A PERSONALIZED VIRTUAL ENVIRONMENT AS A TESTBED FOR ASSISTIVE TECHNOLOGIES

by

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A DISSERTATION

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DISSERTATION ABSTRACT

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The design of successful assistive technologies requires careful personalization for individual users, as well as rapid, low cost cycles for product development and testing. My research brings two modern software engineering models to meet these challenges: Personal and Contextual Requirements Engineering (PC-RE) and Agile Software Development. We adapt these models to the assistive mobile navigation domain for the blind. This dissertation demonstrates that a Virtual Environment testing can significantly reduce testing time, yield meaningful testing results by fully controlling environmental variables, alleviate logistical and safety problems, and serve as an ideal platform for deep personalization. We developed a narrative NAvigation Virtual Environment (NAVE) and compared blind subjects' performance and behavior in wayfinding tasks with tactile maps under field testing versus testing in NAVE. Our experiments showed positive results to support our hypothesis that virtual environments can be useful in replacing field testing for personalized assistive technologies in agile development.

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CHAPTER I

INTRODUCTION

1.1. Motivation

Assistive technologies developed over the last decade have made immense contributions to the quality of life for members of the disabled community. In the case of the blind, for example, successful technologies range from audible screen readers and other “talking” devices, to tactile maps and haptic devices for a range of everyday tasks, as well as multi-modal aids to navigation inside and outside the home.

Computer software plays a diverse and critical role in the development of assistive technologies – during product development and testing, as well as during training of clients. The design of usable, successful assistive technologies depends on a software development process that is tailored to the needs of the target population. A one-size-fits-all approach simply does not work. Instead, personalization of the software development is needed. In addition, many of personal requirements, especially those related to individual skills and abilities, cannot be accurately assessed by self-reflection. This leads us to searching for ways to overcome these shortcomings and realize the need for deep personalization [Yao and Fickas 2007] of assistive technologies. By deep personalization, we mean the personalization in application domains where an individual user may not be self-aware of his or her skills and abilities, and if a system is delivered that does not match the skills or abilities of the user, it may be ineffective, or even abandoned.

Personalization of software for disabled populations is a challenging task. It must make deeper distinctions than is typically made in the development of software for the general population. For example, personalization cannot simply differentiate between blind and deaf populations. Finer distinctions among the blind, such as the underlying cause of loss of sight, the degree of blindness, the age of onset, and previous assistive technologies used by the blind person, all impact the ability of the person to successfully use a new technology. Therefore, personalized software development in this environment is especially challenging because testing and training are constrained due to safety issues as well as availability of test subjects.

Another important requirement for the software development of assistive technologies is a short development cycle, with frequent rounds of testing and client feedback. During our development of assistive technologies for population with traumatic brain injury and those without vision, we found the agile development model's trial-and-error approach was an effective way of personalization with little or no domain theory support. Agile software methodologies thus hold promise in the development of assistive technologies because they shorten the time for product design, development, and testing, thereby reducing the overhead (cost) of product development, which is critical when targeted to small populations of users.

1.2. Research Problem

The general goal of my research is to extend modern software engineering models to the production of assistive technology for populations with special needs. We seek models that can meet the challenges of highly personalized and highly agile software development needed for the disabled. There are two models that can successively be applied to meet these needs: Personal and Contextual Requirements Engineering (PC-RE) and Agile Software Development. The PC-RE model [Sutcliffe et al. 2005] focuses on personalization; it attempts to capture the requirements of individuals as opposed to stakeholder groups. It also addresses the changing requirements that come from changing environments, e.g., the varying locations and situations encountered in a person's activities of daily living. The PC-RE model offers a tight fit with the clinical model of medicine and rehabilitation, where patients are treated as individuals and are given individualized treatment. However, the PC-RE model does not adequately take into account certain individual differences that are extremely important for disabled persons. In addition, when we tried to apply PC-RE model in personalization of navigational assistive aids, we found that we did not have easy ways to assess user profiles in the classic clinical fashion. We had to operationalize personalization in an approach closer to the agile model.

Agile Software Development [Beck et al. 2001] was developed to support frequent development-increments linked to fast turnaround for testing and feedback. End-users are brought into the project early and provide critical feedback on intermediate products. It is not possible to follow a standard Agile approach which mandates frequent field-testing for disabled populations. Field testing is often difficult to control and fraught with logistical and safety problems. For this reason, little to no testing is typically involved in the development of navigational assistive technology applications for users in special populations [Lemoncello et al. 2010]. These are shortcomings that our work aims to overcome.

The research problem addressed in this thesis focuses on the challenge of testing and feedback for mobile applications. More specifically, my research goal is to adapt PCRE and Agile Software Development methodologies to the problem of field testing of navigational aids for blind individuals. This domain presents unique challenges regarding personalization and agile development. For example, blind individuals differ in their sensing of the environment, i.e. it is a highly individualized skill. Thus, the PC-RE model for navigation for the blind needs to be enriched to model the individual's sensing within the real time environment. With respect to agile testing and feedback, we are faced with the difficulty of finding blind subjects as well as the dangers of (repeatedly) subjecting them to field tests requiring them to navigate on city streets. How can we achieve personalized and agile development of navigational aids under these constraints?

The research question in this thesis is how we can alleviate the problem of incremental testing when we apply the agile development mode and the PC-RE model to personalize navigational assistive technologies for the blind. Our proposed solution is to use a Virtual Environment (VE) to meet the need for rapid testing and feedback in the agile approach as well as the requirements for personalization and adaptation of the PC-RE methodology.

While the general research problem discussed above summarizes the intent to evaluate Virtual World testing environment against a Real World testing environment, one primary research question informs the overall design of the dissertation: *How is the problem of incremental testing mediated when applying the Agile Development model and the PC-RE model to assistive technology personalization?* The research question is addressed using a methodology (presented in Chapter IV) designed to evaluate the extent to which each model-based approach affects the personalization and adaption of the assistive technology. Three hypotheses will be tested in this research: 1. A Virtual Environment will reduce the amount of time needed for testing as an alternative to field testing for assistive technologies; 2. A Virtual Environment reduces the cost of testing by alleviating logistical problems.

We explore these research questions by using a case-study methodology [Lazar et al. 2009]. Our case study is looking at the first delivery of personalized tactile maps as navigational aids for the blind to navigate in city environments. We developed a tactile map editor called TAME for rapid production of tactile maps. TAME is the first editor to utilize a standardized tactile symbolism system [Lobben et al. 2007] and was designed to meet the needs for agile software development, i.e., frequent and incremental tuning of maps – it is very easy to customize tactile symbols and other aspects of tactile maps. Through the workshops and user studies we ran on TAME, we realized a great need for personalized tactile maps. We then developed a virtual environment NAVE (NAvigation Virtual Environment) that simulates downtown urban environments for use in testing the efficacy of tactile maps with personalized tactile symbols to aid wayfinding for blind individuals. Our work involved the following phases:

- Refinement of the PC-RE to model the environment-sensing problem for blind persons. We conducted field sessions and interviews with members of the blind population in order to gain an understanding of individual differences in environment-sensing. In particular, we focused on the sensing skills and usage of environmental cues in navigation. We used this knowledge to refine the PC-RE model and later to configure the design of the VE for tactile map feedback and testing.

- Design of the NAVE system for virtual reality testing of the tactile maps for urban navigation. We chose to use a desktop narrative virtual environment to capture a rich set of environmental features including audio, haptic, smell, and other sensory inputs. The NAVE system was configured using individual participant's environmental sensing information to provide a personalized virtual testing environment.
- Testing of blind subjects in field trials for the task of wayfinding on the streets versus using the NAVE system. Four subjects without vision performed navigational tasks using both field tests and virtual tests to learn to use personalized tactile maps made by the TAME with new tactile symbols. Participants' behavior and performance of experiment task were compared across field testing and virtual testing to evaluate our hypothesis.

1.3. Result and Contributions

The results of our work can be summarized as follows:

- We have addressed the need for deeper personalization in the area of assistive technology development by applying the PC-RE model and Agile Software Development model in an integrated way to the case of navigational aids for the blind. Through our study of personalization aspects of tactile maps and differences in environment sensing for blind individuals, we have reached a better understanding of personalization and proposed an extension of the classic PC-RE model.

- We have demonstrated that a virtual testing environment is feasible as a substitute for field testing for our case study of tactile maps for the blind. Our experiments showed positive results in that all users were able to finish navigational tasks in both the field trials and the virtual trials. In addition, most metrics of user performance and behavior patterns in the two testing environments matched up well. This supports the effectiveness of our *personalized virtual environment*, showing that users were able to retrieve similar spatial information about the environment from the virtual environment and interact with it in an effective way for navigational purpose. The results suggest that a personalized virtual environment can be useful in testing tactile maps and potentially for other navigational assistive technologies.

If these results can be verified by extending this work in dimensions of navigation tasks and navigational environments, we can further validate the effectiveness of virtual environment testing, and thus bridge the gap between the PC-RE model and the agile development model for assistive technologies.

1.4. Overview of the Dissertation

Chapter II describes the fundamental research problem addressed in this thesis and our case study approach. Chapter III surveys related research in the areas of

Personalization and Personal Requirement Engineering, agile software development, and virtual environments for navigation for the blind. Chapter IV discusses our refinement of the PC-RE model to characterize the deeper personalization needed for environment-sensing difference among blind persons. Chapter V gives a detailed description of the NAVE virtual environment, and Chapter VI describes the experiments we conducted with blind subjects, comparing the outcome of testing using NAVE versus using on-the-street field testing. Finally, Chapter VII discusses our conclusions and research contributions, as well as future research directions.

CHAPTER II

PERSONALIZED VIRTUAL ENVIRONMENT AS A TESTBED FOR NAVIGATIONAL AIDS FOR THE BLIND

2.1. The Challenge of Testing and the Need for the Use of Virtual Environments

Incremental testing of navigational aids in the field involves multiple cycles in which users/subjects must try out different technologies and configurations under the conditions presented in a dynamic field environment. We can identify two classes of problems in field testing: 1. Controlling variables in the field is difficult, if not impossible. For example, weather and traffic conditions are important for pedestrian navigation, but out of our control; 2. The logistics of field studies is a challenge to manage for disabled populations. It is difficult to set-up a consistent test environment, and it is also often difficult for end-users with special needs to find the time and means to get to the field site and run the tests. Safety issues become a major concern when testing in the presence of traffic, poor street conditions, and unforeseen incidents. The difficulty of doing field-tests means that it rarely gets done [Lemoncello et al. 2010]. In the best case, perhaps a single system-integration test is run at the end of the project in the field. Stated more strongly: little or no testing of modern mobile applications happens in field-studies that introduce changing physical locations, as well as changing situational contexts. This is especially a problem for mobile applications for special populations. Many mobile assistive technology applications avoid the difficulties of testing by replacing disabled end-users with users from the normal population.

It is clear that before we can successfully extend personalized requirements engineering into this domain, we must solve the problem of field studies. My thesis hypothesis is that a Virtual Environment (VE) can be built that 1) is controllable - environmental variables can be set and varied by the researchers, and 2) solves the major logistics problems of convenience and cost. For example, by conducting testing in VEs, we can easily manipulate street navigation environments to model static and dynamically changing conditions for a range of sensory inputs. In a VE, we can reduce testing set-up time and therefore conduct more extensive testing. Furthermore, VEs can allow users to try the assistive technology in contexts that may not be available physically, leading to a wider range of testing possibilities.

The key question is one of validity of results of training and testing using a VE versus field testing. We will use a case study methodology to explore this question, by comparing testing results of personalized tactile maps in field trials and virtual environment trials. To simplify the experiment design, we focus on the first delivery of personalized assistive technologies in our case study, i.e. a snapshot (one product version) of the agile development cycles, as the starting point for the answering our research question.

2.2. Our Case Study: Urban Pedestrian Navigation for the Blind Using Tactile Maps

2.2.1. The TAME Tactile Map Editor

The case study I chose for my investigation of the use of VE to replace field testing is the use of personalized tactile maps in navigation of city blocks. I have been part of a research project directed by Professor Stephen Fickas and Professor Amy Lobben investigating the use of Tactile Maps to aid those with a visual impairment as they navigated in their community [Lobben 2007]. Figure 1 gives an example of one of Lobben's tactile maps for streets in downtown Eugene, Oregon.

With my background in the PC-RE modeling effort, I became interested in the production of personalized Tactile Maps (the "assistive technology" in this domain). One issue was assessment: the PC-RE model rests on being able to assess an individual's skills and then use that to prescribe a solution. Another issue was production: what software methodology can be used to quickly produce tactile maps?

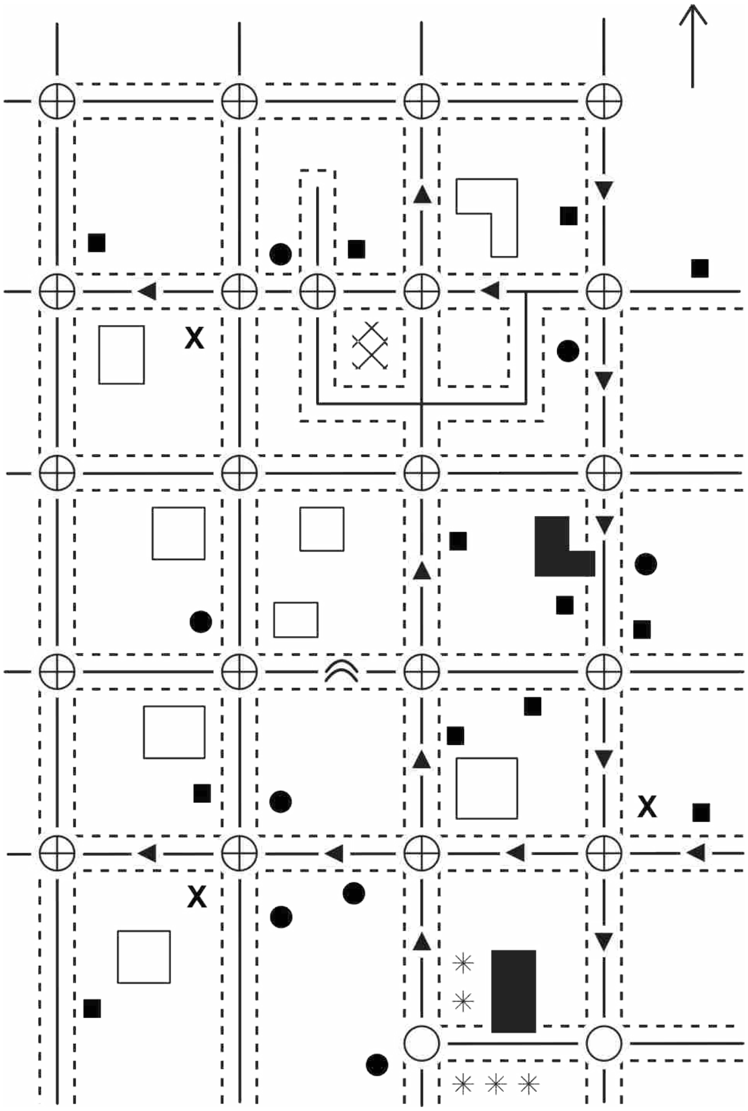


Figure 1. An example of tactile maps of the downtown Eugene (adapted from Amy Lobben's tactile map used in navigational map reading study).

