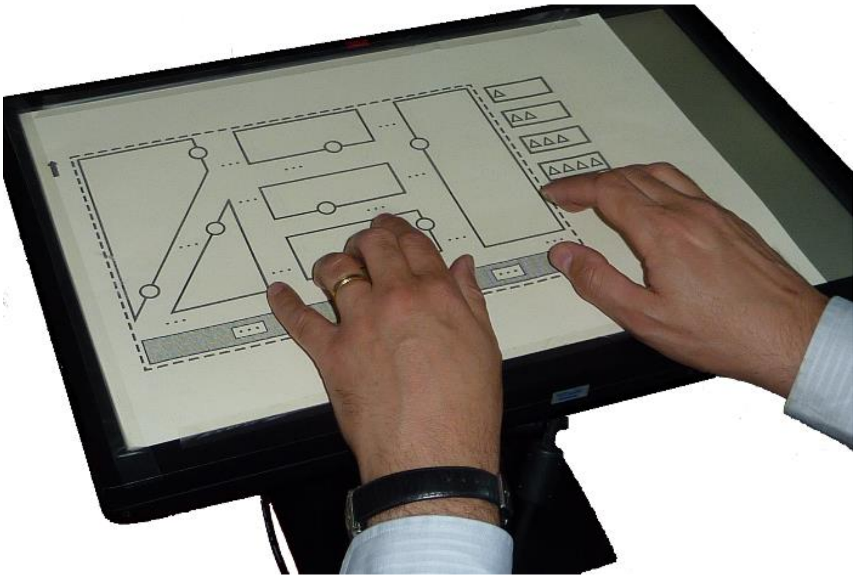

Figure 3: Interactive audio-tactile map prototype composed of a multi-touch screen with raised-line overlay

With regard to interaction techniques, the prototype provided audio-tactile output. The raised lines of the tactile map were the first available sensory cues. For audio output, we used the Realspeak SAPI 4.0 French text-to-speech synthesis (voice "Sophie") which possesses a good intelligibility and user appreciation [11]. It has been observed in several studies that simple taps are frequently generated during exploratory hand movements and thus lead to unintended feedbacks [21]. Consequently, we implemented a double-tap input.

Evaluating the usability of the audio-tactile map

Prior to our project, the usability of accessible interactive maps had never been compared to the usability of raised-line maps with braille text. Therefore, it was unknown whether interactive maps were worse or better solutions than traditional raised-line maps. To overcome this lack of knowledge, we conducted a systematic user study, comparing these two different map types for visually impaired people [8]. Our general hypothesis was that an interactive map (IM) was more usable than a tactile paper map (PM) for providing blind people with spatial knowledge about a novel environment.

We designed a map representing a fictional city center with six streets, six buildings, six points of interest (e.g., museum, restaurant, and metro station), as well as a river (see Figure 3). A second map was created with the same map elements that were rotated and translated, so that both map contents were equivalent. The hotel as central point of interest was common for both maps. One of the maps contained braille labels and was accompanied by a legend explaining those labels (PM) whereas the other map did not have any braille label but was interactive and provided audio feedback (IM). We ensured lexical equivalence of the names of streets and POIs, and we made pretests with a visually impaired user to ensure that the maps were readable, and that they were not too easy or too difficult to memorize.

Both maps were tested by twenty-four blind participants recruited from different associations, through a local radio broadcast for visually impaired people as well as by word-of-mouth. The experimental protocol included a short- and a long-term study that were each composed by two sessions. In this paper we only report about the short-term study (the long-term study is described in [8]). The two sessions took place in a dedicated experimental environment in the IRIT research laboratory in Toulouse, France. During the first session, the subjects first explored a simple map during a familiarization phase, and then answered a questionnaire about personal characteristics. Then, they were asked to explore and learn the first map (either IM or PM depending on the group) with both accuracy and time constraints ("as quickly and as accurate as possible"). Participants were informed that they would have to answer questions afterwards without having access to the map. In order to motivate them to memorize the map, users were asked to prepare holidays in an unknown city and we invited them to memorize the map in order to fully enjoy the trip. Users were free to explore until they considered that they had completely memorized the map. When they stopped, we measured the learning time and removed the map. Subjects then answered questions evaluating the three types of spatial knowledge (landmark, route, survey). The second session took place one week later and started with a familiarization phase followed by an interview on spatial abilities. Participants then explored the second map type (either PM or IM) and responded to the questions on spatial knowledge. We finally assessed their satisfaction regarding the two maps.

