Socio-Technical Environments Supporting People with Cognitive Disabilities Using Public Transportation

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Public transportation systems are among the most ubiquitous and complex large-scale systems found in modern society. For those unable to drive, such as persons with cognitive disabilities, these systems are essential gateways for participation in community activities, socialization, and independence. To understand the magnitude and scope of this national problem, we highlight deficiencies identified in an international study by the Transportation Research Board of the National Research Council, and present specific cognitive barriers identified in empirical studies of transportation systems in several U.S. cities.

An interdisciplinary team of HCI researchers, urban transportation planners, commercial technologists, and assistive care specialists are now collaborating on the Mobility-for-All project to create architectures and prototypes that support persons with cognitive disabilities and their caregivers. We have grounded our research and design efforts using a *distributed cognition* framework. We have derived requirements for our designs by analyzing "how things are" for individuals with cognitive disabilities who learn and use public transportation systems. We present a socio-technical architecture that has three components: a) a personal travel assistant that uses real-time Global Positioning Systems data from the bus fleet to deliver just-in-time prompts; b) a mobile prompting client and a prompting script configuration tool for caregivers; and c) a monitoring system that collects real-time task status from the mobile client and alerts the support community of potential problems. We then describe a phased community-centered assessment approach that begins at the design stage and continues to be integrated throughout the project.

This research has broad implications for designing more human-centered transportation systems that are universally accessible for other disenfranchised communities, such as the elderly or non-native speaker. This project presents an "in-the-world" research opportunity that challenges our understanding about mobile human computer interactions with ubiquitous, context-aware computing architectures in noisy, uncontrolled environments; personalization and user modeling techniques; and the design of universally accessible interfaces for complex systems through participatory design processes.

This paper provides both a near-term vision and an architecture for transportation systems that are socially inclusive, technologically appealing, and easier for everyone to use.

Keywords

cognitive disabilities; complex, socio-technical systems; public transportation system; human-centered transportation; mobility agents; active distributed support systems; distributed cognition; participatory design; universal design; context-aware computing; ubiquitous and pervasive computing; prototyping; assessment; user models; dual use technologies.

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1 INTRODUCTION

Few systems in society rival the ubiquity and complexity of modern public transportation systems. In many urban areas, public transportation is accepted as a preferred transportation alternative for commuting to work, performing errands, or traveling for social events. But for certain members of society, including 15 million Americans with cognitive disabilities (including developmental disabilities, traumatic brain injury, stroke, and Alzheimer's) [Braddock et al., in press] and the growing elderly population who may no longer drive, these systems represent *the only viable option* to live independently, socialize, or hold a steady job. This presents a perplexing dilemma: in order to have the freedom to live independently, socialize, or hold a job, one must be able to understand and navigate cognitively complex systems.

Over the past 35 years, a social movement has quietly taken place as people with cognitive disabilities moved from institutions to public schools and community living settings [Braddock, 2002]. In recognition of these changes, the Americans with Disabilities Act (ADA) was passed on July 26, 1990 to encourage integration and eliminate discrimination against individuals with disabilities in critical areas including employment, housing, transportation, recreation, health services, and access to public services [ADA, 1990].

More specifically, Section 222 of this legislation states:

> "… it shall be considered discrimination … for a public entity which operates a fixed route system to purchase or lease a new bus, a new rapid rail vehicle, a new light rail vehicle, or any other new vehicle to be used on such system … if such bus, rail vehicle, or other vehicle is not readily *accessible* to and *usable* by individuals with disabilities …." (emphasis added) [DOL, 2002]

Accessibility and usability shortcomings in current transit systems are often remedied with fleets of "special access" vehicles that supplement mainstream mass transit systems. These vehicles are necessary for those with significant physical restrictions, yet people *without physical limitations* also use these systems when they cannot understand mainstream systems because of cognitive disabilities. When used in this way, persons with cognitive disabilities and their caregivers face unnecessary constraints and costs including advanced reservation lead times, additional fees, and the loss of flexible ad hoc travel available to mainstream users. These systems also separate users from mainstream experiences and prevent societal integration intended by the 1990 ADA.