The TAME tool was tested in a series of workshops around the northwest with professionals, who work with individuals with visual impairments. We demonstrated that TAME was usable by those without extensive computer experience. Before TAME, a tactile-map maker would need to work with Adobe Illustrator or other complicated graphic design tools [Lobben et al. 2007]. In addition, our study validated the need for the PC-RE model: we found that individual users had different ideas on how the same navigation space should be represented, depending on the traveler they had in mind. Moreover, we realized there were demands of tactile maps for different contexts or locations. For example, some users wanted tactile maps for intersections with detailed information about traffic controls, curb cuts, and crosswalks etc., while some users needed tactile maps showing spatial layout of indoor offices with Braille annotations. In a map-reading and route-following study of the blind using the tactile maps, we observed that the end users varied significantly in their spatial abilities, such as how many tactile map symbols they could memorize after reading and using tactile maps. Moreover, blind users showed different degree of finger sensitivity, which indicated a need to personalize distance among objects on tactile maps. All these suggested the need for personalization in tactile map production.

2.2.2. Refinement of PC-RE to Model the Environment-sensing Problem for Blind Persons

In order to personalize both the tactile maps and the NAVE virtual environment, we conducted interviews with blind clients to better understand the types of environmental factors that impacted their ability to navigate. We also looked at the individual differences in environmental sensing skills and needs blind clients. The results of this study motivated enrichment of the PC-RE model to include deeper personalization than previously included in the model. This phase of our work is covered in Chapter IV.

2.2.3. Design of the NAVE (NAvigation Virtual Environment)

The NAVE virtual environment was constructed to simulate urban environments for those with visual impairments to navigate. After reviewing the existing virtual environments for people without vision, we chose textual narration as the mode to deliver sensory information. In addition, we included environmental cues to represent spatial information collected in our user studies. At the same time, NAVE allows researchers to configure the sensory information for users, based on their individual profiles of environmental sensing in pedestrian navigation. Details of this phase of work are discussed in Chapter V.

2.2.4. Testing of Blind Subjects Using NAVE Vs. Using Field Studies

Finally, we ran a case study with participants without vision to explore our research questions. More specifically, we ran a comparison study that tested tactile maps in both field trials and virtual trials. Four subjects performed four rounds of wayfinding tasks with a tactile map in Downtown Eugene, and they did the same sets of tasks with a tactile map in NAVE that simulated the corresponding virtual urban setting similar to the area of Downtown Eugene. By comparing the performance and behaviors of participants under both the physical setting and the virtual setting, we examined our hypothesis about using a personalized virtual environment for testing tactile maps for those without vision. We discuss details of our experiment set up in Chapter VI and data analysis in Chapter VII.

CHAPTER III

BACKGROUND AND RELATED WORK

We first introduce the relevant background and related work in the areas of PC-RE, agile software development, and virtual environments. At the end of each subsection, we discuss the relation of this work to the dissertation research.

3.1. Personalization and Personal Requirements Engineering

Requirements Engineering (RE) focuses on obtaining the individual user goals and environmental constraints of a proposed system. In traditional RE, users are treated as a consumer-class: what holds for one member is assumed to hold for the rest. However, this one-size-fits-all approach of RE doesn't always work in all application domains. For example, lack of personalization has been a well-documented problem in assistive technologies (AT) [Kintsch and DePaula 2002; Dawe 2006] – there is a mismatch between application specifications and personal requirements of individual users in many assistive technology applications. For this reason, a very high percentage (up to 60%) of AT devices are abandoned [Kintsch and DePaula 2002; Dawe 2006]. Therefore, it is often important to look at the problem of personalization in those domains where individual differences of users' abilities and skills warrant attention, such as AT.

One easy solution for personalization is to allow users to manually configure options or select preferences for personalization purposes. Can we just hand an individual a default device and let them figure out what is best for them? We do not have a definitive answer to this. But we do know that from our experience with tactile maps for those with visual impairments, this approach is not realistic – tactile map users simply cannot configure the maps themselves. The blind users cannot change the maps themselves, but need to give feedback to the map makers and ask for changes of the tactile maps. In addition, users' feedback might be infeasible or bad for effectiveness of the maps. For example, a user wants to add Braille labels of street names on a navigation map. This may make the map clustered that it is not readable. Similarly, this self-reflection and self-configuration is not possible in many assistive technology domains – users either do not have a clear idea of their own abilities and skills, or they do not have enough knowledge of the application domains to make correct configurations.

Another widely used solution for personalization is to apply inference-based methods using machine-learning techniques. A variety of personalization techniques in this style have been applied and studied in the fields of adaptive user interface (AUI) and e-commerce and requirements engineering [Liu et al. 2003; Wu et al. 2003]. Most of them assume existence of large amount of data, and use machine learning or data mining to infer users' goals and preferences, or approach personalization using pre-defined user models. However, in domains such as assistive technologies, such assumption typically does not hold – the needed data points are not available before these devices can be deployed.

One feasible approach for personalization is to use assessment tools to obtain accurate user profiles of skills, abilities, and needs, and then apply mapping from user profiles to configurations of assistive technology applications. In this sense, the question of personalized requirements is one of user profile assessment. Sun et al. [2006] took this approach in personalizing an e-learning system – they developed a set of assessment questionnaires for students' user profiles as well as a set of rules that map user profiles to individual configurations of their systems. This appears a promising approach for assistive technologies if assessment tools are easily available or developed, such as the education domain for the general population. However, for many assistive technology domains, there may not typically exist domain theoretical support for development of accurate user assessment tools. This suggests we take the agile approach, which requires frequent end-user testing in these domains.

Similar to the approach by Sun et al. [2006], a clinical requirements engineering approach [Fickas 2005] has been proposed for integrating assessment and monitoring of individual goals and abilities into the requirements engineering process, particularly in the field of assistive technology. Along this line of thought, Sutcliffe et al. [2006] proposed a Personal and Contextual Requirements Engineering (PC-RE) framework to account for personal and individual goals and characteristics as well as temporal and contextual dimensions of requirements for assistive technologies. Under the PC-RE framework, an assistive technology system should tailor requirements to users' individual differences to achieve the most effective personal assistance.

As shown in Figure 2, the PC-RE model consists of three layers for personal and contextual requirements with two dimensions of change at each layer – temporal and environmental. The model was defined from an earlier set of projects involving assistive technology.

The first (top) level of the model focuses on the general stakeholder requirements as a group. The temporal dimension addresses evolution in changing stakeholder needs over time, for instance, the changing form of public transportation options offered to the public at large. The environmental dimension addresses cultural, language, and gross geographical changes. Together, requirements at this level can characterize a family of products or software product line.

The second level focuses on user characteristics that differentiate one user from another. User characteristics refine the broader specifications (expectation of user abilities and skills), obtained from the general stakeholder group. Here, the temporal dimension addresses how user goals, requirements, or capabilities can evolve over time. The spatial dimension addresses the personal aspects of a user's environment. For example, an individual's transportation method can vary a day, including pedestrian, para-transit, fixed-route transit, taxi. Requirements specified at this level for an individual user dictate how the application should be personalized; equivalently, which member of the product family will meet an individual user’s needs.

The bottom level focuses on individual goals: the user's preferences and desires irrespective of whether they are feasible at level two. For instance, a user's goal may be to travel to a destination that requires complex transit changes, even though this is beyond the user's skills at the moment. It may be that certain goals at this level must be deferred, opening up new opportunities for goal monitoring [Fickas et al. 2005]. The environment dimension addresses how a user would prefer to interact with a system in different contexts.

From the three levels of the PC-RE model, we can see that it makes a clear distinction between personal dimension and contextual dimension of requirements. The personal dimension focuses on effect of user’s individual factors upon product requirements, which could evolve over time. Therefore, it is on the temporal axis. The contextual dimension accounts for effect of spatial location, social or other contexts upon product requirements. Therefore, the contextual dimension is on the spatial axis.

The PC-RE model lends itself well towards assistive technologies, because the three layers of the model combined provide a reference and mindset towards personalization of applications. More importantly, it is a method developed with consideration of individual and personal goals, and their changes based on temporal and contextual dimensions of personal requirements. Therefore, the model is particularly suitable for systems that need to be adaptive with changes of users and their contexts.

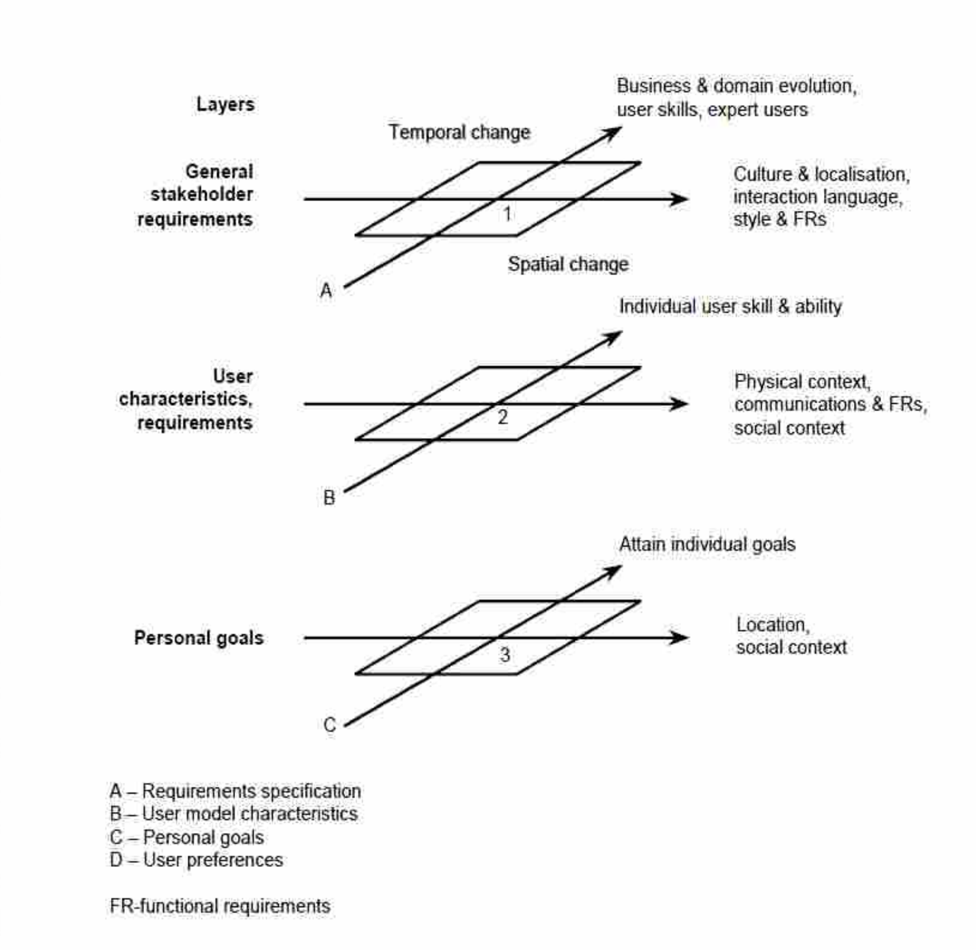


Figure 2. PC-RE framework

The PC-RE model provides a conceptual framework for us to think about the personalization problem of assistive technologies in the personal and contextual dimensions, particularly the Layer 2 of the model. However, there exists a gap in operationalizing the model in assistive technologies where deep personalization is often needed. The PC-RE model assumes the availability of user profiles along these dimensions and the ability to monitor their changes. One major challenge in applying this model is to identify and build an assessment instrument that can gather the critical requirements called for. Deep personalization of navigational aids based on the PC-RE model, for example, would need domain theory support of navigational skills and abilities as well as available instrument to accurately measure such user profiles [Yao and Fickas, 2007]. Unfortunately, we found from our experience working with people with traumatic brain injury or those without vision that we did not have easy ways to obtain users' profile of abilities and skills in navigation in surveys or questions like Sun et al. [2006] did in the education domain. To the contrary, we had to approach this problem in PC-RE model by adopting the Agile Model, which we discuss below. In addition, as discussed later in this dissertation, we discovered that the PC-RE model needed further refinement in Layer 2 (User characteristics and requirements) to correctly model differences in the environment-sensing ability of individual blind persons.

3.2. The Agile Model of Software Development

Agile Software Development focuses on interactive and incremental changes in software development, with requirements and solutions adaptable over the developmental process [Beck et al., 2001]. It emphasized that active stakeholder participation is critical to the successful software modeling and development – end users are required to be involved early and constantly in the design and development and provide rapid feedback to allow swift modification [Leffingwell 2011]. The Agile methods have thus gained growing popularity and applied in many user-centered or human-centered software development in practice [Kazman et al. 2003]. One important feature the Agile Model has in common with the PC-RE model is that it was developed with adjustment and adaption of software products in mind, though from a different perspective.

The TREK group [Fickas et al. 2008] first took on the challenge of working with survivors of a traumatic brain injury (TBI), and assessing their requirements to use public transportation. Through a series of field studies and an extensive survey of travel trainers across the country, they were able to specify a general model of the skills necessary to use public transportation (across populations). These skills were drawn from both the physical domain and the cognitive domain. They also extended the PC-RE model to link deficits (missing skills) with compensatory help in the form of assistive technology (navigation delivered on a mobile phone).

In a follow-on study with Dr. Stuart Faulk, a Software Pharmacy model [Sohlberg et al. 2011] was devised to link the output of assessment into a Product Line of assistive technology. This work is ongoing, but has achieved promising early results in the form of a navigation assistant for a photojournalism assignment around the school: students participating are part of a resource (special needs) classroom at a middle school in Eugene, and use an Android phone to both take pictures and get navigation help.

I was peripherally involved with the TREK and Software Pharmacy projects and became interested in a critical shortcoming in this model (and the PC-RE model in general): it is often not easy if possible to accurately assess user profiles needed for personalization. The Software Pharmacy model was more like delivering glasses than delivering medicine. In other words, we did not find any easy way to conduct one-time assessment of accurate user profiles and then “prescribe” individualized requirements for assistive technologies, in the fashion as the medical doctors do in the classic clinical environment. To the contrary, we found it necessary to do frequent adjustment of the assistive technologies until you find the best fit for a user, in the fashion as the optometrists provide eye exams for glasses. Because there does not exist enough domain theory support for constructing assessment instruments for acquisition of accurate individual user profiles, we have to involve the end users and rely on repeated trials, feedbacks, and adjustments in settling on correct personal requirements in the design space. This naturally requires an Agile Approach, i.e. we need a process of incremental testing: there was a trial period where a user would test out some delivered device, note problems, tweak the device, etc. Through an incremental adjustment process, eventually a good-fitting device would be delivered.