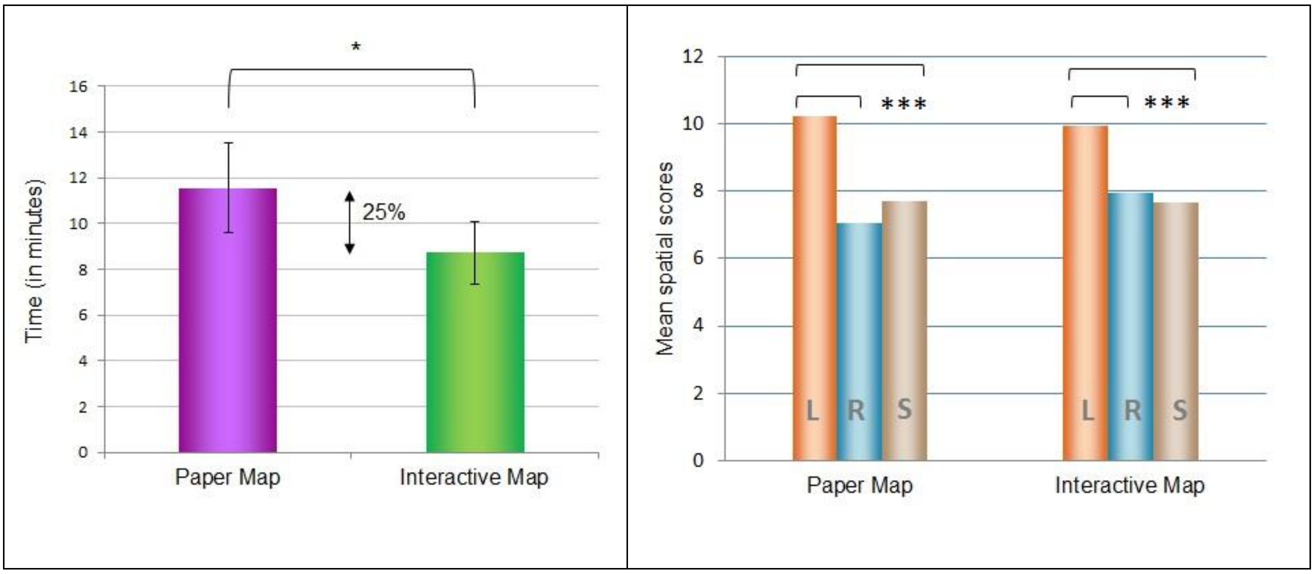

Figure 4: Experimental Results
(a) Learning Time (mean values measured in minutes) for the paper map (left) as compared to the interactive map (right). The Learning Time for the interactive map was significantly lower than for the paper map (lower is better).
(b) Mean spatial scores for responses to landmark (orange), route (blue) and survey (brown) questions (paper map left, interactive map right). Mean scores for the landmark tasks were significantly higher than those for the route and survey tasks (higher is better). There was no significant difference between R and S questions. * $p < .05$, *** $p < .001$

We made the assumptions that: 1/ exploration duration (corresponding to the learning time) reflects efficiency; 2/ the quality of spatial learning (measured as spatial scores) reflects effectiveness; 3/ map preference reflects user satisfaction. Learning time was significantly shorter for the interactive map than for the paper map. As shown in Figure 4(a), using a 2*2 repeated measures ANOVA ($F(1,22) = 4.59$, $p = .04$), Learning Time appeared to be significantly shorter for the interactive map ($M = 8.71$, $SD = 3.36$) than for the paper map ($M = 11.54$, $SD = 4.88$). Regarding spatial learning, there was no significant difference between both map types. However, significant differences were observed when comparing scores for L, R, and S questions (Figure 4 b).

Pairwise Wilcoxon rank sum tests with Bonferroni correction (alpha level = .017) revealed that the difference between L (*M* = 10.1, *SD* = 2.0) and R (*M* = 7.5, *SD* = 2.9) was significant (N = 45, Z = 5.20, p < .001) as well as the difference between L and S (*M* = 7.7, *SD* = 2.7) questions (N = 43, Z = 5.06, p < .001). There was no significant difference between R and S questions (N = 41, Z = 0.41, p = .68). Finally, when asked which map they preferred, more users answered in favor of the interactive map: of a total of 24 users, 17 preferred the interactive map, six users preferred the paper map, and one had no preference. Furthermore, as reported in [8], we also observed correlations between the observed variables and personal characteristics. As two examples, people who are frequently using new technologies (smartphones, computers) needed more time for reading the paper map with braille text, and early blind people and those who were better braille readers experienced a higher satisfaction towards reading the paper map. To roughly sum up, this study confirmed that visually impaired people are able to memorize and mentally manipulate both route and survey spatial knowledge. In addition, it demonstrated that interactive audio-tactile maps are more usable than regular tactile maps with braille text for blind users.

Non-visual gestural interaction for geographic maps

The non-visual interaction techniques implemented in our experimental prototype as described above were quite simple. The main interaction was a double tap that allowed receiving vocal feedback about names of streets, buildings, etc. Following this study we aimed at including supplementary information—such as opening hours, entry prices, distances, etc.—in the map prototype. One possibility to make touch screens accessible without sight is using gestural interaction [17,21]. However, gestural interaction had never been combined with a raised-line map overlay. We implemented basic gestural interaction techniques provided by the MT4J API [18], an open-source and cross-platform framework for developing multi-touch applications [6]. Among these we selected a lasso gesture (i.e., circling around a map element without lifting the finger) to retrieve information associated with points of interest. Additionally, we implemented a tap and hold gesture. In this case, the user had to tap on a map element and maintain the finger pressed until a beep sound confirmed the activation. When tapping on a second map element, another beep confirmed the activation, and the distance between these elements was announced.

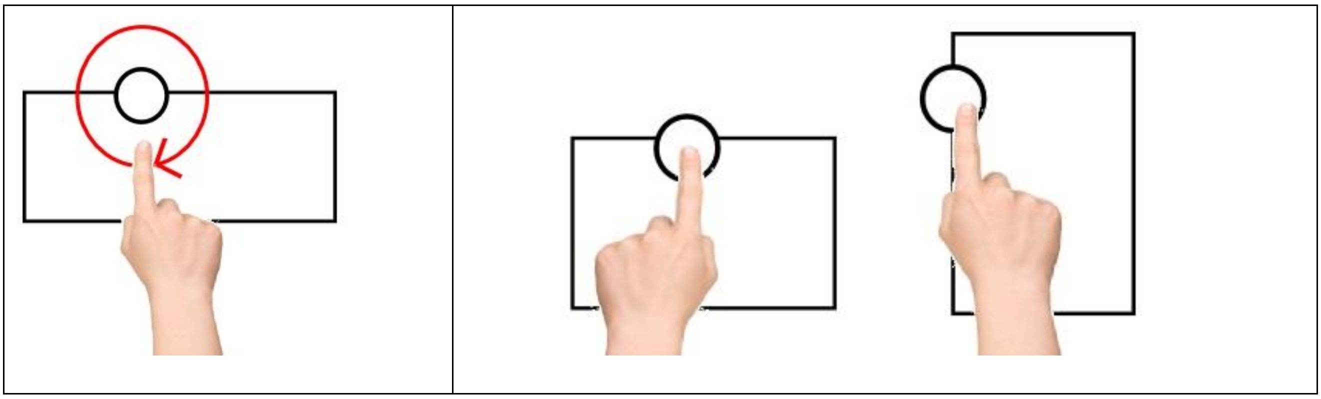

Figure 5: Gestural Interaction (a) Lasso, (b) Tap and Hold

Perspectives

In the continuity of the research presented in this paper, the AccessiMap project (http://www.irit.fr/accessimap) has the objective to exploit the availability of Open Data (e.g. OpenStreetMap) and make them accessible using tangible interaction. The consortium consists of two research centers, a company, and a specialized center for visually impaired people. It pursues several technical and scientific objectives including: designing a web-based editor allowing graphics transcribers to quickly elaborate tactile graphics relying on Open Data; designing a prototype of a collaborative tangible tabletop allowing the evaluation of non-visual interactions for graphical data exploration; assessing mental spatial representations of visually impaired users after exploration; improving the overall accessibility of Open Data; and launching cheap or free accessible apps for tablets and smartphones.