2 DISTRIBUTED COGNITION: A CONCEPTUAL FRAMEWORK FOR DESIGN-FOR-ALL

In most traditional approaches, *human cognition* has been seen as existing solely 'inside' a person's head, and studies on cognition have often disregarded the physical and social surroundings in which cognition takes place. The fundamental assumptions underlying our research are: (1) *distributed cognition* provides an effective theoretical framework for understanding what humans can achieve and how artifacts, tools, and socio-technical environments can be designed and evaluated to empower humans beings and to change tasks; and (2) applying this framework to people with *cognitive disabilities* in design-for-all approaches creates new unique challenges, and in return will create a deeper understanding of distributed cognition.

The theory of distributed cognition [Fischer, 2003a; Hollan et al., 2001; Hutchins, 1994; Salomon, 1993] provides an effective conceptual framework for understanding human-computer interaction, including a fertile framework for designing and evaluating artifacts specifically for the cognitively disabled. In distributed cognition theory, cognition involves mental processes and representations in the mind as well as cognitive artifacts (e.g. landmarks) located in the environment [Carmien et al., 2004]. This involves interpreting knowledge in the world and integrating it with knowledge in the head [Norman, 1993]. Even people without disabilities *sometimes* have problems interpreting their surroundings; people with disabilities *often* have this problem. Our approach is to develop *context-aware socio-technical systems* [Dey et al., 2001] that interpret knowledge in the world and can then present *"the 'right' thing at the 'right' time in the 'right' way for the 'right' person"* [Fischer, 2001b].

Information Prosthesis: Minds are Improvable. Anatomy and cognitive abilities are not destiny — an important intellectual or philosophical grounding of this mission is provided by Postman [Postman, 1985] *"The invention of eyeglasses in the twelfth century not only made it possible to improve defective vision but suggested the idea that human beings need not accept as final either the endowments of nature nor the ravages of time. Eyeglasses refuted the belief that anatomy is destiny by putting forward the idea that our minds as well as our bodies are improvable!"* The observation that "our minds are improvable" [Bruner, 1996] through media and technologies has led to the following research objectives for the Cognitive Levers project [CLever, 2003; Gorman et al., 2003]:

- exploring the design implications of the assertion that the cognitive abilities of all of us are limited—the most convincing example is provided by the limitations of our memories that were addressed by the invention of reading and writing [Goody, 1968]; and
- developing computational media that provide unique opportunities to "improve our minds" (and especially the minds of those of us who have a cognitive disability) leading to fundamental research challenges in distributed cognition, informational prosthesis, and media as extensions of humans [Engelbart, 1995; McLuhan, 1964].

In design-for-all [Newell & Gregor, 1997], the standard tool sets often fail because people with disabilities are lacking the cognitive requirements to use the tools. More than "alterations" to existing tools that were developed for people without disabilities are needed, namely tools and socio-technical environments explicitly designed and developed for the unique abilities of people with cognitive disabilities.

As the Clever project began to explore ways to develop socio-technical environments for people with disabilities and their support communities, we found it useful to develop a scenario [Gorman et al., 2003] that provided an overarching vision. This scenario describes several prototypes that together provide a comprehensive solution involving research in:

- **social network support tools** for caregivers [dePaula, 2004];
- **evaluation and recommendation tools** to match technology solutions to users' needs [Kintsch & dePaula, 2002];
- **task support tools** for people with limited memory and/or executive functions; [Carmien, in Press; Carmien et al., 2003];
- **customization tools** to allow caregivers to personalize assistive technology (e.g., see Figure 6) [Carmien, 2003; Carmien, 2004; Carmien, in Press];
- **mobility agents** to assist people to use transportation systems (e.g., see Figure 5) [Fischer & Sullivan, 2002a]; and
- **distributed monitoring and support tools** for caregivers providing remote client assistance (e.g., see Figure 7) [Carmien et al., 2003; Gorman, 2003].

This paper focuses on the latter three research themes and specifically the development of an architecture that allows distributed cognition to be leveraged in socio-technical environment [Fischer et al., 2004].