In short, we could fill in the gap of the original PC-RE model, by adopting an agile approach in personalizing assistive technologies: when there is no easy way to accurately assess a user profile for personalization, we do trial-and-error until we find the best fit for an individual. One essential question here is how we can do frequent and incremental testing with users required by the agile approach. As was discussed in the last chapter, we proposed addressing this issue by virtual environment testing.

3.3. Virtual Environments as a Testing Alternative

3.3.1 Virtual Environments for Spatial Behavior Studies

Many researchers have developed virtual environments to examine navigational behaviors of the general population as well as for those with disabilities. For example, studies have used virtual environments to investigate assessment of spatial abilities [Cockburn and McKenzie 2002; Waller, 2005], cognitive mapping [Gillner and Mallot 1998; Darken and Peterson 2001], individual differences [Waller 1999; Sjolinder et al. 2005], and spatial knowledge transfer [Waller 1998; Wilson et al. 1997], relations between age and navigation performance [Sayer, 2004; Sjolinder et al. 2005], usability of navigation aids [Burigat and Chittaro, 2007]. Chewar and McCrickard [2002] used VR as an assessment tool in choosing presentation modes of navigational instructions, in their case using brain lateralization as a focus. Livingstone and Skelton [2007] applied VR to investigation of the deficit of spatial abilities of people with traumatic brain injury (TBI). Many of these virtual environment studies assume existence of vision in user population, and focus on simulation of visual stimuli.

For the population with visual impairments, some virtual environments have been developed using audio [Sánchez et al. 2010] or haptics [Lahav et al. 2008] to simulate environmental cues for navigation and other spatial tasks. However, they typically focus on a small set of questions on navigation, and often are not suitable for testing assistive technologies for pedestrian navigation of those with visual impairments.

Firstly, although many existing studies simulate the physical world and examine navigational behaviors and spatial abilities, they are not designed for testing assistive technology applications. It is not surprising to see that most of these VEs are not realistic in simulating pedestrian navigation settings. The virtual environments tend to be abstract, and fail to cover many problems that the users have to handle during pedestrian navigation in their real life. For example, finding places is a task this population is performing all the time in the navigation but not well supported in these existing virtual environments because they miss many environmental features people with visual impairments take advantage of.

In addition, most of these virtual environments use computation-intensive low-level sensory simulation such as spatial audio and haptics. This technically limits what navigation environments they can generate – most existing virtual environments for these population either provide only a small subset of environmental features (often abstractly), or they pose navigation problems far less complicated than what users really have to face. For example, Lahav et al. [2008] only simulated geometric shapes of objects in indoor settings in their studies, which was far from a realistic setting for pedestrian navigation (see Figure 3). Sánchez et al. [2010] created an Audio-based Environment Simulator (AbES) for studying navigational behavior and spatial cognition of those with visual impairments (see Figure 4). The AbES could generate desktop virtual environments in a fixed building in a maze-like fashion. However, those with visual impairments mostly need help for their outdoor pedestrian navigation, rather than indoors. Therefore, AbES is not suitable for our purpose of substituting field trials for pedestrian navigation assistance such as tactile maps.

Another problem in existing VEs is that little attention has been paid towards individual differences among those with visual impairments. It has been well documented that human beings differ in their navigational abilities and skills [Carroll 1993; Eliot and Smith 1983; Lohman 1988; McGee 1979; Hegarty et al. 2006]. In addition, those with visual impairments vary often considerably in their physical conditions, and spatial abilities. For example, different performances have been identified among late blind, congenitally blind, and early blind in similar spatial tasks [Thinus-Blanc and Gaunet 1997]. Development of VEs for this population must take these personal variances into consideration. Furthermore, these groups of users also differ in technological assistances they use in their daily navigation. This naturally leads to different requirements on what environmental cues VEs need to simulate for testing navigational assistive technologies. I found from my preliminary study (more details in the next section) that blind individuals differed in what the environmental cues they used for navigation. For instance, one participant did not mention information about obstacles in the sidewalk at all since her guide-dog circumvented them, while the other user detected obstacles on the sidewalks to travel by his cane. In addition, one participant constantly used the time of the day and the sunshine for orientation, while the other one did not. Although these discrepancies in this user population require different environmental cues be simulated by VEs, none of the existing studies for the blind have addressed this issue. Therefore, we can imagine that these virtual environments may very likely fail to work for some groups in the population with visual impairments. To overcome these problems, I chose to use the textual modality of representation so that VEs are flexible and expressive in representing environmental cues.

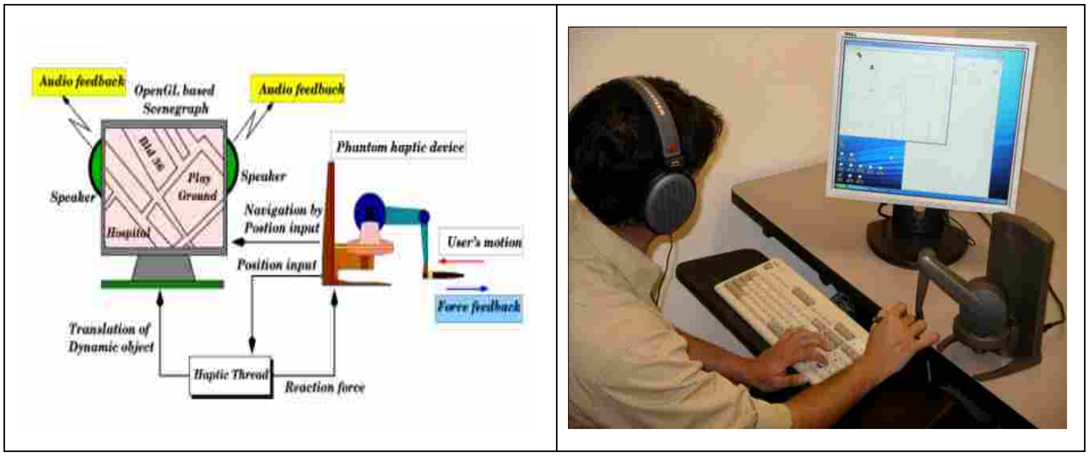


Figure 3. The BlindAid system developed by Lahav et al. [2008] that uses haptic and audio cues to allow users to explore geometric layouts in rooms and develop cognitive mapping.

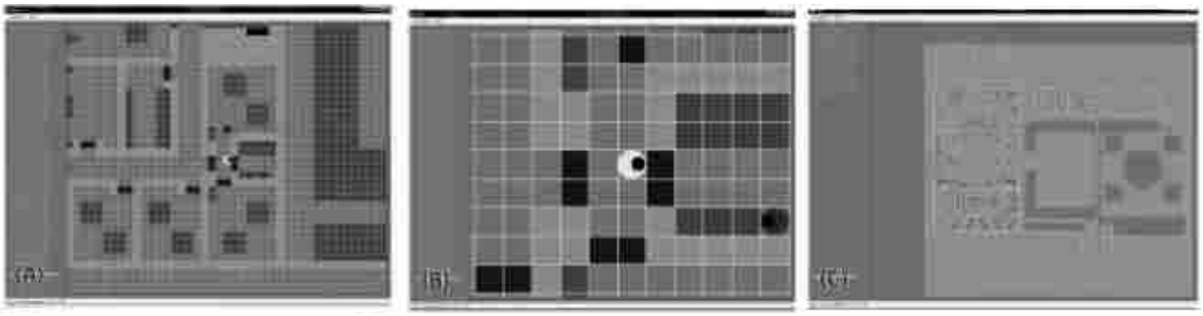
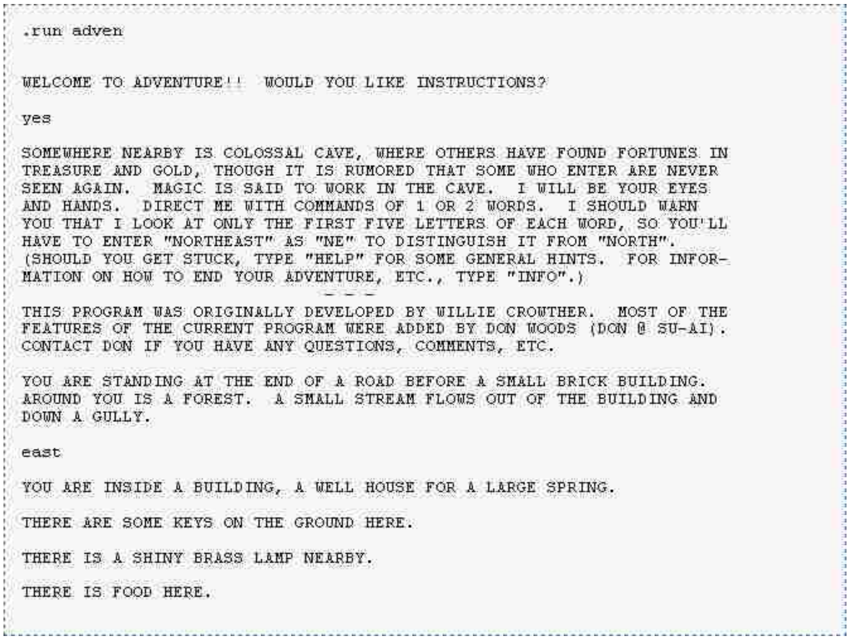


Figure 4. Screenshots of Audio-based Environments Simulator (AbES) by Sánchez et al. [2010]. AbES simulates navigation in an office building, and generates maze-like virtual environments to study navigational behavior and cognitive mapping, and test navigational applications for the population with visual impairments.

3.3.2. Textual Virtual Environments

Textual narration is a typical modality of spatial information representation, other than graphics, audio or haptics. For example, we usually use textual mode when we ask for directions in streets. Another example is text-to-speech directions given by in-car GPS devices when we are driving. Therefore, text-based virtual environments may be a promising approach for my research purpose. First, text-based interface was developed well before graphical user interface in history, and has been the interface those computer users with visual impairments most familiar with. Many people with visual impairments use screen readers on a daily basis. Second, there have existed plenty of text-based virtual environments that are well used. For example, a popular text-based game in 1970s called Colossal Cave Adventure [Rick 1998] can be considered a text-based virtual environment that allows users to navigate in an environment using textual narration and commands (Figure 5 below shows the opening of the game). Dieberger [1994] studied textual virtual environments for spatial representation, and indicated the textual modality can be a very effective representation of spatial information. In addition, we can also find text-based virtual environments for those with visual impairments in well-known applications such as MUD and Second Life [Folmer 2009].



```
.run adven

WELCOME TO ADVENTURE!!  WOULD YOU LIKE INSTRUCTIONS?

yes

SOMEWHERE NEARBY IS COLOSSAL CAVE, WHERE OTHERS HAVE FOUND FORTUNES IN
TREASURE AND GOLD, THOUGH IT IS RUMORED THAT SOME WHO ENTER ARE NEVER
SEEN AGAIN.  MAGIC IS SAID TO WORK IN THE CAVE.  I WILL BE YOUR EYES
AND HANDS.  DIRECT ME WITH COMMANDS OF 1 OR 2 WORDS.  I SHOULD WARN
YOU THAT I LOOK AT ONLY THE FIRST FIVE LETTERS OF EACH WORD, SO YOU'LL
HAVE TO ENTER "NORTHEAST" AS "NE" TO DISTINGUISH IT FROM "NORTH".
(SHOULD YOU GET STUCK, TYPE "HELP" FOR SOME GENERAL HINTS.  FOR INFOR-
MATION ON HOW TO END YOUR ADVENTURE, ETC., TYPE "INFO".)
                              - - -
THIS PROGRAM WAS ORIGINALLY DEVELOPED BY WILLIE CROWTHER.  MOST OF THE
FEATURES OF THE CURRENT PROGRAM WERE ADDED BY DON WOODS (DON @ SU-AI).
CONTACT DON IF YOU HAVE ANY QUESTIONS, COMMENTS, ETC.

YOU ARE STANDING AT THE END OF A ROAD BEFORE A SMALL BRICK BUILDING.
AROUND YOU IS A FOREST.  A SMALL STREAM FLOWS OUT OF THE BUILDING AND
DOWN A GULLY.

east

YOU ARE INSIDE A BUILDING, A WELL HOUSE FOR A LARGE SPRING.

THERE ARE SOME KEYS ON THE GROUND HERE.

THERE IS A SHINY BRASS LAMP NEARBY.

THERE IS FOOD HERE.
```

Figure 5. Crowther/Woods Colossal Adventure Game that used textual descriptions to present a virtual world to users (from URL: http://en.wikipedia.org/wiki/Colossal_Cave_Adventure).

We chose to use a text-based narrative style environment for NAVE for the following reasons: 1) A text-based virtual environment is computationally inexpensive to build, and it is good to start from the simplest point for exploring our research question; 2) Text-based virtual environments (or in similar systems) have been used by the population without vision, and have been shown to be effective in spatial simulation; 3) Textual narration is very flexible to represent rich dimensions of spatial information to users navigating in virtual environments.

CHAPTER IV

MODELING THE ENVIRONMENT-SENSING PROBLEM FOR BLIND PERSONS WITH PC-RE

The first phase of my research investigated the nature of personalization in assistive technologies for blind persons. We hypothesized that a deeper level of personalization is needed in this context and that the PC-RE model did not adequately address this need. In particular, we examined the types of environmental sensing that are needed by blind persons to navigate urban streets, with focus on the individual differences. Our investigation of these differences in environment-sensing motivated a propose change in the PC-RE model to support the need for personalization in Layer 2 (User Characteristics and Requirements). The results of this study were instrumental in the design of the NAVE virtual environment.

4.1. Individual Differences in Environmental Cue Usage in Blind Navigation

There are two major issues in existing VEs for people with visual impairments: First, VEs do not provide realistic environmental simulation (see the previous section for details); in addition, typical VEs are one-size-fits-all, and ignore individual differences. To resolve these shortcomings, we needed to better understand 1) what environmental cues people without vision use for navigation; 2) how these differences impact navigation in general and the use of tactile maps in particular.

We conducted a preliminary study to address these questions. In this pilot study, two participants without vision were asked to talk-out-loud as they navigated a specified route. One participant was a cane user while the other was a guide-dog user. Both participants studied a specified route on a tactile map produced by TAME for 15 minutes to familiarize themselves with the route (see Figure 6). Then the participants were brought to the start of the route and oriented, before performing the navigation task. During navigation, participants would describe out loud what environmental cues they could detect and what they used for navigation. If they became confused, they could request to re-examine the tactile map.