Designing with and for visually impaired users

An important principle in HCI research is to include users throughout the whole design cycle in order to ensure that the developed technologies meet the users' needs. This can be done through the use of participatory design or codesign methods [35]. This principle is also very important—if not even more important—when designing for people with special needs. Indeed, designers or researchers without impairments cannot easily design adapted assistive technologies. Basing the development of assistive technology on the emergence of new technologies and not on users' needs, leads to a high abandoning rate [30].

Our research with visually impaired people relied on participatory design methods for all design phases: analysis, ideation, prototyping and evaluation. Through a close collaboration with the Institute of Young Blinds in Toulouse (CESDV-IJA), we have been able to meet a large number of visually impaired people as well as locomotion trainers and specialized teachers. As most design methods make use of the visual sense (for instance, sharing of ideas during a brainstorming session by writing them on a whiteboard), we have experienced the need to adapt existing methods accordingly when working with blind people [9].

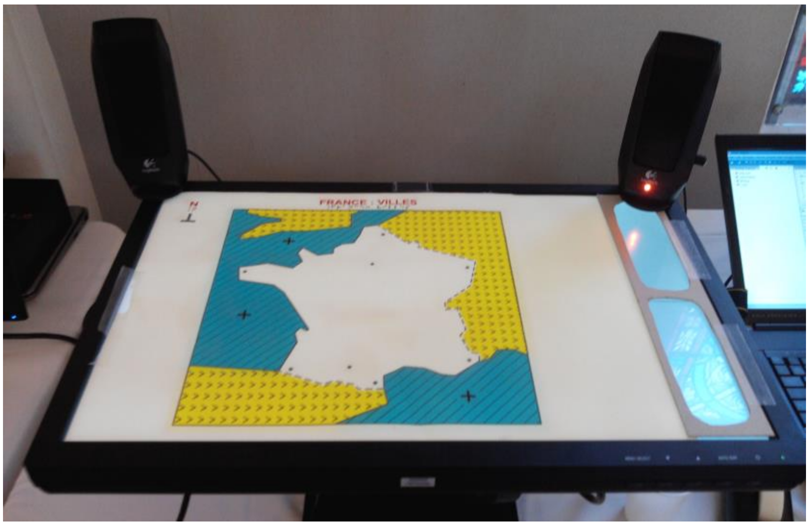

Figure 6: Adapted Version of the interactive map prototypes as it is used in the Institute of Young Blinds in Toulouse (CESDV-IJA) for teaching geography to visually impaired children.

The close collaboration with the Institute of Young Blinds has enabled us to move our prototypes from the lab to the field. Thus, an extended version of the above mentioned prototype is currently used in classrooms for teaching geography to visually impaired children. Figure 6 illustrates a geography lesson where France is represented with surrounding countries and seas. In this map, many levels of information—such as local dialects and music—are associated to each point of interest. The user can navigate between the different levels using the menus on the right.

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Dr. Christophe Jouffrais is with the IRIT Lab (UMR5505, CNRS & Univ of Toulouse) in Toulouse, FR. He is a CNRS researcher with a background in Cognitive Neuroscience, HCI and Assistive Technology. His current research focuses on perception, action and cognition without vision with an emphasis on non-visual Human-Computer Interaction, and Assistive Technologies for visually impaired people.

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Figure 7. Our vision is to transform the way street-level accessibility information is collected and visualized. With our new scalable data collection methods, we aim to support a new class of accessibility-aware map tools such as (a) accessibility-aware navigation tools that provide personalized route information based on a user's reported mobility level and (b) visual analytic tools that allow citizens and governments to easily assess a city's street-level accessibility.

Introduction

Poorly maintained sidewalks and street intersections pose considerable accessibility challenges for people with mobility-impairments [13,14]. According to the most recent U.S. Census (2010), roughly 30.6 million adults have physical disabilities that affect their ambulatory activities [22]. Of these, nearly half report using an assistive aid such as a wheelchair (3.6 million) or a cane, crutches, or walker (11.6 million) [22]. Despite comprehensive civil rights legislation for Americans with Disabilities (*e.g.*, [25,26]), many city streets, sidewalks, and businesses in the U.S. remain inaccessible. The problem is not just that street-level accessibility fundamentally affects where and how people travel in cities, but also that there are few, if any, mechanisms to determine accessible areas of a city *a priori*. Indeed, in a recent report, the National Council on Disability noted that they could not find comprehensive information on the "degree to which sidewalks are accessible" across the US [15]. This lack of information can have a significant negative impact on the independence and mobility of citizens [13,16] For example, in our own initial formative interviews with wheelchair users, we uncovered a prevailing view about navigating to new areas of a city: "*I usually don't go where I don't know [about accessible routes]*" (Interviewee 3, congenital polyneuropathy). Our overarching research vision is to transform the way in which street-level accessibility information is collected and used to support new types of assistive map-based tools.

Traditionally, sidewalk assessments have been conducted via in-person street audits [19,20], which are labor intensive and costly [17], or more recently, via smartphone applications, which are done on a reactive basis and require physical presence [27]. Although some cities offer sidewalk information online (*e.g.*, through government 311 databases [21]), these solutions are not

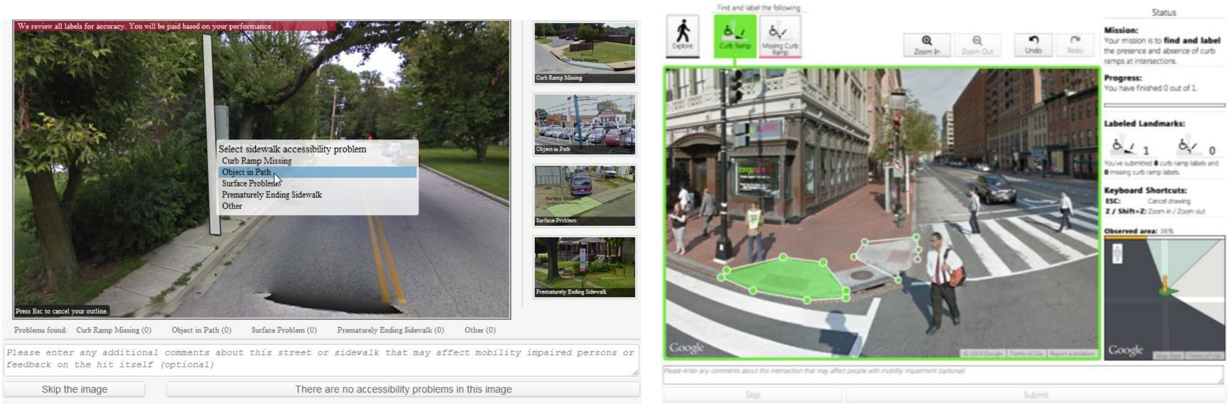

Figure 8. Our custom image labeling tools on web browsers: (a) The early version of the interface, which lets a user mark the location of the sidewalk problem and categorize the problem type (*e.g.*, an obstacle in a path) on a static GSV images [6]; (b) The labeling interface from our most recent work [10], which allows a user to adjust the camera angle (pan and zoom) and search for and label accessibility attributes in GSV.

comprehensive, rely on *in situ* reporting, and are not specifically focused on collecting and providing accessibility information. Some work exists on modeling and visualizing accessibility information in the built environment [3,12,13]; however, again these models are constrained by a lack of data describing street-level accessibility and the resulting systems have not been widely deployed.