3 COGNITIVE DISABILITIES: UNIQUE CHALLEANGES FOR HCI

The Diagnostic and Statistical Manual of Mental Disorders (DSM-IV) [American Psychiatric Association. Task Force on DSM-IV., 2000] defines a person with cognitive disabilities as one who is "significantly limited in at least two of the following areas: self-care, communication, home living social/interpersonal skills, self-direction, use of community resources, functional academic skills, work, leisure, health and safety". It classifies four different degrees of cognitive disability: mild, moderate, severe, and profound. Eighty percent of people diagnosed with cognitive disabilities have mild disabilities. Another 14% have moderate to severe delays. Cognitive disabilities, and more specifically mental retardation, results from a variety of developmental etiologies including Down's syndrome, certain genetic disorders, birth defects, and some people with cerebral palsy and autism spectrum disorders. Other cognitive disabilities result from acquired disorders such as Alzheimer's, and dementia.

There is a dilemma that each individual with a disability represents a "universe-of-one" [Fischer, 2001b]. Just as there is no such thing as the average person [King, 2001; Norman, 1990] there is no typical cognitive disability. Many disorders are best described as a spectrum, and there are varying degrees by which a person may be affected. Furthermore, a person with disabilities often experiences multiple disabilities that together interact with individual personality traits in a way that creates a truly unique and ever changing condition or universe-of-one. While universal usability argues that technology should be designed for all, the larger context in which a person with disabilities lives, as well as her or his abilities and disabilities, make each person unique.

Designing technologies to support persons with cognitive disabilities provides a challenging environment in which to study fundamental human-computer interactions with new interactive media in open, dynamic environments. At a global level, this represents a multi-tiered "proxy design" problem:

- end-users may not be able to articulate *what they want or need*;
- communities who are able to articulate what *should be designed* (i.e. caregivers and family members) are usually not the same communities who create the needed technologies; and,
- communities who know how to develop, select, or customize technical systems are usually unable to offer this service directly to end-users.

4 HUMAN CENTERED PUBLIC TRANSPORTATION SYSTEMS

Mobility is a basic human need and transportation systems of all kinds have been developed to satisfy this need. Public transportation systems are among the most ubiquitous and complex large-scale systems found in modern society. For those unable to drive (e.g., the cognitively disabled or the elderly), these systems are essential gateways for participation in community activities, socialization, and independence. To use current public transportation, it is necessary to comprehend, manipulate, and process *essential navigation artifacts* (i.e., maps, schedules, landmarks, labels and signs, and clocks) [Lynch, 1960] encoded often in compact and efficient representations. Because of their generality, these navigational artifacts create cognitive burdens for travelers who are only interested in a small fraction of the information presented.

In collaborations in our Mobility-for-All project [Sullivan, 2004] with assistive technology specialists, urban designers, and technology researchers, we have identified the following needs and opportunities for making public transportation systems better serve the needs of people with disabilities [Fischer & Sullivan, 2002a]:

- to reduce the complexities of the current systems with the powerful role of technology as a social medium for socialization, independence, and self-worth;
- to support both users with cognitive disabilities and their support communities;
- to move beyond "one size fits all" solutions based on "the average user myth" for all users in all situations [Fischer, 2001b]; and,
- to exploit the emergence of ubiquitous, location-aware, mobile technologies to deliver personalized information tailored to individual needs and abilities [Fischer et al., 2004].

To explore solutions to these problems, an interdisciplinary design consortium has been assembled to design, build, and evaluate socio-technical architectures and prototypes for mobile travelers with cognitive disabilities and their caregiver communities. Project participants include:

- **Academic and research institutions**: (1) the *Center for LifeLong Learning and Design [L3D, 2004]*, a multi-disciplinary research center that studies the design of intelligent systems that serve as amplifiers of human capabilities; and (2) the *Coleman Institute for Cognitive Disabilities* [Coleman] at the University of Colorado, which supports computer science and information technology initiatives to address issues and challenges faced by people with cognitive disabilities and their families.
- **Organizations that prepare those with cognitive disabilities for independent living:** (1) assistive technology specialists from Boulder Valley Public Schools [BVSD, 2004]; (2) state-level assistive technologists including Colorado Assistive Technology Partners [ATP, 2004]; and (3) Imagine! Colorado [Imagine!Colorado, 2004], a community-based assisted living non-profit organization.
- **Transportation organizations:** including state, regional, city and campus transportation leaders, planners, and managers.
- **Industry participants:** (1) Intuicom, Inc. [Intuicom, 2003] a manufacturer of high-precision mobile Global Positioning Satellite (GPS) equipment for public transit vehicles for local and state buses; (2) AgentSheets, Inc. [AS, 2004] an agent-oriented software company formed from an L^3D research initiative; (3) Communication Arts [CommArts, 2004], an urban design firm responsible for international public transportation system designs.