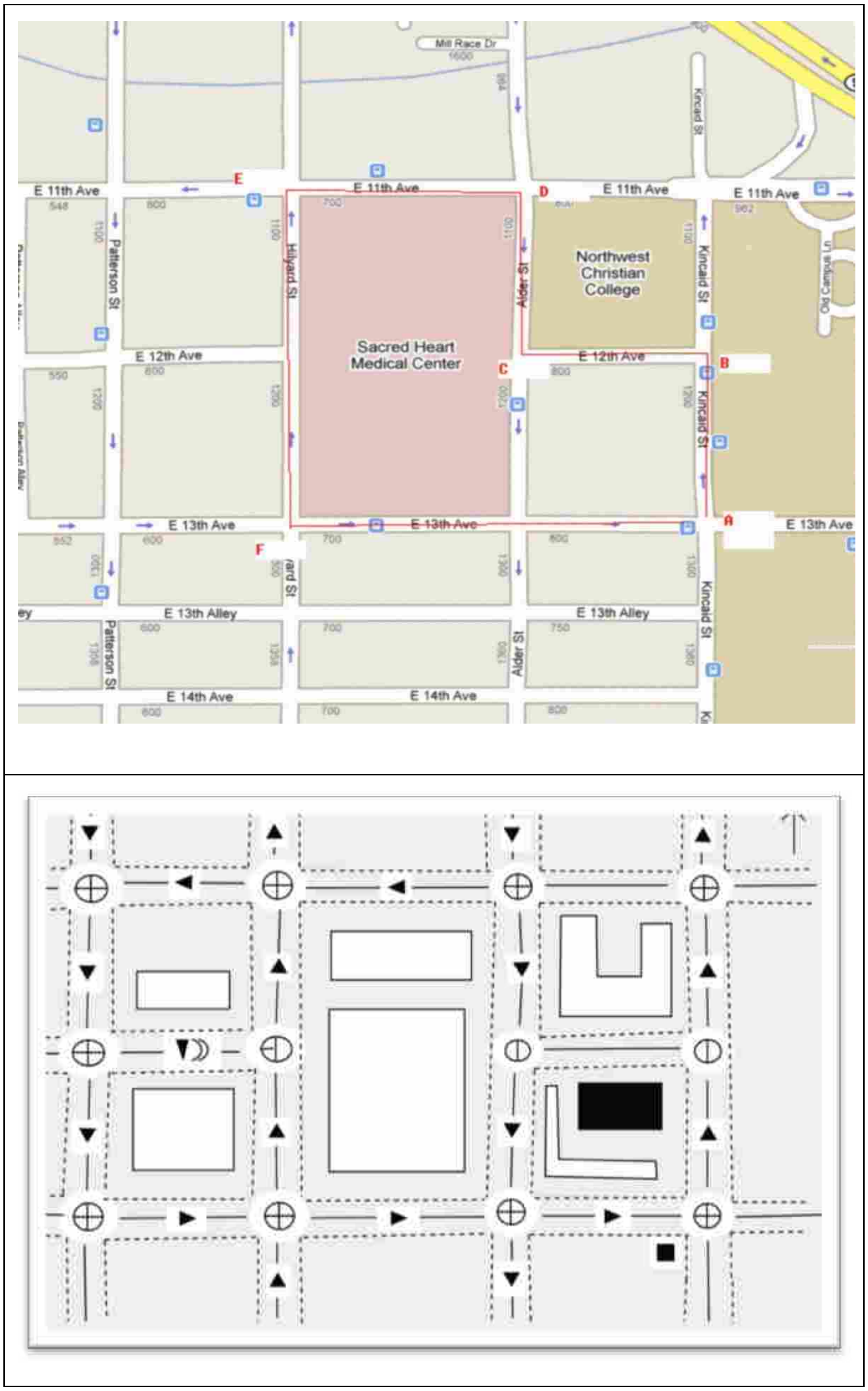


Figure 6. The route the participants navigated in the environment-sensing study. On the non-tactile map on the top, the red lines specified the actual route. The red letters on this map represent the major choice points along the route (starting from point A). On the bottom is the tactile map for the route of navigation, where the start point is represented by the small black square symbol in the lower right corner.

This preliminary study identified a rich set of environmental features that people without vision detect and use for navigation. They include:

1. Audio: these include sounds and noise from traffic (cars, buses, and bikes), buildings, parking spaces, lanes, overpass, trees and bushes, and poles etc.

2.Haptic: the participants can sense tactile information such as textures and hardness from the ground surface. They can also detect surrounding traffic from ground vibrations,. They can feel the special texture (e.g. raised dots) at curb cuts.

3. Smell: participants can detect nearby restaurants, laundry, hospital, and vegetation by olfaction.

4. Other environmental information: participants explicitly identified other environmental features such as sunshine, wind, and shadow they used to help their orientation and wayfinding.

We also found that individuals differed in the usage of environmental cues for navigation. These individual differences may be a result of participants' navigational skills or habits, or assistive devices. For example, one participant consistently used the sunshine to orient herself during the navigation, while the other participant did not mention sunshine at all. Another example is that the participant sensed obstacles on the sidewalk using his cane, while the other participant did not pay much attention to obstacles since her guide-dog circumvented them for her. According to our updated PC-RE model, the personalized context here, the interaction between the blind users' environment sensing abilities and the assistive technology they use, stipulates that the NAVE needs to configure sensory information for each user individually.

Another important factor in the construction of the virtual environment involves decisions about what action or movement is allowed for users in the virtual reality environment. There are three standard choices: 1) macro-level movements (e.g., “go forward three blocks”); 2) micro-level movements (e.g. “turn left and walk forward 5 feet); 3) block-level movement (e.g. “go forward and reach the end of the block”). The preliminary study showed that participants focused primarily on navigational decisions at the block level, i.e. they didn’t need to think about micro and macro level movements until they needed to make a decision, for example about turning or crossing intersections at a choice point. As a result, we chose to use block level movements in the NAVE virtual environment. However, the meta-level tool we developed for constructing virtual environment (see more details in the next chapter) does not limit researchers to block level movements only, but allows macro and micro level movements as well.

4.2. Extending the PC-RE Model for Deeper Personalization

Our study of the environment-sensing differences in pedestrian navigation among individuals without vision motivated our refinement of the PC-RE model. The original PC-RE model represents each layer as having two continuous dimensions. In Layer 2, which models user characteristics and requirements, the “individual user skill and ability” is modeled as a continuum from low level to high level. Similarly, the "Physical context" is represented as a continuum from few to many. While this current context dimension for users is expected to change, it is a one-size-fits-all approach in general: if two people are at the same spot, the physical environment is the same. While this may be true in some cases, our studies on environmental sensing suggested that the model is not universally true. In other words, the current PC-RE model misses to represent possible interaction between the temporal dimension and the spatial dimension of user characteristics. The PC-RE model needs to represent the variation that two people in exactly the same spot will represent as their environment. Clearly, it is not the same context! In addition, the fact that these two dimensions are perpendicular to each other in the original model indicates that there exists no interaction between them. This is not correct from our observation either. This leads to our refinement of the PC-RE model: For the PC-RE model to be effective, it must take into account the variation in the means that individuals sense their context. In essence, it must add the notion of personalized contexts. Therefore, we refined the PC-RE model to represent personalized context between individual skills and the physical contexts. Figure 7 below shows the re-configured Layer 2 model for our blind subjects. For the purpose of personalization, it is important to find out the personalized contexts, i.e. where users' abilities and skills converge with their physical contexts.

According to the new PC-RE model, a virtual environment for people with visual impairments should be tailored according to users' personalized context. More specifically, in this study it would make sense to set up the virtual environment so that narratives would differ, not only according to the physical environment, but also from individual difference in environmental sensing and its usage in navigation. For example, a virtual environment needs to provide environmental information to a blind individual in ways that make sense to him – for a blind participant, if he never uses the wind for orientation or navigation purpose at all, this information from the environment should be filtered out for him. To the contrary, such information could be very important to present to a participant in the virtual environment, because he may depend on the wind or the sunshine for orientation and wayfinding. In this case, the personalized context is a production of interaction between the user's skills and abilities, and the physical environment.

Based on our observation, the refined PC-RE model requires that a virtual environment for blind navigation should be configured according to a user's profile to be effective. More specifically, the virtual environment should not deliver all the environmental information of the simulated area, but filter out the set of information that will not be sensed or used by the individual during navigation. This filtering can depend on what kind of assistance the blind use daily in navigation, such as the guide dog or a cane, or a list of environmental cues they use for orientation and wayfinding, and their order of importance. This way the virtual environment would construct a "personalized context" for an individual user, which is the product of the interaction of the blind person's environment sensing abilities and skills, and the simulated physical context. We will describe our NAvigation Virtual Environment with a personalized context for the blind in the following chapter.

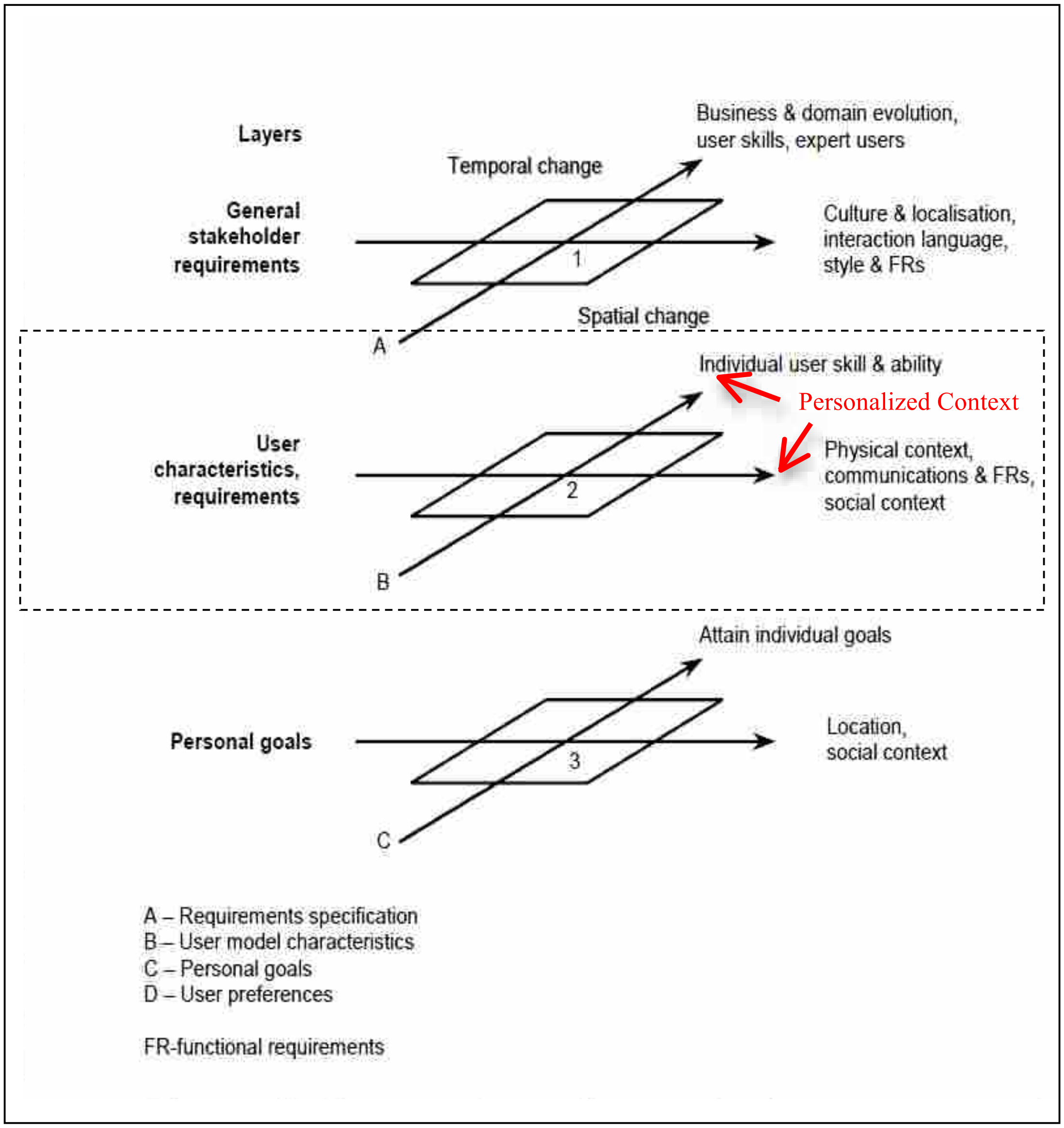


Figure 7. A refined PC-RE model with personalized context. The red arrows in the figure indicates that there exists interaction between physical contexts and social contexts individual users' skills and abilities.

CHAPTER V

THE NAVE VIRTUAL ENVIRONMENT FOR URBAN STREET NAVIGATION USING TACTILE MAPS

The NAVE Virtual Environment provides a two-dimensional virtual navigational space representing a typical urban downtown street environment. NAVE's virtual space corresponds closely to the space represented in TAME's tactile map. NAVE incorporates a rich array of environmental cues identified for navigation for the blind in our earlier study using the method of audio textual narration.

In this chapter we describe the NAVE editor that is used (by sighted persons) to configure a specific streetscape (see Figure 8 below for the interface), and the NAVE interface used by blind persons as a substitute for field testing of tactile maps. As discussed earlier, the design of NAVE was guided by our study of the environment sensing of the blind and individual differences in using environmental cues in pedestrian navigation, and is an instantiation of the principles of the refined PC-RE model with personalized context. In addition, it is intended to facilitate incremental testing needed in the agile software development.

5.1. The NAVE Virtual Navigation Space and Configuration Editor

A virtual environment produced in the system consists of the following objects, represented internally in an XML document:

- Tours: each tour represents one complete virtual environment, and it can consist of one or more maps.
- Maps: maps are a sub-section of a space simulated by a virtual environment. A map usually is a geographic unit or region to be separate from other areas. For example, if you want to simulate a university campus, each building itself would be very likely be represented as a map so that users can navigate.
- Nodes: nodes are choice points in navigation, where users need to make a decision and movement during their navigation. For example, if a virtual environment contains a map of a street grid in an urban setting, then each intersection can be a node in the map -- users need to decide whether they need to move forward, turn left or right, or turn around and go backward to the last node. In the NAVE, the nodes store textual descriptions about environmental features immediately around that choice point.
- Edges: nodes are connected by edges in the NAVE, and edges are directional. If two nodes A and B are connected by edges E1 and E2, that means user can move from A to B via E1, or move from B to A via E2. In an urban setting simulation, edges often represent sidewalks that connect two intersections. Edges are the other places in the NAVE where narrative description of environmental features is stored. An edge typically contains what users can access when a user goes between choice points connected by it.

- Environmental features: each node or edge contains some information about the environment that the NAVE is simulating, as described above. List 1 below shows what types of environmental information the VE in this study is using.