In contrast, for the past three years our research group has been pursuing a twofold alternative vision [5–10]: **first**, to develop scalable data collection methods for remotely acquiring street-level accessibility information using a combination of crowdsourcing, computer vision, and machine learning along with online map imagery such as Google Street View (GSV) and high resolution top-down photographs such as satellite or flyover imagery. **Second**, to use this new data to design, develop, and evaluate a novel set of navigation and map tools for accessibility. For example, imagine a mobile phone application that allows users to indicate their ambulatory ability (*e.g.*, motorized wheelchair, walker) and then receive personalized, interactive accessible route recommendations to their destination (Figure 1a). As another example, inspired by walkscore.com, imagine an interactive map visualization tool that allows you to quickly assess the a city's street-level accessibility (Figure 1b)—how might such a tool impact where people choose to live, how governments invest in street-level infrastructure, or even how property values are assessed?

In this article, we provide a brief history of our work starting with initial studies exploring the viability of using GSV imagery as a reliable source of street-level accessibility and ending with a treatment of our current work on what we call assistive location-based technologies—location-based technologies that specifically incorporate accessibility features to support navigating, searching, and exploring the physical world. We close with a summary of open future work and a call to action for others in the community to work on this important problem.

Previous Research

A majority of our work thus far has focused on the first part of our vision: developing scalable data collection methods using a combination of crowdsourcing and automated methods to locate, identify, and characterize street-level accessibility attributes in GSV. Below, we discuss GSV as a viable physical-world accessibility data source, the development of our initial crowdsourcing labeling tools, and our more recent work on semi-automated labeling of accessibility features in GSV imagery.

Viability of GSV Imagery as a Source of Accessibility Information

We describe two threads of work evaluating GSV imagery as a viable source of street-level accessibility information: first, can people with similar mobility impairments find and agree on accessibility problems in GSV imagery? Second, given that GSV images are collected semi-infrequently, is image age a problem—that is, how well do problems identified in GSV represent the current state of the physical world?

Towards the first question, we recruited three electric wheelchair users to investigate whether they could consistently identify accessibility problems in GSV [6]. Independently, the three participants were asked to locate and categorize accessibility problems in 75 curated static images of GSV using our custom-made image labeling tool (Figure 8a). In addition, they participated in an exit interview where we asked about their personal experiences with street-level accessibility. Two key results emerged. First, our participants had high inter-labeler agreements, indicating that accessibility problems could be consistently identified solely from GSV imagery. Second, one of our participants stated that he already used GSV to examine an area for traversability before leaving his house—a result that has been echoed by more recent interviews that we conducted with 20 mobility impaired participants. Thus, though not specifically designed for this purpose, it appears that GSV is already being appropriated as a valuable source of accessibility information, reinforcing its use in our research.

Towards the second question, perhaps the most significant concern about using online map imagery to remotely collect accessibility information is image age. The built environment evolves over time and accessibility issues found via GSV may no longer exist and/or new problems may emerge. While Google does not publish information about how often its GSV cars drive and capture new images, major cities appear to be updated approximately once every year or two (*e.g.*, downtown Washington DC has seven captures in eight years). Less populated cities are updated less. Although previous work has reported high concordance between audits conducted in the physical world *vs.* using GSV imagery [2,17], the focus was not on accessibility. To this end, we physically audited 273 intersections in nearby cities (Washington, D.C. and Baltimore, MD) and compared them with audits performed with GSV images. We found nearly perfect agreement despite an average GSV image age of 2.2 years (SD=1.3). The 6 disagreements were due to recent or ongoing construction. Thus, based on our own physical audit and reports from prior work, we are confident that GSV is a viable source of street-level accessibility information. In addition, with the movement towards self-driving cars, drone-based photography, and more frequently updated satellite imagery, we expect that GSV-like datasets will become even more common and more frequently updated in the future.

Crowdsourcing Sidewalk Accessibility Information

With GSV imagery established as a reasonable dataset to collect street-level accessibility information, we began developing and studying interfaces to allow minimally trained online users to remotely find, label, and characterize sidewalk accessibility. We performed multiple studies [5,6,8,10] with Amazon Mechanical Turk, an online labor market where users are paid to perform small tasks. In our earliest work [6], we manually collected and curated 229 GSV images from Washington DC, Baltimore, NYC, and LA. Using our custom labeling tool (Figure 2a), workers were asked to draw an outline around four main types of accessibility problems and indicate their severity (Figure 2a). Unlike the traditional GSV interface, users could not pan, zoom, or move around in this version of our labeling interface, which was done to simplify interactions. To create a ground truth dataset, two members of our research team independently labeled all 229 images