4.1 Social Relevance

In 2001, the Transportation Research Board (TRB), a research unit of the congressionally mandated National Research Council, issued a report on "Communicating with Persons with Disabilities in a Multi-modal Transit Environment" [TRB, 2001]. The TRB report surveyed transportation system operators in nineteen major North American transit agencies to identify the "systems, technologies, and practices for communicating with persons with disabilities." A major goal of this study was to identify widespread problems that prevent people with cognitive disabilities from learning and using mass transit systems.

The most common problems identified by the TRB report included:

- reading and understanding directions;
- accessing the correct vehicle;
- exiting at the correct station or stop; and
- understanding operator announcements.

4.2 Understanding How Things Are

Our team used the design methodology seen in Figure 1 to understand the low-level cognitive barriers in transportation systems. We conducted two pilot studies observing people learning and using public transportation systems to understand "how things are." The first study surveyed six major public transportation systems in the United States. This survey focused on the navigation behavior of travelers and the information artifacts that they used. The second study observed students with cognitive disabilities learning to ride the bus. Based on our findings and research in the literature, we developed research hypotheses regarding the cognitive skills, knowledge, and artifacts required for the task of using public transportation. These provided a context for the design of socio-technical architectures and prototypes [Ehn, 1989] that instantiate "how things could be."

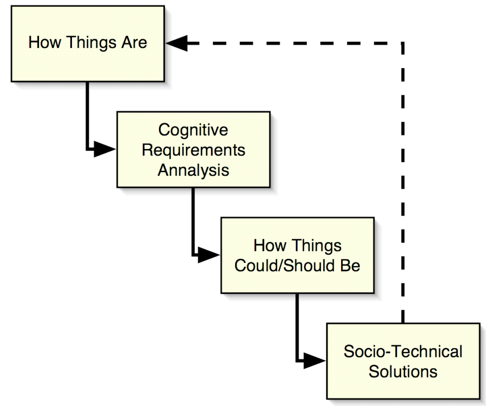

Figure 1: Research Methodology

4.2.1 Survey of six major transportation systems

We began with a survey of existing bus, light rail, subway, and transportation information technologies. The goals of this study were to (1) observe how travelers actually used these systems (2) better understand existing structures, constraints and technologies within these large-scale infrastructures, and (3) identify specific cognitive barriers to be addressed by socio-technical architectures and prototypes. By focusing on users' navigation behavior and use of information artifacts, we hoped to gain a perspective that was complementary to the high-level TRB study which collected survey data from transportation system operators.

Our study considered bus, light rail, and subways in five major cities (Denver, Milwaukee, Chicago, Washington DC, and Tokyo). We also analyzed a "next generation" bus system (Vail, Colorado) that employs mobile Global Positioning Systems (GPS) with dynamic digital data displays at each bus stop to provide real-time estimates for arrivals.

System-provided navigation artifacts (see Figure 2) were identified throughout the transportation systems such as maps, schedules, labels, and clocks. Patrons were observed as they engaged in navigational activities including meta-level tasks of planning waiting, and traveling. Informal, unstructured interviews were conducted with randomly-selected patrons regarding their navigation strategy, frequency of use and general familiarity with the system. Where available, transportation system operators were asked about common navigational problems seen with patrons. In total twelve interviews were conducted. The data were collected through written notes and photographs.

This survey yielded the following insights:

Finding #1: public transportation users generally fall into one of two categories:

- *everyday users*: regular commuters who routinely use public transportation systems on one or more routes; and
- *infrequent users*: first-time users, out-of-town visitors, or familiar users attempting to learn a new route.

Finding #2: Infrequent users engage in a series of high-level activities that include planning, waiting, and moving. These activities can be further decomposed into atomic cognitive steps of: *reflect→choose→act* [Schön, 1983].

Each high-level activity (plan, wait, and move) also involves a series of lower-level cognitive tasks. For example, while waiting users reflect on where they are in the journey, what vehicle they are waiting for, how to identify and select the correct vehicle, and where to move and board. In other words, every step – including the appearance of "doing nothing" – imposes significant cognitive loads.