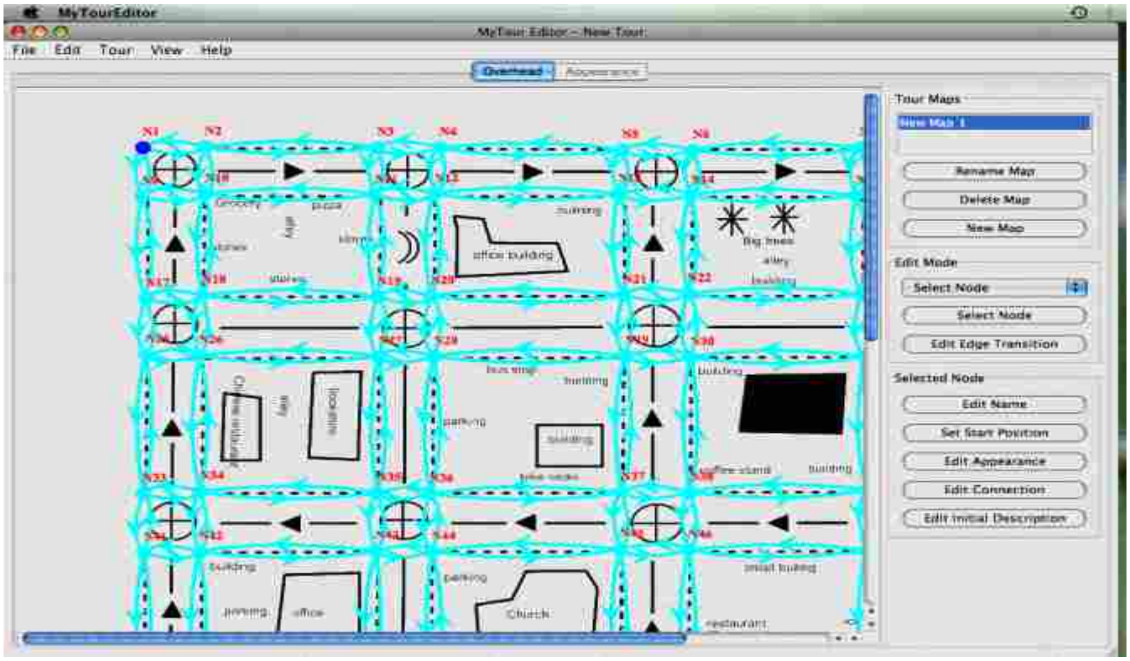


Figure 8. A navigational space that covers nine city blocks in an urban area similar to Downtown Eugene, Oregon. Each node on the screen corresponds to a choice point during navigation. The edges (shown as arrows in the figure) connect nodes, and indicate connectivity (and direction) among choice points.

When constructing a virtual environment for users with visual impairments, the designer can attach textual descriptions environmental cues to choice points. Below is a list of choices that are available, but more information can be added if necessary:

1. intersection;

2. traffic: numbers of lanes, direction (one way vs. two way), vehicles (cars, buses, bikes), traffic movement, engine noises;

3. building: types, size, entrance, busy or not (people in and out);

4. parking lots: open, crowded, vehicles in and out;

5. obstacles: obstacles on the sidewalk;

6. vegetation: trees, bushes, and lawns;

7. sidewalk;

8. curb cuts: slope, tactile paving, pavement, cross-path, stop signs;

9. pedestrians, bicyclists: moving (direction, speed), stopping;

10. signalized intersection: (some are audio): audio prompt, user to push or not;

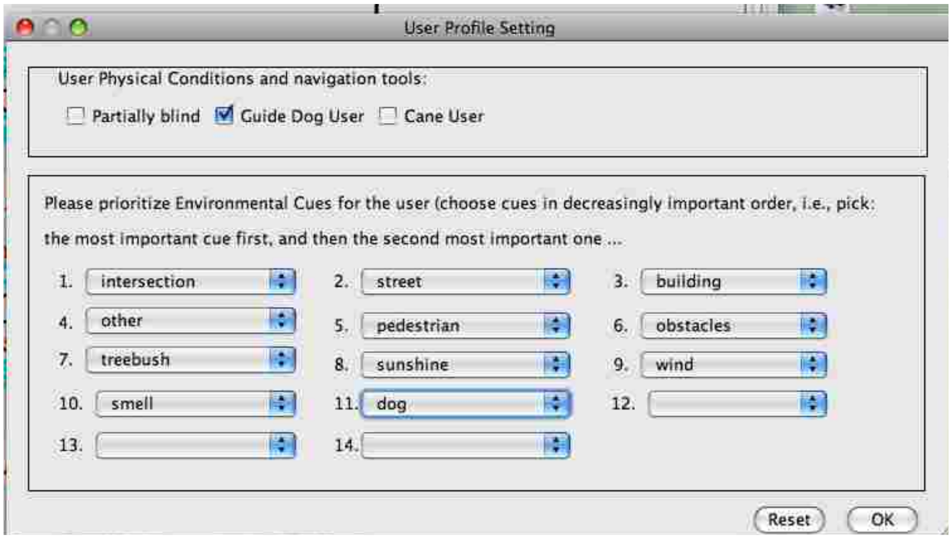
11. dog: guide-dog movement (move, stop, detour, response to user movement/command);

12. sunshine, wind, shadow : direction (used for orientation);

13. smell: restaurants, hospital etc.;

14. other environmental features.

The current system only supports four cardinal directions (north, south, east, and west). Thus there are only four directions of movement between neighboring choice points. This might limit the virtual environments created. However, this constraint is not as important as it seems – neighboring choice points lie in the cardinal directions relative to each other in our urban field testing environment. This is true for many urban environments. In addition, this problem was alievated in this study by my choice of block-level movements in the virtual environment, since users often only need to move in cardinal directions at the block-level in many city streets.



User Physical Conditions and navigation tools:

☐ Partially blind ☑ Guide Dog User ☐ Cane User

Please prioritize Environmental Cues for the user (choose cues in decreasingly important order, i.e., pick: the most important cue first, and then the second most important one ...

1. intersection
2. street
3. building
4. other
5. pedestrian
6. obstacles
7. treebush
8. sunshine
9. wind
10. smell
11. dog
12.
13.
14.

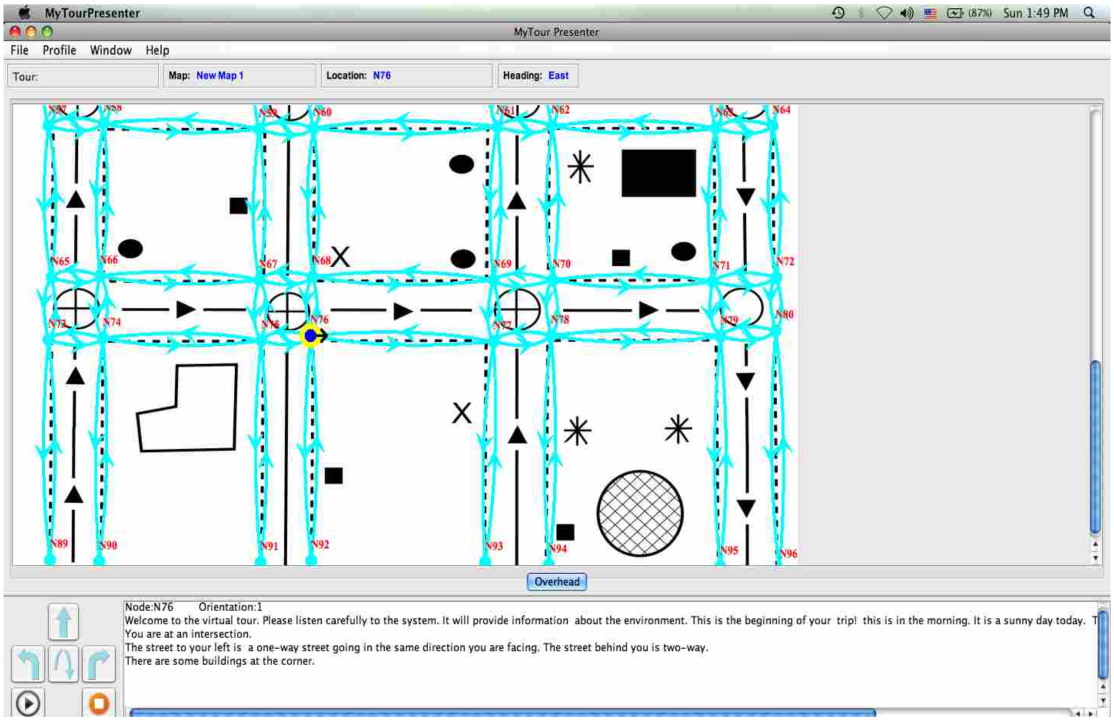
Figure 9. A user profile configuration dialog in the virtual environment. This example shows the profile for a guide-dog user. The configuration will determine what information to present to a user at each node or edge when the user navigates in the NAVE system.

Before a user without vision begins to navigate in the virtual environment, a profile can be configured to include which kinds of environmental information narratives to represent to him or her by the virtual environment. As the Figure 9 showed, we configured the NAVE by choosing a subset of environmental cues from the list above. This way NAVE could filter environmental information so that a participant would only receive meaningful narration for him or her. For example, a cane user would not receive information about the guide dog, or a blind person would only hear description about the wind if this information was mentioned to be used in this person’s daily pedestrian navigation. In addition, the configuration also determined the order of these environmental cues spoken to the blind users.

5.2. NAVE User Interface during Operation by Blind Persons

After the user profile is set, a virtual environment is launched by loading the XML model into the system. Then the user can begin virtual navigation. When the user navigates in NAVE, the virtual environment will use text-to-speech to turn textual descriptions of environmental information at a choice point (node), in the XML document, to audio narration for the blind user. In this way, users of the virtual system can acquire environmental information via textual descriptions. The textual descriptions are able to represent a wider range of environmental factors than other types of representations such as audio (e.g. the narrative “a bird is singing” instead of bird chirping sounds).

Figure 10 shows the GUI of the virtual environment in operation. Texts of audio descriptions presented to the users are shown in the big text area at the bottom, for the convenience of researchers. Users with visual impairments can perform their movements by using a game joystick (as is shown in Figure 11 below). They can control representation of the environmental information narratives, by using the joystick buttons to play or stop audio narration at any time during their virtual navigation. When navigating to the edge of the virtual environment, i.e. when the subject is not able to move forward, the virtual environment will tell the users “ you are at the edge of the virtual environment”. In addition, the system does not allow the user to go further.



Tour:
Map: New Map 1
Location: N76
Heading: East

Node:N76 Orientation:1
Welcome to the virtual tour. Please listen carefully to the system. It will provide information about the environment. This is the beginning of your trip! this is in the morning. It is a sunny day today. T
You are at an intersection.
The street to your left is a one-way street going in the same direction you are facing. The street behind you is two-way.
There are some buildings at the corner.

Figure 10. Graphic interface of the virtual environment used in the experiment. Current orientation of the user in the virtual navigation is shown as a small arrow, and in the text at the top in the "Heading" text box. Navigation in the virtual environment and text-to-speech of environmental information is controlled by mouse-clicking the buttons at the lower left of the screen, or by using Logitech Game Joystick (Extreme 3D PRO). The user can use a joystick or a keyboard to navigate (the arrow keys on the lower left corner, location node and heading information on the top are for researcher observation convenience). The users can play or stop textual narration of the VE as they like by a joystick or the keyboard.

In this study, the virtual environment was running on a MacBook Pro with a 15 inch screen. Participants controlled virtual navigation using the joystick connected to the laptop. The virtual environment used Mac OS X Leopard's built-in text-to-speech engine and used the normal speaking speed of MacOS X's system voice "Alex".

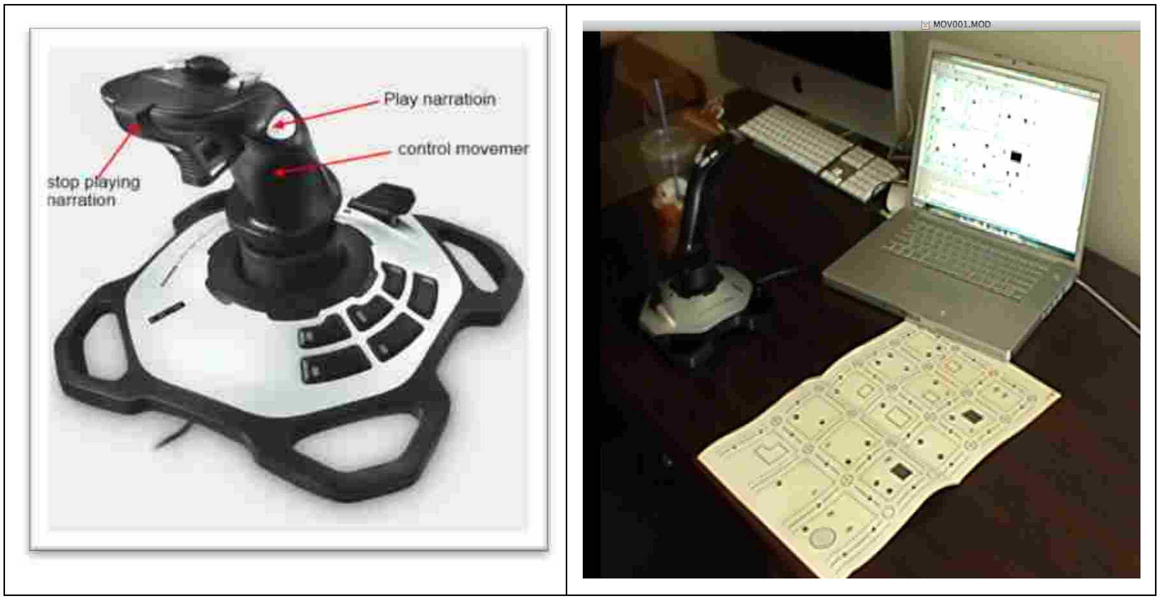


Figure 11. NAVE control and setup for the experiment. On the right is the Logitech Extreme 3D Joystick used by participants to control the virtual environment. On the right is the virtual environment setup for the virtual trials. As the red arrows in the left picture shows, users can control navigation movement using the joystick. Users turn left or right by rotating the joystick, go forward by pushing the stick forward, and turn around by pulling the stick backward. Users can also start or stop playing narration by clicking on assigned buttons on the joystick.

The NAVE was developed uner the principle of our refined PC-RE model. It was able to provide a personalized virtual environment for the blind, based on user profiles of environmental sensing. We were able to use it as a platform for testing personalized tactile maps we were interested in.

CHAPTER VI

THE EFFECTIVENESS OF TESTING USING NAVE VERSUS FIELD TRIALS

With the narrative virtual environment constructed, we went on to investigate whether the narrative virtual environment can replace field trials for the purpose of testing tactile maps (the assistive technology of interest). We looked for user behaviors that matched up precisely under both the virtual environments and the real world; similarly, we looked for user behaviors that did not match up well. Our goal was to investigate for tactile maps of the same types and complexities, the similarities and differences between participants' behavior in the two testing environments.

We designed a case study examine this problem. As was mentioned before, we found there is a great need for personalized tactile maps. From the feedback in the previous workshops and user studies of TAME and tactile map making, we identified a great need to add tactile symbols for places that the blind visited most often in urban pedestrian navigation: bus stops, food places, and banks. We decided to add tactile map symbols for these three types of destinations as custom tactile symbols (see Figure 11 for symbols), and wanted to test how well new tactile maps with addition of these symbols work with our end-users. In the case study in this dissertation, we only looked at testing our first delivery of the tactile maps, which allowed us to focus on comparison between field testing and virtual testing. Although there typically will be multiple versions of personalized tactile maps in an agile development model, we only took a snapshot of the agile cycles and concentrated on testing one version of the map. If virtual testing could work well in testing this one version of tactile map, then we would have a good starting point.