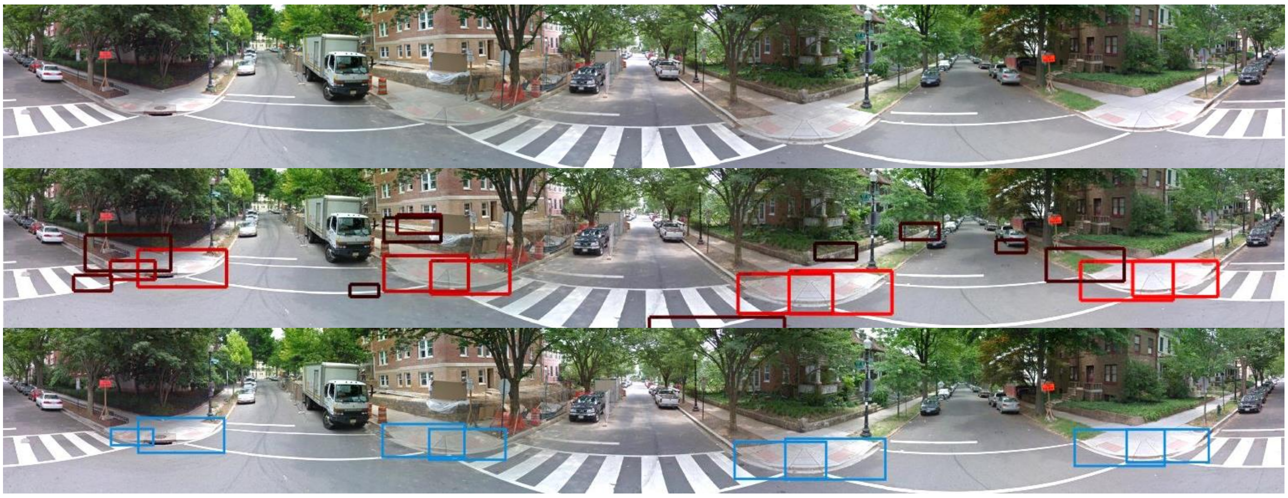

Figure 9. We developed Tohme, a scalable system for semi-automatically finding curb ramps in Google Streetview (GSV) panoramic imagery using computer vision, machine learning, and crowdsourcing. The images above show an actual result from our evaluation: (a) Raw Google Street View image, (b) results of computer vision curb ramp detection (lighter red is higher confidence), and (c) results after crowdsourced verification.

and found: 67 images with Surface Problems, 66 images with Object in Path, 50 with Prematurely Ending Sidewalk, and 47 with Curb Ramp Missing.

We then conducted an online experiment with 185 crowd workers. When compared to ground truth data, the workers correctly identified the presence of problems with 81% accuracy. Using majority voting as a simple quality control mechanism, this accuracy jumped to 87% with three workers and over 90% with five or more workers. We ran two subsequent crowdsourcing studies for collecting accessibility information on bus stop landmarks (*e.g.*, bus stop shelters) [8] and curb ramp infrastructure [10] and found similar results—that is, above 80% labeling accuracy with a single crowd worker per location. This indicates that minimally trained online workers are indeed capable of remotely finding and labeling street-level accessibility problems and that simple quality control mechanisms can be used to reach accuracies of around 90%. We believe that these results can be improved through better training, providing active monitoring with feedback to help users learn when they have made a mistake, and warning or even eliminating poor quality labelers from the system.

Increasing Data Collection Efficiency with Semi-automated Methods

While our prior work showed that crowd workers could find and label street-level accessibility problems with high accuracy, this sole reliance on human labor limited scalability. To this end, we investigated ways to combine computer vision and machine learning in the data collection process [9,10]. We created *Tohme* (Figure 3), a system to collect geo-located curb ramp data using a combination of crowdsourcing, computer vision, machine learning and online map data [10]. In this work, we only focused on sidewalk curb ramps because of their significance to accessibility as well as their visual saliency and geospatial properties (*e.g.*, often located on corners), which we thought would ease automated detection.

Key components of Tohme include: (i) a web scraper for downloading street intersection data; (ii) two crowd worker interfaces for finding, labeling, and verifying the presence of curb ramps (Figure 2b); (iii) state-of-the-art computer vision algorithms for automatic curb ramp detection; and (iv) a machine learning-based workflow controller, which predicts computer vision performance and dynamically allocates work to either a human labeling pipeline or a computer vision + human verification pipeline. The system workflow is as follows. svDetect processes every

GSV scene producing curb ramp detections with confidence scores. svControl predicts whether the scene is difficult for a computer vision algorithm. If svControl predicts that the automated detections are likely to fail on a given scene, the detections are discarded and the scene is fed to svLabel for manual labeling instead. If not, the scene/detections are forwarded to svVerify for human verification. The workflow attempts to optimize accuracy and speed.

To evaluate Tohme, we conducted a study using data collected from 1,086 intersections across four North American cities. We evaluated Tohme's performance in detecting curb ramps across our entire dataset with 403 turkers. Alone, the computer vision sub-system currently finds 67% of the curb ramps in the GSV scenes, indicating that computer vision alone cannot solve this complex problem. However, by dynamically allocating work to the CV module or to the slower but more accurate human workers, Tohme performs similarly in detecting curb ramps compared to a manual labeling approach alone (F-measure: 84% *vs*. 86% baseline) but at a 13% reduction in human time cost. To put this in context, for a medium sized city like Washington, D.C. (which has 8,209 intersections [21]), we can reduce the cost to collect curb ramp labels by 30 human hours (from 214 to 184 human hours). This is just the beginning. Our overall aim is to create semi-automated methods that reduce total human hours by at least an order of magnitude. Though challenging, we think we can get there with new workflow algorithms, additional advances in computer vision applied to built infrastructure (*e.g.*, [1]), and better user interfaces.

Ongoing Research

In summary, our previous work demonstrated (i) the viability of using GSV as a massive source of street-level accessibility information, (ii) the feasibility of using crowdsourcing to identify accessibility problems, and (iii) methods to combine computer vision and machine learning techniques to increase the scalability of the data collection methods.

Building on the above work, we are currently focused on two trajectories: (i) investigating how to coordinate crowds and machines to further increase the efficiency of our methods; and (ii) designing and developing the accessibility-aware applications that mentioned in the introduction (Figure 1). Towards (i), we are exploring new methods to semi-automatically separate and triage areas that need accessibility inspections. For example, with our labeling interfaces, we can randomly place crowd workers anywhere in a city (virtually via GSV). If some of these workers begin reporting significant accessibility issues, we can begin triaging those areas and assigning additional workers (and fewer workers to other areas). Relatedly, we are also investigating techniques to try and assess under examined areas in real-time. For example, imagine using the accessibility-aware navigation smartphone application shown in Figure 1a. If you inquire about a potential route that lacks accessibility information, we would like to develop methods capable of semi-automatically crowdsourcing that information in near real-time (similar to VisWis [4]).