Finding #3: To use public transportation, patrons must comprehend, manipulate, and process essential navigation artifacts*.* These artifacts are described in detail in Table 1.

Table 1: Essential navigation artifacts found in public transportation systems

Artifact	Purpose
maps	show spatial relationships between one's current location and destination; identify routing options; provide an abstract means to assess overall trip progress.
schedules	provide temporal information about route availability at a given day and time.
landmarks	to confirm global progress and anticipate important events or tasks that will come next, such as preparing to get off, etc.
labels and signs	to understand the local environment, including: current location, where to meet transportation vehicles; identify the "right" vehicle; where to get on and off; where to pay; etc.
clocks	to synchronize schedules with physical events, including transportation vehicle arrivals and departures.

As illustrated by the Chicago Transit Authority maps (Figure 2), essential navigation artifacts are often encoded in *compact* and *efficient* representations. These representations are compact because different layers of information are represented in the same small space, separated through the use of color, shape, texture, and size [Tufte, 1990]. These representations are also efficient because they can be universally displayed throughout the system and are easily carried on brochures by the traveler.

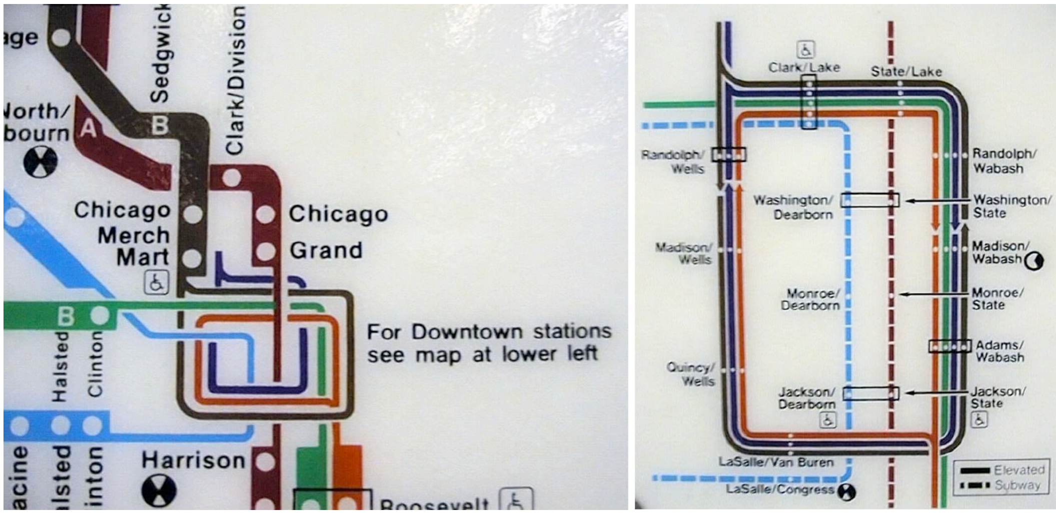

Figure 2: An example of cognitive complexities found in transportation system map displays.

The map on the left provides a context for details encoded on the right, illustrating an efficient and compact representation achieved through *spatial layering* and *separation*.

Because of this generality, such knowledge representations create unnecessary cognitive burdens for the traveler who is only interested in a small fraction of the information presented. Executive function skills [Kintsch, 1998] are necessary to understand how to obtain spatial bearings and decode, extract, and remember personally relevant information from these abstract representations.

Finding #4: Even "familiar users" make mistakes [Norman, 1981; Reason, 1999] when using public transportation systems. Mistakes are caused by:

- *system errors:* mislabeled buses, buses not running on schedule, or taking a detour from the normal route; and
- *user errors:* falling asleep; misreading signs or labels; failing to hear or understand the announcement of an upcoming stop; forgetting to signal intentions to get off at the next stop; getting on the wrong bus, or getting off at the wrong stop; becoming lost.

Although nearly all "everyday users" could describe a personal situation involving a system or user error, our survey did not find any fail-safe components designed to detect or assist recovery from such unexpected situations. When users discovered they had made an error they reported using essential navigation artifacts (Table 1) to get back on track.