6.1. The Case Study Approach

One prominent feature of this study is the case study experiment with a small set of subjects, instead of a study with a large sample population and statistical analysis. Case studies can facilitate in-depth investigation of a small number of cases and examine participants' behavior in context. This methodology has been well used in human-centered studies in fields such as Human-Computer Interaction (HCI) to 1) allow exploration and new understanding of novel problems or situations, 2) develop models to understand the context of technology use for explanatory purposes, 3) help documentation of a system or a context of technology use, 4) demonstrate how a new tool/technology can be successfully used [Lazar et al. 2009].

The case study methodology fits well with the user-centered approach that I emphasize in my research with disabled people. First, the clinical approach of PC-RE to assistive technology and personal requirements engineering methodology in developing assistive technologies focuses heavily on individual users' personal requirements, rather than treating users as a group. However, in the area of pedestrian navigation of those without vision, I did not have existing domain theories for developing assessment tools for profiling individual differences. Nor did I have large amount of user data to train a probabilistic user model for tailoring the TAME tool towards end-users or personalizing tactile maps. In addition, the assistive technology device I chose to test is an application in development. Therefore, we need deep insights into users' experience and behavior when using these maps in situ. A case study approach, in this situation, allowed me to make close observations of user behavior and thus better understand their interaction with tactile maps.

Second, the environment-sensing study described in the previous section suggested that the virtual environment for each participant also needs to be tailored to the users' personal requirements related to using tactile maps in pedestrian navigation. The individual-centered case study methodology provides intensive observation that can lead to analysis of personal behaviors and performance that statistics fail to reveal. For example, the participants' facial expressions and body movements during navigation can indicate whether they were confused or disoriented. In contrast, these factors could not be easily identified by performance data such as navigation time and map reading time. The case study approach, therefore, facilitates the understanding of personal requirements for both the assistive technology (tactile maps) and the virtual environment where the tactile maps are tested.

Finally, the case study approach is much more logistically feasible than statistical studies with a big sample size, when participants belong to populations with disabilities. There is only a very limited population of people without vision locally in Eugene, Oregon. There are even fewer candidates that are able to read Braille and regularly navigate by foot independently in urban settings. This makes recruitment of subjects a particular daunting challenge for this project. Logistical problems such as transportation and weather conditions also add to the difficulties. Thus, a case study approach allows us to deal with the limited number of participants and provides the opportunity to develop in-depth understanding of subjects' behaviors and performance through direct observation of individual subjects during the experiments.

To improve the validity of the data collected, all the experiment tasks were videotaped for data analyses purpose. Performance data such as how many mistakes, participants made, how long participants spent on reading maps, were recorded. At the same time, researchers annotated participants' performance during the experimental process to provide documentation of participants that were non-explicit from performance data. After the participants finished their tasks, they were interviewed regarding the tasks and the maps they used.

6.2. Experiments

Our experiments examined the behavior and performance of four blind subjects. To make the subjects representative, this case study included two users canes and two users with guide dogs. For ease of reference, we called them P1, P2, P3, and P4 in the rest of the thesis. P1, a 57-year-old female cane user, was born with congenital glaucoma and lost all her vision at the age of 27. P2, a 58-year-old female cane user, lost his vision because of an accident and diabetes at the age of 27. P3 is a 63-year old female guide-dog user, and P4 was a 58-year-old female guide-dog user. Both P3 and P4 became blind soon after birth, because of Retinopathy of Prematurity (ROP). All participants are active pedestrian navigators and could walk independently for more than an hour and a half.

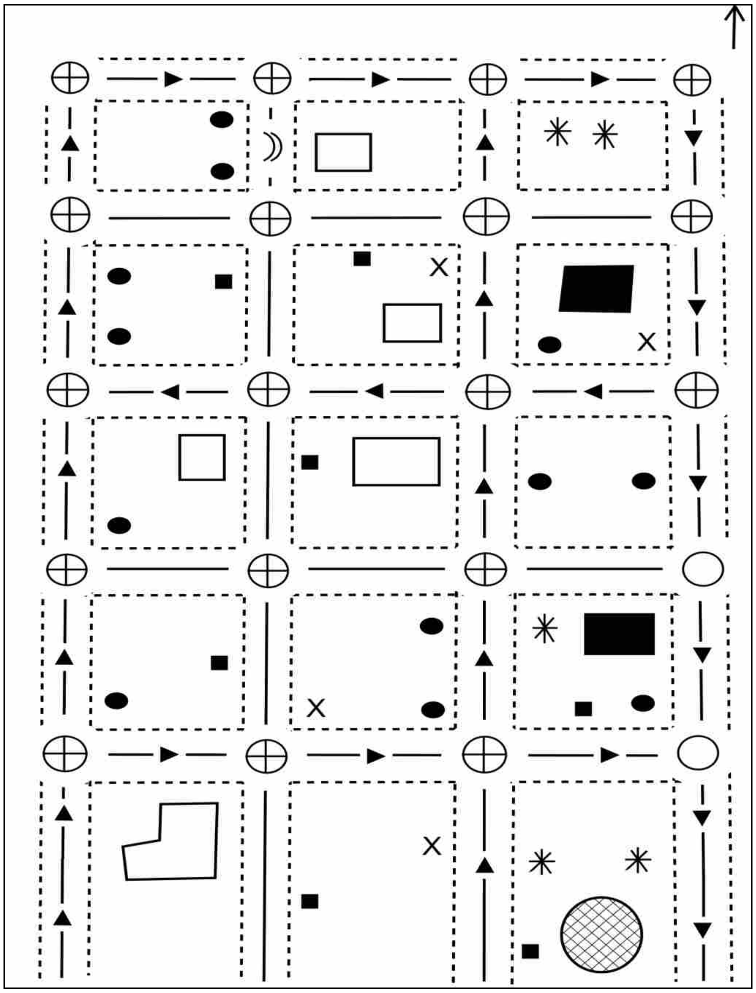


Figure 12. The tactile map used in the virtual trial. The arrow on the upper right indicates north. “X”’s stands for banks, small solid squares stand for bus stops, and small solid circles stand for food places.

The experiment consisted of two sessions for each participant: 1) a field trial where the user performed way-finding tasks in Downtown Eugene, Oregon with a tactile map; 2) a virtual trial where the user performed the task in the NAVE virtual reality application with the same tactile map. . Please see Figure 1 for the tactile map in field testing and Figure 12 for the tactile map for virtual testing. For each participant, the field trial happened before the virtual trial. The virtual reality setting was configured to match the area in Downtown Eugene used in the field trial, in terms of complexity, including physical characteristics, and the number and type of outstanding environment features encountered during the field trial. Both the field trial and the virtual trial consists of two parts: 1) the participants were given a tactile map with tactile symbol legends to study until they felt comfortable with the map; 2) participants performed way-finding tasks using the tactile map in the environment (either the physical or the virtual one). There were two researchers involved in the experiment sessions. One researcher was in charge of video-taping the experiment sessions, while the other one gave instructions and accompanied participants during their tasks.

In part 1) the participants first read tactile map symbol legends with braille descriptions, and then studied the tactile maps to get familiar with the tactile maps (see Figure 13 below for legends of tactile map symbols) before they started the experiment tasks. Participants' reading of legends and maps were video-recorded so that we could analyze their individual patterns of tactile map reading.

In these tasks, participants were first shown the destinations (restaurants, bus stops or banks on the tactile maps). After they understood what places they needed to look for and planned the routes, the participants started navigating to find those places in the environment.

Figure 13. Legends of tactile map symbols used in the experiment. From the top to the buttons are: bus stops, food places, bank, one way street, two way street, sidewalk, no traffic control, 4-way control, vegetation, general passageway, buildings, parking lots. The tactile maps used in testing were the one in Figure 1 for the field trials, and the one in Figure 12 for the virtual trials.

After reading the tactile maps, participants were asked to perform way-finding and route-following tasks with the help of the tactile maps. Restaurants, bus stops and banks were identified by participants in my preliminary studies as the places they visit most often in their pedestrian navigation in urban settings. Therefore, I chose finding these places with the help of tactile maps as the experiment tasks. As Table 1 below shows, both the field trials and the virtual trials had four rounds of tasks. In each session, a participant performed a given wayfinding task four times. The complexity of all other rounds increased with growing numbers of destinations to find and growing numbers of choice points along the routes. The field testing and virtual testing tasks were matched on their complexity. In the first round, the participant was asked to find one place for practice so that he (or she) could better understand the task requirements. After the practice round, the subject repeated the tasks in three rounds with increasing numbers of places to find – the first round consisted of 1 place, the second 4 places, and the third round 8 places. At the beginning of each round, participants were shown the tactile maps so they could identify their destinations and the best routes to reach them. After that, the maps were put aside. However, anytime during their navigation and wayfinding, participants could ask for the tactile maps for reference. Participants' wayfinding process and map-reading during the tasks were also video-taped. In the field trial sessions, one researcher always accompanied the participants during navigation to guarantee their safety, as well as to correct participants when they made mistakes such as going off the routes or crossing a wrong street. The researcher would also present tactile maps when requested. At the end of each session, participants were asked some survey questions regarding the tactile maps, and experiment tasks.

Table 1. Four rounds of wayfinding tasks in testing trials. Both the field testing and the virtual testing have four rounds with the same numbers of destinations to find as well as the same numbers of the choice points along the routes.

Round Number	**Number of Destinations to Find**	**Number of Choice Points on the Route to All Destinations**
1 (practice)	1	1
2	1	2
3	4	5
4	8	17

In the field trial session, participants studied the maps indoors in the foyer of the Eugene Public Library located downtown, and then were taken to the field to perform the tasks. After their finished, they were taken back to the library to answer the survey questions. The whole field trial took between one hour and two hours, depending how fast the participants navigated and finished all four rounds of their tasks.

For each participant, the virtual session was conducted at least one week after the field trial session to avoid the learning effect of the tactile maps and the experiment tasks – from our experience in a previous study of tactile map reading and route-following with the blind, we observed that participants could not remember details of the tactile map they studied during navigation several hours afterwards. For the virtual-environment trials, the participants were asked to finish the same way-finding tasks in a virtual world using the joystick and narrative environment cues under NAVE running on the researcher's laptop computer in the researcher’s computer lab, except for P3 the researchers brought the whole setup to her office for her convenience. As mentioned above, the virtual world simulated the urban setting of the Downtown Eugene area in the field trials, in terms of complexity and dynamic environment. The virtual trials followed the same pattern as the real-world trials: the participants first studied the destinations and routes on the tactile map, were oriented by the researcher when they felt ready, and then started their tasks. After the participants studied the tactile maps (with legends) and felt comfortable to start navigation tasks, the researcher started the virtual reality system, configured the participant’s user profile, and loaded the virtual environment corresponding to the field trials. The virtual environment welcomed the user and start speaking about the environment and the current choice point:

> “Welcome to the virtual tour. Please listen carefully to the system. It will provide information about the environment. This is the beginning of your trip! This is in the morning. It is a sunny day today. The wind is blowing from the west to the east. You are at an intersection. The street to your left is a one-way street going in the same direction you are facing. The street behind you is two-way.
> There are some buildings at the corner.”

As explained in Chapter V, textual descriptions of the virtual environment also appear at the bottom of the screen for the convenience of the researchers. In addition, the participant’s current orientation in the virtual environment, and the choice point number he or she has reached are shown at the top of the screen. After the researcher shows participants how to move and control text narration via the joystick, the participants started navigating the virtual environment and performed way-finding tasks with the tactile map. Participants had the very first task as a practice run so that they could get comfortable with controlling and navigating the virtual environment. They then performed the same set of tasks as they did in the field trial – see Figure 12 above. We also video-taped the virtual environment session and conducted an interview with the client after the tasks were completed.

CHAPTER VII

DATA ANALYSIS AND DISCUSSION

The experiments we performed were designed to investigate whether use of the virtual navigation environment can successfully replicate the use of field studies in testing assistive navigational aids. As the subjects performed the tasks described above, we observed the following through timing measurements, videotaping, and post-task interviews:

1. Useful tactile navigational symbols;
2. Total testing time;
3. Number of navigations errors;
4. Number of references to the tactile map;
5. Total map reading time (overall and per task).

If the virtual environment is successful at replicating the field environment, we would expect to see similar trends in success rates and error rates under both environments: participants' rank in these performance metrics would be consistent across field testing and virtual testing; in addition, we would see the same performance pattern regarding task complexity in both field testing and virtual testing – with the number of destinations to find increase, the number of map references and the total time on map reading will increase too. If the trends differ significantly, we would conclude that the virtual environment we designed falls short of its goal to substitute for on-the-street field testing.

We also looked at how these metrics varied between the following subgroups: guide-dog users and cane-users. Meaningful differences in task performance between these two user subgroups support our claim that deeper personalization is necessary when dealing with the disabled persons.

7.1. Useful Tactile Navigational Symbols

Users indicated in interviews after the trials that, in both testing settings, the tactile maps were very easy to read and that some of these tactile map symbols were helpful in acquiring spatial information and orientation in the experimental tasks. It is important to note that participants' choice of the most useful symbols for completing the wayfinding tasks were consistent between the physical environment and the virtual environment. Overall, the subjects identified as most useful the subset of symbols related to destinations and intersections. Other symbols, such as buildings and parking lots, were only mentioned sporadically or not mentioned at all during the interviews or testing trials. Table 2 below shows these symbols for each participant, which were same across field testing and virtual testing. We can see some difference among the subjects. It is not a surprise that all these symbols were directly relevant to their tasks. These data and observation supported our hypothesis in that participants seemed to use the same set of symbols from the tactile map for navigation and wayfinding tasks in both testing environments.

Table 2. Most useful tactile symbols for wayfinding tasks participants chose in interview after the testing sessions.

Participant	Most Useful Symbols
P1	street, sidewalk
P2	destination
P3	street, sidewalk, traffic control (intersection)
P4	traffic control (intersection), destination

7.2. Total Testing Time

Figure 14 above shows that the total amount of time spent in testing in the physical environment was significantly greater than that in the virtual environment. Although such difference varies among participants, on average the total time of the whole testing session including the training task in the field is about 38.9% longer than the total time for the virtual trial average. This can easily be explained by the fact that movements in the physical environment (actual walking) took much longer than those in the virtual environment (virtual movement controlled by maneuvering the joystick). In addition, the field trials were somewhat a challenge physically for these participants who were all over 57 years old, possibly magnifying the difference between field trial times and virtual trial times (compared to a younger set of subjects).

Figure 15 which shows the percent decrease in testing time when comparing field testing to virtual testing is more interesting. While the magnitude of decrease varies, the trend is consistent across all four subjects indicating that virtual testing takes less time than field testing. Again while not surprising, the consistent decrease in total task time supports the utility in using the virtual environment to shorten training time for blind subjects.