Towards (ii), we are designing and developing what we call assistive location-based technologies—location-based technologies that are geared towards supporting people with disabilities (Figure 7) to show the transformative value of our accessibility data. For example, our accessible heatmap mockup shown in Figure 7a would allow users to quickly understand and explore accessible areas (green) and inaccessible areas (red) of their cities and to 'drill down' into specific neighborhoods. Our hope is that this would allow people with mobility impairments to make better decisions about where to live in a city or where to stay when they are traveling. Similarly, we are working on accessibility-aware navigation tools (Figure 1b), which provides both a shortest path and a series of accessible path recommendations depending on the user's reported mobility level. Crucially, however, both these tools require large amounts of geo-located accessibility information—exactly what our scalable data collection methods hope to provide. Furthermore, we believe that these tools will enable governments, public health researchers, and urban planners to more easily assess the health of neighborhoods and to help them smartly allocate resources to improve city infrastructure. Our tools should also provide value to non-mobility impaired persons—for example, those with situational impairments due to pushing a baby stroller, pulling a cart, etc. And, ideally, our hope is that the data could be integrated into pre-existing map-based tools such as Google Maps or OpenStreetMap rather than exist solely in specialized research prototypes.

To collect large amount of accessibility data to advance these projects, we are transforming our data collection tools—which thus far have only been deployed on Amazon Mechanical Turk—into public facing applications so anyone can contribute to the data collection. Inspired and informed by online citizen science website (*e.g.*, zooniverse.org), we are creating a webpage that allows both volunteers and paid crowd workers (turkers) to label the accessibility problems in the physical world. Here, we are investigating, for example, if intrinsically motivated people like wheelchair users or their caregivers perform differently or provide different types of labels from turkers. The image labeling interface is similar to the one shown in Figure 8b with small updates like more label types, ability to freely "walk" around in the virtual world, and detailed feedback on their contribution to collecting street-level accessibility data. Our interfaces also allow users to comment and upload more recent photos if there is a discrepancy in GSV.

As a start, we are collecting accessibility data in two US cities: Washington, D.C. and Baltimore. These cities were selected because of their relatively large population and land area [23,24] as well as their proximity to the University of Maryland, which makes them both convenient for conducting on-site audits. Based on our own calculation using OpenStreetMap (openstreetmap.org), Washington, D.C. and Baltimore have total street lengths of: 670 mi and 1,400 mi respectively. We are planning to ask multiple contributors to audit each street and label sidewalk accessibility problems in GSV, which will allow us to get more accurate data through majority vote based data aggregation (*i.e.*, similar to our prior work [6,8]).

Future Work

We will publish the collected accessibility information as a data dump and provide API access. We hope that this will enable and spur the development of a broad range of new applications and provide new tools for research. It will offer opportunities for HCI researchers and commercial entities to design accessibility-aware tools beyond what we described above, and we invite you to join us in these efforts. For example, we imagine a tool like Yelp incorporating our accessibility data to enhance its search capability—restaurants could be searched not only with location, cuisine and reputations but also based on their level of accessibility. The accessibility data could also be used in broad interdisciplinary research areas. For instance, we expect public health researchers and urban planners to use our data to analyze relationship between neighborhood accessibility and health of those who live there, similar to the studies that investigated how neighborhood characteristics like the presence of amenities (*e.g.*, recreational facilities) and perceived safety affected residents' physical activity levels [11,18].

The key future challenges are to collect comprehensive data about indoor accessibility and capture changes in accessibility of the built environment. While mobile crowdsourcing applications like Wheeelmap and AXSMap attempt to collect granular indoor accessibility information (*e.g.*, presence of accessible bathroom), the data remains sparse due to limited adoption by users and there are no known scalable data collection solutions. Similarly, there are no prescribed ways to react to temporary accessibility barriers that arise in daily or hourly basis (*e.g.*, constructions that obstruct sidewalks, changes in pedestrian density). Some possible solutions here include exploring the use of potentially rich but untapped sources of accessibility information such as daily-updated satellite imagery (*e.g.*, planet.com) or even surveillance video streams (*e.g.*, placemeter.com).

Conclusion

We described our twofold vision to, first, invent and study new scalable methods to collect street-level accessibility information and, second, to use this data to design, develop, and evaluate new map-based tools for accessibility. Our research thus far has demonstrated that GSV is a viable, massive untapped data source for accessibility information, that minimally trained crowd workers are capable of locating, labeling, and characterizing accessibility problems in GSV images using specially designed interfaces, and that automated methods can be used to increase the efficiency of data collection. Our on-going efforts include design, development, and evaluation of scalable data collection system in the wild as well as development of accessibility-aware applications. We expect our work to open up future research avenues in areas not limited in HCI, but also in public health, urban planning, and GIS. This is a large, on-going research effort and we are always looking for interested collaborators. Please feel free to contact us for more information.

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ACCESSIBILITY LAYERS: LEVELLING THE FIELD FOR BLIND PEOPLE IN MOBILE SOCIAL CONTEXTS

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Introduction

Enabling access to a computing device is likely to have a huge impact in the quality of life of a person. Every once in a while, new technologies are devised and impact the way we communicate, work and even, how we have fun. Paradigmatically, it is often the case that a new technology empowers the general able-bodied user and fosters exclusion of people with disabilities. The emergence of touch-based smartphones as the *de facto* mobile interaction gadget created a gap between those that were able to use the device as it was deployed in the market and those that were not able to do so. The potential usages of these devices exploded and users that were at that time able to use mobile phones with physical keypads similarly to their peers, saw themselves living in the past of mobile interaction, from one day to the other. This was the case of blind people when smartphones started to dominate the market *circa* 2007.

It is not a surprise that the inclusion of *VoiceOver* as a built-in accessibility feature in the iPhone 3GS version is a major turning point in the recent history of accessible computing. At the time, when it was launched in 2009, smartphones were already established as a person's handheld computer, way beyond a simple communication tool, and had an impact in people's lives that could not be overseen. Apple democratized access to smartphones and the others followed, always a little behind. Researchers focused, for the following years, mostly on understanding the impact of the built-in accessibility features and enabling or improving specific tasks and applications (e.g., text-entry [16]), but generally accepting the *VoiceOver modus operandi*. This research was carried mostly in the laboratory limiting the understanding of the integration of these gadgets in one's life, particularly to what respects the relationship with peers.

Besides the tools and applications paraphernalia that came along with these new devices, another reason to adopt them lingered: social acceptance. Feature phones became obsolete and, despite their recognized higher accessibility, became socially undesirable [8,19]. There are a number of online testimonials and videos on the benefits and proficiency of using a modern touch phone. On the other hand, little is known about the learning process of this new technology and, once again, what these users lost in their transition from older to newer devices and how long it took for them to regain a similar level of control over these new tools. Anecdotally, we have observed blind people that learned to manoeuvre them, feel victorious and proud, and, looking back, see a great evolution from the smartphone early days, when these were inaccessible to them. Compared to other challenges they faced in their lives, this is likely to be a minor one.