4.2.2 Observing individuals with disabilities learning to use public transportation

The transportation survey allowed us to develop general hypotheses about the navigation behavior and artifacts of users of public transportation systems. To understand how these behaviors and artifacts change for individuals with cognitive disabilities, we (1) observed high school students with cognitive disabilities as they learned to use local bus systems and (2) informally interviewed specialists who help teens with cognitive disabilities in the "school-to-work" transition.

Our pilot study included 13 high school students with cognitive disabilities from two school districts, as they learned to use the local bus system. Students were participating in an educational program directed at individuals with moderate cognitive disabilities who are motivated to use public transportation, display appropriate and safe behaviors in the community, are able to walk to and find bus stops, follow directions, and identify landmarks. They had a variety of disabilities including Down's syndrome, cerebral palsy, autism, and other pervasive developmental disabilities. While all students were independently ambulatory, some did have significant gross motor problems. In each of the observations written notes were made and photographs were taken of students completing various aspects of the transportation tasks, instructors providing prompts, and adapted navigational artifacts. We observed the students studying in the classroom as well as practicing on a real bus trip accompanied by teachers. The observations lasted approximately three hours.

We also conducted informal interviews with five specialists from three different school districts who instruct teens with cognitive disabilities. These specialists prepare students to use public transportation systems as part of their independent living programs. We asked these instructors how they determined an individual was a successful public transportation user, how long it took their students to learn to travel independently, and what sort of tools they used to teach students. We also asked what percentage of students continued to use public transportation after graduation and the reasons why or why use was not continued.

The interviews revealed that training was moderately successful for selected students: 45 to 75 percent of students selected learned to use public transportation for unsupervised routine travel on at least one route after considerable training. However, training users to ride public transportation is labor intensive and lengthy: training can take three or more years, and one year is the average. Once the student knows how to ride the bus, she can learn a new route in as little as one week but may take up to eight weeks. We also learned that too often sucessful students did not use public transportation once they left public school programs. Parents frequently express worry about safety, especially due to the lack of an easy way to check on their child's progress, and the lack of time to teach their children new routes.

These pilot studies also revealed insights about how students with cognitive disabilities are taught to navigate on public transportation:

- instructors trained students for the same high-level activities observed with our survey of unfamiliar users: planning, waiting, and moving;
- planning activities were completed in a classroom before traveling and involved creating simple maps and schedules and extracting trip information from system maps and schedules (Figure 4). Instructors discussed the connection between bus schedules and clocks, but it was not clear how many could comprehend this concept since most students did not use a watch and many do not have a good understanding of time;
- as students moved to and from bus stops, labels and landmarks were verbally highlighted by the instructor. Tremendous concentration was needed to identify and understand essential

navigation artifacts, and only one of eight students demonstrated an ability to actively track trip progress using a simplified map while traveling; and

- navigation lessons were interleaved with other essential life skills such as social etiquette. These skills are needed to safely use public transportation, but it created problems with focusing on navigational tasks.

For individuals with cognitive disabilities, the ability to use public transportation impacts one's ability to live and work independently. One experienced instructor stated that about one-half of the adolescents in the program would likely learn to use public transportation for unsupervised routine travel after considerable training. Even those who successfully learn to use public transportation may not use it because of parents' safety concerns, and lack of ability to keep track of their children as they travel. Those who are unable to travel independently rely on caregivers or family members to personally accompany them to events outside the home, or schedule Special Access transportation approximately one week in advance of events.

4.2.3 Implications for persons with cognitive disabilities using public transportation systems

The two surveys (described in sections 4.2.1 and 4.2.2) allowed us to identify specific cognitive barriers for persons *with* and *without* cognitive disabilities. These observations and other research in urban wayfinding have led to the formulation of the following research hypotheses:

- navigating public transportation systems involves complex and difficult executive function cognitive skills [Kintsch, 1998];
- infrequent users rely on abstract navigation artifacts (maps, schedules, etc.) and knowledge from general previous experience to navigate, whereas repeat travelers utilize personally meaningful artifacts such as landmarks and local, specific experience while navigating [Stern & Portugali, 1999];
- unfamiliar users face many of the same problems as those with memory and attention deficits [Newell & Gregor, 1997]. There is, however, one major difference: unimpaired users may be able to "generalize" about what to do in novel situations from past experiences, while persons with memory or attention deficits must receive instruction for each situation;
- for many individuals with cognitive disabilities, maintaining a "routine" is important, and unusual situations such as system or user errors may cause them to panic or abort previously mastered routes [American Psychiatric Association. Task Force on DSM-IV., 2000]; and
- if a memory or attention deficit is severe, the task of learning a new route may interfere with previously learned routes.