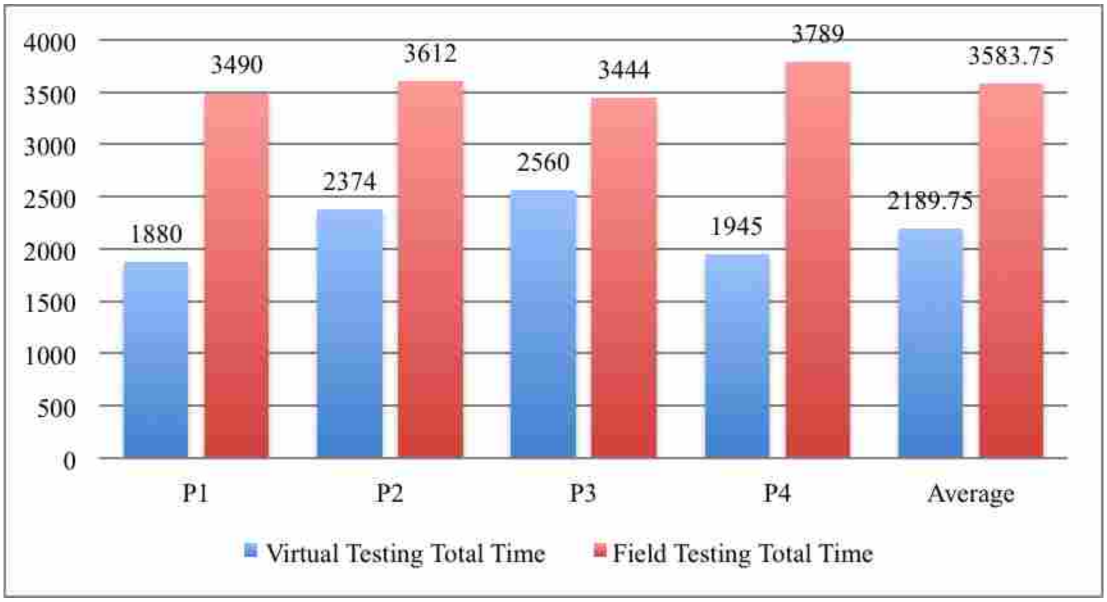


Figure 14. Total time spent on testing in field testing and virtual testing.

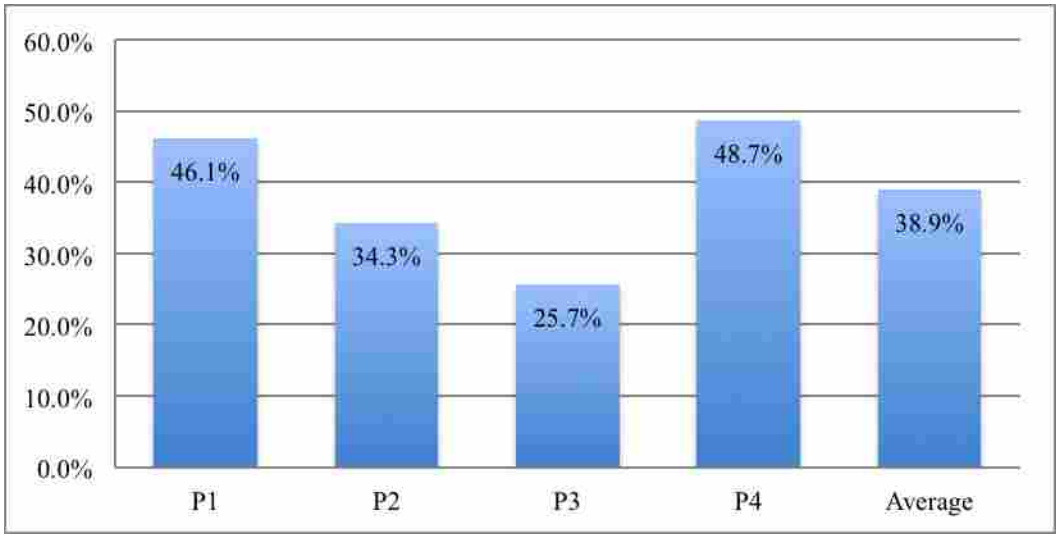


Figure 15. Percentage of decrease of testing time from field testing to virtual testing.

7.3. Detailed Performance Metrics

In addition to the observations described above, more detailed performance measurement were used to analyzing participants' performance including: 1) how many mistakes were made in the trials, defined as wrong movements (going forward, turning, going backward, and crossing intersections), loss of orientation, and mistakes in recognizing destinations; 2) how many times users referred to the tactile maps; 3) how long users read the tactile maps. These data were compiled by combining video-analysis and researcher observation during the trials. Figure 16 shows the total number of mistakes in testing, Figure 17 shows the total number of map references in testing, and Figure 18 shows the total time spent on map reading in testing trials. Figure 19 shows map reference times by task round, and Figure 20 shows total time spent on map reading by task round. We discuss these results below and in subsections 7.4.

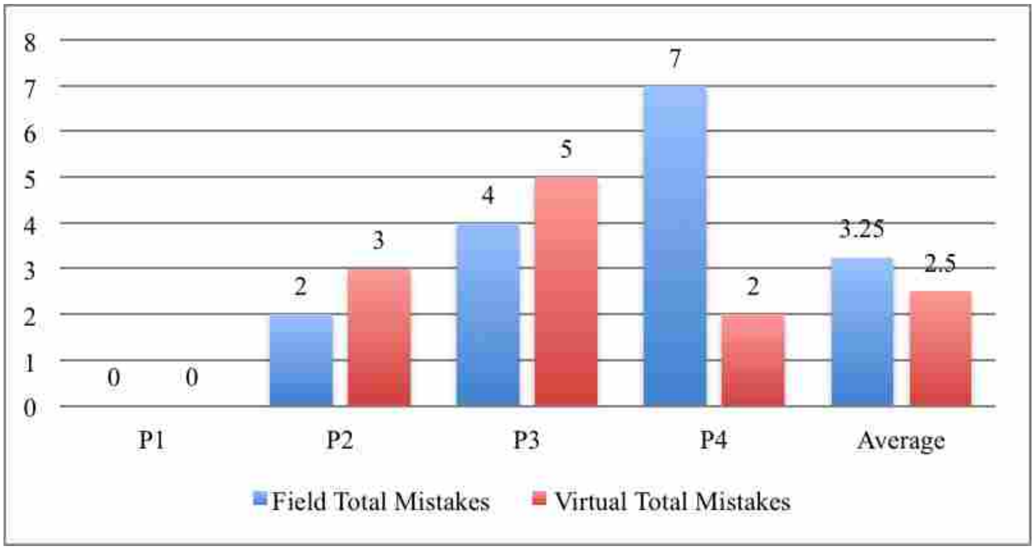


Figure 16. Total Number of Mistakes in testing.

In our experiments, we particularly looked at the impact of varying task difficulty upon participants' performance, as described in the previous chapter. Figure 19 below shows a consistent trend for all four participants: the greater the number of destinations to find, the greater number of map references. This trend holds true for both field testing and virtual testing. Similarly, Figure 20 shows that the total time spent on reading maps also increased with the increase in task complexity, i.e. numbers of the places to find, across both the field trial and the virtual trial.

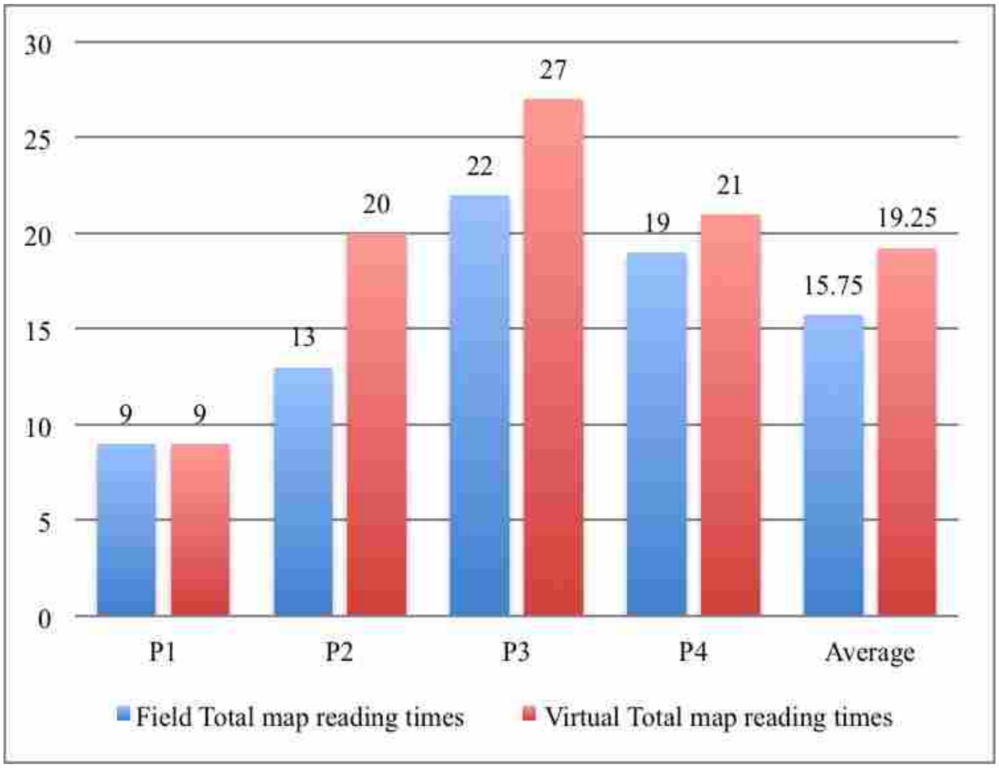


Figure 17. Total number of map references in testing.

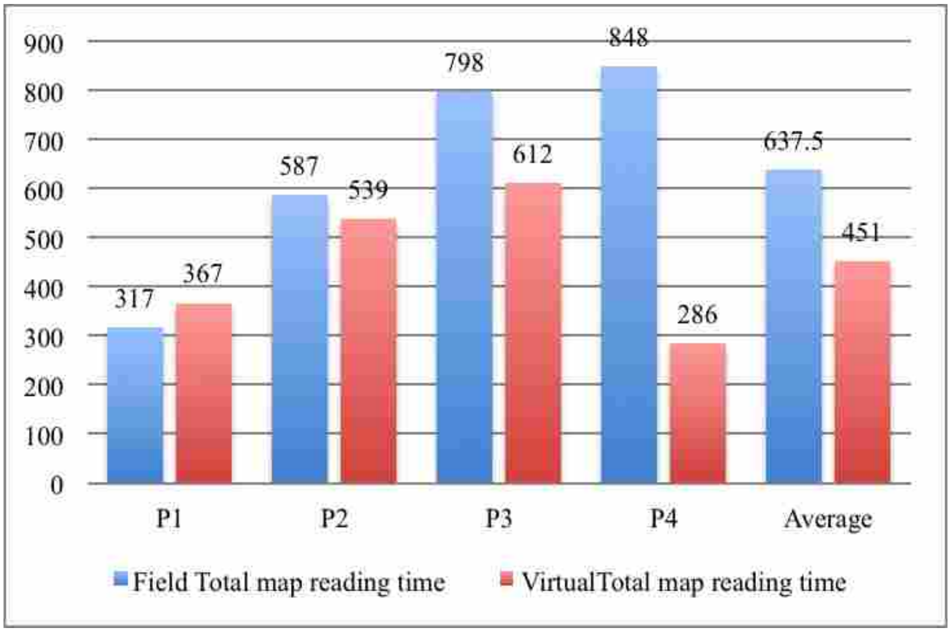


Figure 18. Total time spent on map reading.

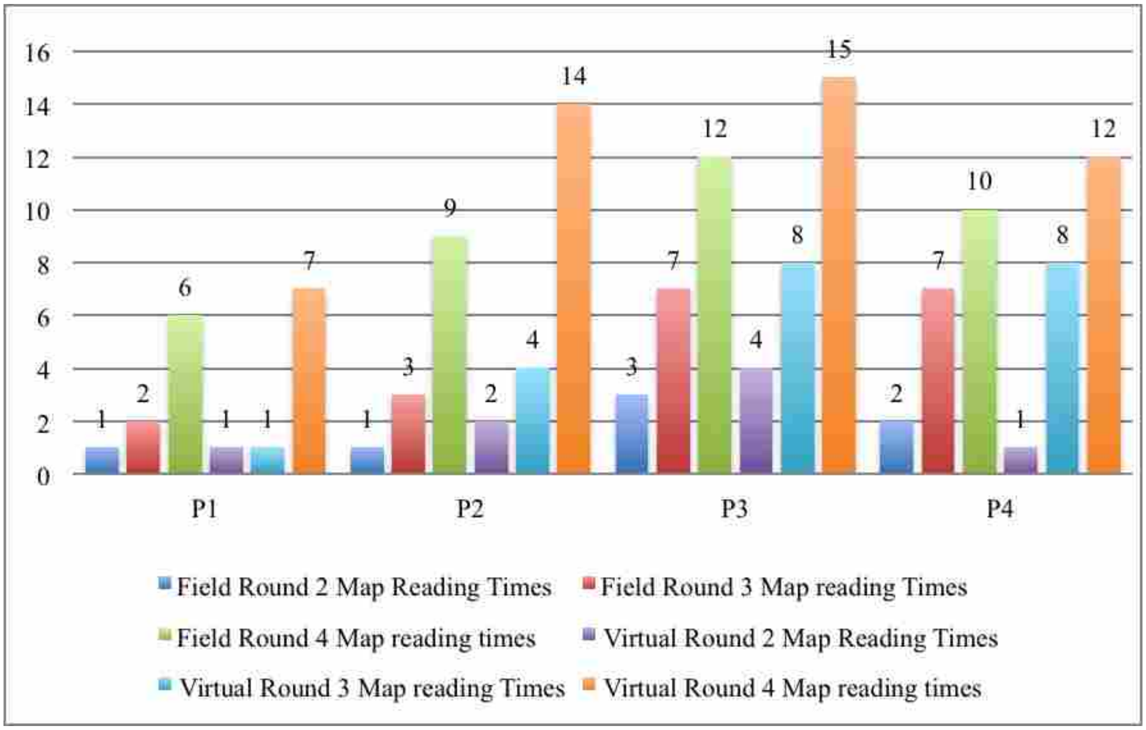


Figure 19. Map reference numbers by task round.