A side effect of this generalized idea (users, manufacturers, and society) that smartphones are now fully accessible and that, in the particular case of blind people, they have regained the control they once had with their feature phones, is that relevant layers beyond physical access to the device and its contents are overlooked.

In this article, I focus my attention on the shortcomings of current mobile devices, particularly in the social arena. I motivate and present work (performed in collaboration with others) in the areas of security and privacy, inconspicuous interaction, and social context awareness. With the emergence of new technologies it is relevant to keep in mind that enabling physical access is not enough as social aspects, and other layers, need to be guaranteed. These layers beyond access need to be pursued and added until we are able to state that people with disabilities stand in par with others in social contexts and are not disabled by technology.

Layers of Accessibility

When presenting my own work on mobile accessibility, even to other researchers, I was several times faced with the question "but wasn't that **solved** with the iPhone? I saw a blind person working with an iPhone, and boy, she was fast". I have also seen several blind people interacting with such devices, more proficiently than I do. Conversely, when talking with blind people, I still witness a great deal of people reluctantly adopting a touch phone or waiting until they are forced to do so. The question that arises is what the meaning of **solved** is in the question posed by these well-intended people. If we are talking about physical access to a device, then *yes*, it has been solved. If we try to look deeper and understand how easy it is to start using such devices, it is dramatically harder to adopt and learn how to use them, than for a sighted person [16]. In that sense, *no*, it is not solved. If we try to look at the daily experiences of using a smartphone non-visually, we witness several barriers, some of them unsurpassable without help from a sighted person. In that sense, *no*, it is not solved. If we consider a social context, where everyone should be able to decide what to be made available to others and what should be private, blind people face the decision between postponing mobile interactions or expose themselves to others. In that sense, *no*, it is not solved.

The following sections cover the work we have been doing to go beyond physical access levelling the field for blind people in the mobile social arena.

Accessible Privacy

> ***Privacy*** *is the ability of an individual or group to seclude themselves, or information about themselves, and thereby express themselves selectively.*
>
> – retrieved *from* ***Wikipedia***

Mobile devices contain an increasing amount of personal information stressing the need for their owners to secure access. While authentication methods are available to address the threats by the probable adversaries, they fail in the case of a closer threat (e.g., friends, family, or lovers) where device and passcode sharing is common [11]. Privacy also goes beyond physical access to these devices: while interacting with a mobile device, our private information may be exposed to others. There is the need for inconspicuous ways of interaction. This need is drastically augmented in particular cases like the one of blind people: the *de facto* assistive technology, screen readers, alongside the need to be aware of the surrounding environment (making headphones undesirable), makes mobile phone usage by blind people a highly conspicuous one, severely jeopardizing the right to privacy.

Accessible Authentication

Travelling back in time to the era of physical keyboards, a blind person could input a PIN by feeling the keyboard, while maintaining the audio feedback muted. As with several other interactions, this was easier and more effective in the past that what is achieved nowadays. The advent of mobile touch phones came with new challenges in respect to guaranteeing security to blind owners. The *modus operandi* of these devices supposes that the keys are read out loud when touched; if this does not happen, it is hardly usable. In an authentication setting, where others can be looking or eavesdropping, this authentication method is inadequate or highly demanding. Previous research has looked at this challenge seeking to provide alternatives that were not dependent on the step-by-step feedback provided by traditional methods [3].

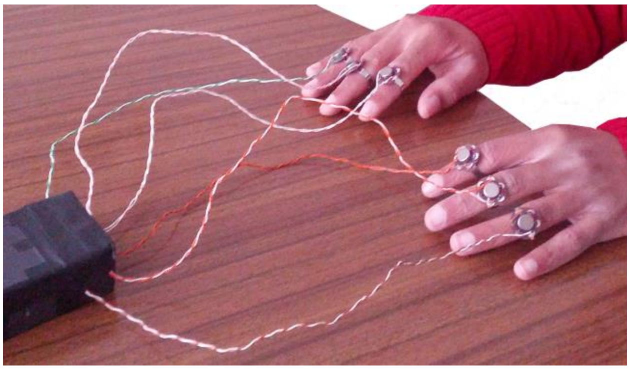
Our first project explicitly in the area of accessible privacy sought to develop an authentication method resilient to smudge and shoulder-surfing attacks that could be used non-visually [9,10]. This method relied on unbounded tap phrases (requiring a single template) and proved to live up to the expectations by disabling observers to mimic the authentication rhythmic key. While these alternative methods provide a barrier for access that is more usable to the blind user and still, and even more so, resilient to attacks, it is a single barrier that does not totally address the possible social scenarios that have been reported extensively in the usable privacy literature [1,6,11]. One particular scenario, very common for novice blind users [17], is the one of device sharing, for example, when asking for help. In these settings it is paramount to find new methods that allow blind people to maintain awareness, similar to the one achieved visually, of what is and was accessed by the one holding the device momentarily. Future work should address awareness on non-owner usage to mimic the close control achieved by blind people.

Private & Inconspicuous Interaction

The non-visual usage of mainstream touch-based smartphones is closely tied to the usage of a screen reader, i.e., auditory feedback. This is due to the absence of physical cues in the screen along with a reasonable set of targets spatially located onscreen. When we consider tasks like text-entry, the number of targets is large and their size is small, rendering non-visual localization without alternative feedback impossible. Gestural approaches have been presented [15] and although they do not require onscreen localization, without auditory feedback, maintaining state of the evolution of the writing would also be a herculean task.

Recently, we have witnessed the appearance of approaches based on Braille [4,5,15,16]. The representation of a Braille cell and the analogy with writing on a Perkins Brailler are the basis for these approaches and they enable blind people to input chords, which is arguably performed without the need for confirmation. Approaches vary in the way a chord is entered: dot by dot [15], row by row [12], column by column [4], and full cell at a time [5]. One of the main issues with such approaches has been its low accuracy when compared to input with traditional methods.

In this context, we have developed our own version of a one-step Braille input method [15], similar to BrailleTouch [5], but with the ability to adapt to the user's changing finger positions, as with Perkinput [4]. Although this approach could slightly improve accuracy it was still not usable, in a sense that one could not efficiently and effectively write a comprehensible message. To tackle this, we developed B#, a correction system for multitouch Braille input that uses chords as the atomic unit of information rather than characters [15]. This method builds on the way chords are performed and outperforms a popular spellchecker (Android's) by providing correct suggestions for 72% of incorrect words (against 38%).