4.2.4 Related Work: prompting systems for individuals with cognitive disabilities

As part of understanding "how things are," we examined technological systems that are available today to assist individuals with cognitive disabilities. We focused on systems that support prompted task completion, which is needed by many individuals with cognitive disabilities [Lancioni et al., ; Lynch, 1995]. We highlight three such systems because the creators showed great insight and vision of how technology can be used, , but also certain limitations that reveal opportunities for improvement. These systems provided an inspiration for much of our work.

The Isaac project, a Swedish research initiative [Isaac, 2003] in the mid nineties, outlined a vision of supporting independence for persons with cognitive disabilities. Their vision of the PDA as a support for independence included incorporating GPS, cell phone, and digital camera technology in an apple Newton base. The envisioned system would include a support center that could provide one-on-one support for breakdown situation. This was a remarkable combination of technologies that are only becoming common ten years later. Unfortunately, due to technical limitations and changing interests, Isaac never went beyond the prototype phase. The key contribution of the Isaac project is a collection of rich design rationale documentation.

A PC-based prompting and scheduling tool entitled The Visions System [Baesman & Baesman, 2003] uses stationary touch screens distributed throughout a user's home in an attempt to provide prompts that aid in the performance of simple domestic tasks. The Visions System uses a collection of picture cards to assist in such away-from-the-system tasks as grocery shopping. Although this system is successful for some users, it has never become widely adopted. We have attributed this to the inaccessible reconfiguration process: if a user's needs or conditions change and the system needs updating, typically an onsite visit by a Visions developer is required to add or modify task scripts.

Acknowledging the limitations of housebound systems (i.e., support ends when the user leaves the house), AbleLink Technologies developed a line of PDA-based prompting systems that were direct descendants of The Visions System. These include the Pocket Coach and Picture Coach, which provide auditory and visual prompting, respectively [Davies & Stock, 1996]. These systems store a sequence of auditory and visual prompts, which the user can step through in a linear fashion by pressing a button as each task step is completed. Even though Pocket Coach and Picture Coach provide a mobile prompting solution, these systems have a few significant limitations. First, the systems have no context awareness and so are unable to detect when an error occurs or a user is off task. Consequently, the systems can't help users recover from errors. For example, there is no way to backtrack if a user signals the completion of a task step before the step is actually completed (as might happen if the "next" button is accidentally pressed twice in rapid succession). Also, like The Visions System, these systems lack an easy-to-use caregiver interface to update and create new scripts.

From these systems, especially Visions, we have learned that for a prompting system to be truly useful it must provide a way for non-technical caregivers to create and modify scripts easily and quickly. As a result, our architecture is designed with two "first-class" user groups in mind:

- *individuals with disabilities* who benefit from prompting, and
- *caregivers* who design and create scripts for these individuals, and are able to monitor their progress and safety through task completion.

4.3 Summary

Our pilot studies suggested two major design strategies for creating a more human-centered system for using public transportations:

approach-1: design components that *simplify* the complex navigational artifacts (Table 1 above) encountered in public transportation systems; and

approach-2: design architectures and components that *transcend* the need to understand complex artifacts and serve as a dynamic "navigational assistant."

Our studies indicated that traditional teaching approaches often approximate the first design strategy. For example, instructors use a standard bus map (Figure 3, left) to create simplified and colorized personal maps (Figure 3, center) to simplify the process of planning the route. Landmarks significant to the students were also identified on the map. Additionally time cards were developed for each route (Figure 3, right). For example, if students wanted to go to the local mall they would find the index card marked mall to see the route color they would need, transfers necessary and what time each hour the bus came. Cards also included similar return information. This system worked, provided that the students always traveled directly to and from school and did not try to go anywhere else.