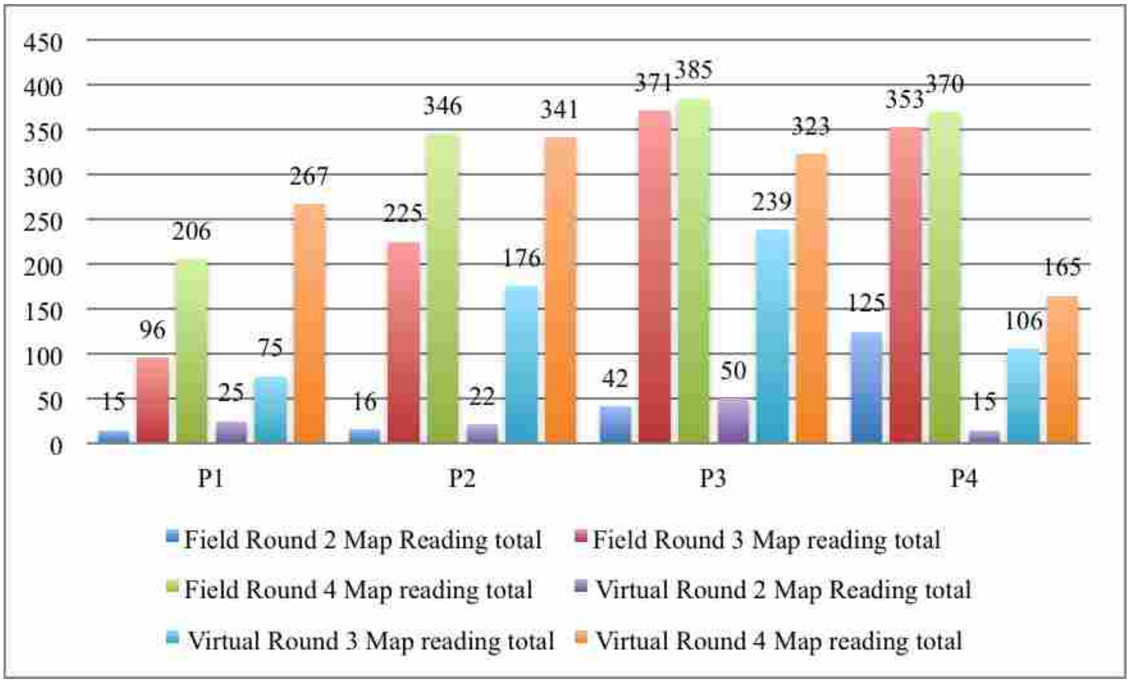


Figure 20. Total map reading time by task round.

7.4. Individual Differences among Participants

One significant finding is that users showed great variance in their performance and behavior in testing, and many of such differences were consistent across both testing environments. Figure 16 showed that participants' mistakes ranged from 0 to 7 in field testing, and 0 to 5 in virtual testing. In Figure 17, the number of map references ranged from 9 to 22 in field testing, and 9 to 27 in virtual testing. Figure 18 showed that total map reading time ranged from 317 seconds to 848 seconds in field testing, and 286 seconds to 612 seconds in virtual testing.

P1 was the best performer in all aspects. Figure 14 shows that P1 made fewest mistakes (in fact no mistakes), and made fewest map references (9 times) in both field testing and virtual environment. As for average map reading time of each map reference, we did not identify a pattern related to navigation mistakes – P1 did not spend shortest or longest time on map reading among all 4 participants. This indicates that map reading for each map reference is probably not a good indicator of performance – a person could read the map too fast and ignore some details important for their wayfinding tasks, while another person could spend long time reading map because he is lost or confused.

P2 made fewer mistakes and map references than P3 in both field testing and virtual testing. P2 also made few fewer map references than P4 in both settings, and he made few mistakes than P4 in field testing. P4 was separate from all other participants in that she performer poorly in field testing (in terms of number of map references and mistakes), but she performed very well in virtual testing. P4's good performance was probably due to her regular usage of a similar text-based virtual environment on her computer at home.

The variance of performance metrics among participants supported our assumption that there existed individual differences in spatial abilities and navigational skills among blind users of tactile maps. In addition, the data supports our hypothesis that navigational behavior and performance in virtual testing matches up with those under the virtual testing. The most useful symbols participants chose in the interviews after testing also supported these two points.

Another obvious similarity in user behavior involved the participant P2 who spent very little time reading the map before the experiment tasks in both the field testing and the virtual testing. She also had trouble with orientation during navigation. In the field trial, she explicitly asked the researcher to rotate the map for orientation purpose each time she read the tactile map. In the virtual trial, she made several mistakes in orientation. In occasions where she did not make mistakes, it was obvious that she needed some efforts on orientation – she explicitly repeated to herself her current orientation and the orientation to turn to while reading the tactile map in the virtual session.

7.5. Comments from the Subject Interviews

The interviews after testing trials showed that all participants agreed that the tactile maps were easy for them to read, and the map layouts did not contain too many symbols (See Appendix A for detailed information). This was consistent with the performance data discussed earlier in this chapter.

Some more interesting comments came from the worst performer P4 and the best performer about comparing the virtual environment testing and the field testing. P4 felt the experimental task was easier in the virtual environment, because

> "[T]actile maps are a lot easier to use with the virtual environment: there was less distraction in the virtual environment when the traveling time is much shorter from one end of the block to the other – I don't need to do much thinking."

She also mentioned during the interview that she used a program from Sendero at home to virtually explore an unfamiliar area in advance before travelling. The "Virtual Explore" software [Sendero] requires the input of GPS coordinates and allows users to understand street layouts and points of interests within a given radius near the input location. This explained the result that P4 made much fewer mistakes in virtual testing than in the field, and that her number of references (21 times) to the map in virtual testing was above average (19.5 times), but her total map reading time (286 seconds) in virtual testing was significantly bellow average (451 seconds). She also commented that the tactile maps would benefit from the addition of Braille street labels. These comments were consistent with P3's comments that the tactile maps were clumsy to carry and use during travelling, and that it would be more useful to learn about layout of an area at home before travelling.

The best performer P1 had a different comment on the virtual environment. She suggested it would be very important for users to be able to turn on or off the audio narrative of environmental information when desired. "[T]he VE sometimes provides too much information and will make [her] confused" because the textual narration may be too long and she could forget what she wanted to do during listening.

The differences between these participants on their performance and feedback on the tactile map testing in the NAVE supported our hypothesis that the virtual environments need personalization. In addition, users' comments showed more dimensions in which to further personalize the virtual environment.

In conclusion, our experiments showed that the virtual environment was useable by the participants to test the tactile maps. In addition, this positive result indicated that users were able to receive environmental information through textual narration in the NAVE virtual environment used in this study. Furthermore, this experiment supported our hypothesis that the virtual environment need to and could be tailored in sensing information towards users' individual differences, and demonstrated that the personalized context of NAVE based on participants' sensory information was effective. In addition, the virtual environment setup made it easy to run the testing – the artifacts were portable and therefore the testing could be easily run at locations convenient for participants. The virtual testing also saved significant testing time. All this demonstrated that virtual testing could the logistical problem of testing for the population with disabilities.

CHAPTER VIII

CONCLUSION AND FUTURE WORK

This thesis integrates two important software engineering models (the PC-RE model and the Agile Development Model) and applies them to the development of assistive technologies for populations with special needs. The PC-RE model provides a conceptual framework for personalization of applications such as assistive technologies. However, deep personalization in the PC-RE model assumes accurate assessment of user profiles, which is often not available for assistive technologies due to lack of domain theory support. During our application of the PC-RE model in navigational aids for those with traumatic brain injury and those without vision, we found our approach was more towards the Agile Model that used trial-and-error method to find the best fit. However, the agile approach requires frequent and incremental testing to provide user feedback. As we demonstrate in the specific domain of navigational assistive technologies for populations with disabilities, this is a daunting challenge, because 1) it is very difficult if not impossible to control field testing environments (e.g. weather conditions and road construction); 2) it is difficult logistically to conduct field testing with special populations due to limited availability of these subjects as well as concerns for their safety. To overcome these problems, we proposed the testing of assistive technologies in virtual environments as an alternative to field studies, especially in frequent incremental testing as required by the agile software development model. In addition, as the PC-RE model suggests, we showed we were able to configure the VE to have a personalized context for each individual user according to individual user profile of environment sensing. In addition, these individuals were able to successfully perform navigation and wayfinding tasks in such personalized virtual environment.

In this dissertation, we applied the PC-RE and agile software development models to the development of navigational aids for the blind. More specifically, we focused on for those with visual impairments based on our study that demonstrated that tactile map production has strong requirements for personalization and frequent incremental user testing. We worked with cartographers in our research group to develop personalized tactile maps with new tactile symbols for urban settings as the assistive technology for testing. We chose testing personalized tactile maps integrated with new tactile symbols as a case study to investigate our hypothesis that a virtual environment, which meets the demand for deep personalization and agile development, can substitute for field testing.

Our contribution to deep personalization lies in our investigation of the question: what personalized sensory information is needed for setting up the virtual environment? We studied environment-sensing needs through talk-out-loud field sessions with members of the blind population in a user study that differentiated individual's environmental sensing in pedestrian navigation. We found that when placed in the same physical environment, individuals differed in the types of sensory information each used to navigate. This led to our refinement of the PC-RE model to include a new dimension of personalized context to more accurately model the interaction between the physical and social context and individuals' skills and abilities (Level 2 in the classic PC-RE model). We observed individual differences in their usage of sensory information for navigation. Then we used the list of sensory information individuals used in their navigation and their order to personalize the NAvigation Virtual Environment, our text-based narrative style virtual environment for navigation for those without vision.

We conducted a series of navigational tasks using tactile maps with a group of blind subjects in both the field trials in Downtown Eugene, Oregon and using the NAVE virtual environment. Our experiments demonstrated that we could easily configure the virtual environment to suit individual users' personal environment-sensing skills (i.e., agile personalization of NAVE for individual blind users as the personalized context in our refined PC-RE model). By comparing wayfinding performance through close observation of participants' behaviors in both field trials and the virtual trials, we found that performance and behavioral patterns during wayfinding tasks with tactile maps matched up well between field testing versus the virtual environment. Overall, the two testing environments were consistent with respect relative task completion time, useful tactile symbols, number of navigational errors, number of references to the tactile maps during navigation, and total map reading times. Furthermore, we observed consistency of wayfinding performance for individual participants. These results support our hypothesis that testing of assistive technologies in a virtual environment can be useful to replace field testing. We believe this positive result will encourage greater use of virtual reality technology in assistive technology development where deep personalization, early user involvement, and frequent user testing is critical for the assistive applications to be effective. This will eventually help bring the PC-RE model, the conceptual framework, and the Agile Development Model, the operational model, together for developing effective personalized assistive technologies.

Our work also helped us identify areas for future investigations. We did not identify scenarios where there were obvious performance and behavioral mismatches in the virtual trials and the physical trials, which we would also expect from our hypothesis. A closer look at the data did reveal that participants made a few more references to tactile maps during the virtual trials, and some of these occurrences of map reading were not due to confusion, but rather because participants wanted to confirm the current position or orientation. In general, we need to conduct additional experiments with a focus on uncovering mismatches or inconsistency in performance in the two environments.

We also found indications where deeper personalization analysis can guide the direction of assistive technologies. Two users commented that the tactile maps were bulky to carry and clumsy to read in field testing. This might also explain why read the maps less often during field testing than in virtual testing where they did not also need to carry their canes or hold their guide-dogs. This lead us to consider a future study that replaces tactile maps with more convenient assistive technologies such as mobile devices for use in the field, so that users can access the devices with equal ease regardless of their personal characteristics. Our future work would then compare testing in the virtual environment with field studies using these more convenient mobile devices.

Another important extension of our comparison between field testing and virtual testing is to utilize a wider range of urban settings, and with greater variance in movement granularity discussed in Chapter IV. That may lead to identification of occasions where performance and behaviors of virtual testing fails to match well with those of field testing.

Overall, if our work is extended to broader types of navigation tasks and navigational environments, we may be able to further validate the effectiveness of virtual environment testing, and thus more fully bridge the gap for incremental testing between the PC-RE model and the Agile development model for assistive technologies, as well as bring the use of virtual testing environment to the forefront for use in the safe and economic testing if assistive technologies for disabled populations.

APPENDIX

INTERVIEW QUESTIONS AND PARTICIPANT ANSWERS

1. Interview Questions:

1. Is the tactile map easily to read ?

   Strongly disagree (1) Disagree(2) Not sure(3) Agree(4) Strongly agree(5)

2. Does the tactile map have too many symbols for you?

   Strongly disagree (1) Disagree(2) Not sure(3) Agree(4) Strongly agree(5)

3. Which symbols are most useful for your tasks?

4. What do you like most of the map?

5. What environmental cues did you use for your task? List in the order of importance

6. Open comments?

2. Participant Answers

2.1. P1 Answers after Field Testing

1. Strongly agree (5)
2. Strongly disagree (1)
3. Street, sidewalk
4. Symbol legends, they are helpful to explain what is on the map.
5. Sidewalk/ramp, sound of traffic, smell of foods, traffic patterns (straight lines), sunshine, tactile signals (restaurant matt, furniture, bus stop poles etc.)
6. The map is too clumsy to carry.

2.2. P1 Answers After Virtual Testing

1. Strongly agree (5)
2. Strongly disagree (1)
3. Sidewalk and street
4. Tactile symbols and legends
5. Sun and wind (used for orientation), traffic direction (one way, two way)

6. The virtual environment provides same information about environment as mobility training I received. However, the VE sometimes provides too much information and will make me confused, and I need to turn them on or off as I like to.

2.3. P2 Answers After Field Testing

1. Agree (4)

2. Disagree(2)

3. Destination symbol, sidewalk

4. Clarity of layout, location of things, and orientation symbol.

5. Sidewalk, edging, direction of traffic at corners, curbs, ramps.

6. Tactile presentation will be very helpful for totally blind cane users.

2.4. P2 Answers after Virtual Testing

1. Strongly agree(5)

2. Disagree (2)

3. Target symbols, and sidewalk symbols

4. Traffic control symbols on the map

5. Sunshine, description of passed objects, position (relevant to traffic), wind (not quite reliable in real life).

6. Map orientation and object relations are very interesting. The virtual environment is similar to field trial: the map helps me figure out orientation at each decision point.

2.5. P3 Answers after Field Testing

1. Agree (4)

2. Disagree (2)

3. Street, sidewalks, traffic control (intersections)

4. Clear layout

5. Sunshine, sounds and traffic noise, smell

6. The tactile maps will be good for studying areas in advance, but are awkward to carry in travelling.

2.6. P3 Answers after Virtual Testing

1. Agree (4)

2. Disagree (2)

3. Street, sidewalks, traffic control (intersection)

4. I like street designation, one-way, and traffic control symbols most.

6. Street direction, sunshine and wind, landmarks (e.g., parking lot)

7. Tactile maps were useful for studying the area in advance. The virtual environment is particularly useful in this point, I can try the map out and have a better sense what are out there in the area.

2.7. P4 Answers after Field Test

1. Strongly agree (3)

2. Strongly disagree (1)

3. Traffic control (intersections), sidewalks

4. Traffic control symbols, clear layout of the map

5. Sound, parking lot, traffic flow, nearness to intersection, location on the block

6. Sometimes it is confusing, and it is hard to tell which streets things are on. The map needs Braille labels, and I preferred to it use with other tools, such as virtual reality exploration at the same time at home first so that I could have an idea of where things are in advance.

2.8. P4 Answers after Virtual Testing

1. Strongly agree (4)

2. Strongly disagree (1)

3. Traffic control(intersection), destination symbols

4. When I used the map, there were no distractions in virtual environment. I found it find much harder in real environment.

5. Direction of streets (including traffic information), intersection, landmarks (buildings and others)

6. Some tasks were too complicated, and I need to break down them to smaller ones. Tactile maps are a lot easier to use with the virtual environment: There was less distraction in the virtual environment when the traveling time is much shorter from one end of the block to the other – I don't need to do much thinking. Street labels in Braille would be really helpful on the maps.

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