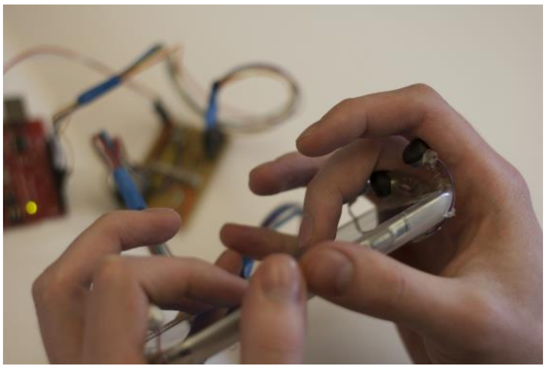


Figure 1. Vibrotactile feedback prototypes. (Left) UbiBraille: reading Braille by feeling vibrations in the fingers. The fingers used to input a Braille chord with a Perkins Brailler vibrate all together to issue a character. (Right) HoliBraille: writing Braille while receiving feedback of the input character with multi-point vibrotactile feedback. Also enables reading Braille as with UbiBraille.

Building on the rebirth of Braille as a tool for inclusion in the 21st century, we placed our efforts in understanding if the Braille alphabet could also be used to enable reading on mobile devices. As with Braille input, previous projects have explored reading a Braille character by providing feedback of the touched dot (marked or not) on the graphical onscreen representation of a Braille character [7] or by issuing sequential vibrotactile patterns to transmit a character [2]. Searching for a method that enabled inconspicuous but efficient output of information, we presented and evaluated UbiBraille (Figure 1, on the left), a method that could deliver a Braille chord, all *dots* at once [13]. This prototype was composed of six rings to be used in the user's fingers (the ones used to input a character with a Perkins Brailler) that vibrated simultaneously to issue a letter. Besides achieving a number of interesting results on character and word recognition, anecdotally, users could *read* complete sentences by feeling characters with a 250 ms stimuli and a 250 ms interval between them.

Being able to input and receive information privately was at this point available by resorting to Braille and its renewed usages. HoliBraille (Figure 1, on the right) was our last effort to provide inconspicuous input and output of information: a holistic approach to enable Braille I/O with mainstream mobile devices [14]. To this end, we built a case with 6 vibrotactile motors combined with dampening materials to be attached to current capacitive touchscreen devices enabling multipoint localized feedback on the user's fingers. Results on perceiving Braille chords were in par with the ones achieved with UbiBraille revealing that the prototype could be used for Braille output but also to transmit other semantic information [20].

Inconspicuous interaction for blind people is desirable and within reach. The advent of other mainstream devices attached to one's body, devices that are socially accepted as they are to be used by everyone (e.g., smartwatches and bracelets [21]), are an opportunity for more subtle and intimate interaction methods that can built on the research presented here.

Outlook

Although there is a large body of work on non-visual interaction with mobile devices, they are still a challenge for blind people, particularly when in search for a subtle interaction in social settings. The built-in accessibility features rely on audio feedback which is still demanding in public environments and results in high exposure of the blind person and her information. The advent of new devices along with the research in the area should consider what was conquered to and by people with disabilities and build upon that knowledge to maintain and provide new layers of accessibility. The future promises change in how people interact with their devices and surroundings; new challenges and opportunities arise.

Challenges

History shows that, with new mainstream technologies, a period of exclusion is likely to occur. Depending on the relevance of the new technology, the impact on the disabled populations varies. There is a growing tendency for accessibility-by-design and the inclusion of accessibility built-in features. However, several accessibility layers remain unattended and are only, if ever, addressed in later versions. Today, we are witnessing an increasing usage of wearable devices, like smartwatches or bracelets. Tomorrow, other *futurables* will appear. It is a challenge to maintain the attained inclusion with older devices and halt the accessibility rollercoaster, on these newcomers, and devices of the future. Particularly, awareness of accessibility layers required in the social arena need to be built-upon rather than ignored in future designs.

It is also a challenge to maintain awareness of the real state of the accessibility provided by new technologies. As our research with smartphone adoption by blind people [17] revealed that this process is still far from being fast and easy, other misconceptions may be in place. Research that seeks to understand the in-the-wild difficulties and coping mechanisms of people with disabilities is needed as laboratory measurements are not enough nor is stating it to be **solved** by witnessing success, if people battled exhaustively to achieve it. Others may not be able to.

Opportunities

Considered as a challenge, new devices also provide opportunities for improved accessibility. Considering physical access, these devices can benefit from the lessons learned with previous ones. Particularly, in the case of smartwatches, the novelty comes with size and placement, as touch and other sensors were already available in their companion devices, i.e., smartphones. The iWatch is already incorporating *VoiceOver* enabling blind people to use these devices out-of-the-box; an example of using wearables and lessons learned as an opportunity to promote inclusion. Regarding other layers, and particularly to what concerns security and privacy, these devices are even more personal and intimate than their in-pocket counterparts, providing clear opportunities for inconspicuous interaction methods.

Research shows that stigmas and misperceptions towards assistive technologies affect their usage and acceptance [8,19]. *Mainstream* was the way to go and the iPhone is a success case of a device being used proficiently by sighted and blind people, at a distance of a simple software-based assistive technology. This is and was not always the case for other assistive technologies that are often awkward and bulky. It seems that somehow technology and social acceptance may be meeting in the middle; the advent of smartwatches, Google Glass, and tracking devices, wearables, once seen as assistive technology, are now becoming mainstream. This unveils novel opportunities for the development of accessible solutions that are accepted both by the user and society.

The emergence of new sensors is also likely to go beyond providing access to a device and can bridge the information gap blind people face in social settings, where knowledge of the environment, particularly to what concerns people in the whereabouts, is dependent on reliance on social norms and etiquette, which does not always happen [18].

Future Work

Our future work will focus in enabling and improving subtlety in non-visual interaction fostering a usable combination of efficient access, and inconspicuity and privacy. To do so, we will explore new mainstream devices like smartwatches and enrich them with layers. Further, we acknowledge the importance of mobile devices and personal contents they detain, and will seek to provide blind people with monitoring and auditing tools that enable them to be more aware of the usages of their devices as well as using them to provide awareness of the surrounding environments. Overall, we will continue pursuing the goal to have blind people interacting with their devices in par with their sighted fellows.

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