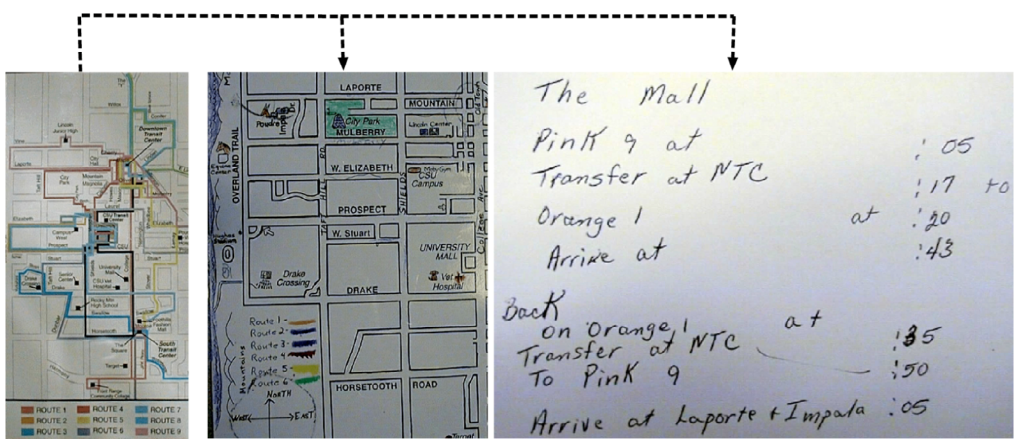

Figure 3: Traditional artifacts personalized during training

Despite using these simpler artifacts, our studies also showed that (1) there was limited success for those unable to comprehend spatial, time, or executive function navigation concepts, and (2) each student still required a significant amount of personal coaching, training and "confederate tracking." Confederate tracking involves using an unknown instructor to follow a person traveling alone in order verify navigation skills *after* the student is judged capable of using public transportation without assistance [Newbigging & Laskey, 1996].

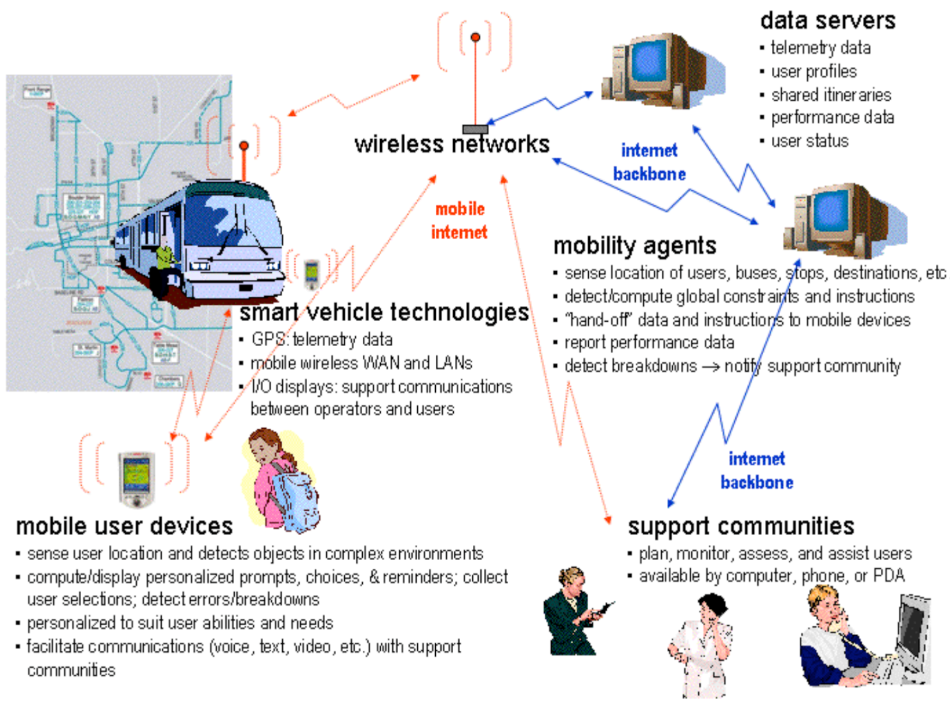

Figure 4: A socio-technical architecture to support mobile users and their support communities on transportation systems.

5 MOBILITY-FOR-ALL: A SOCIO-TECHNICAL ENVIRONMENT

Our findings led us to focus on the second design approach described above: devising architectures and technologies that eliminate the need to master complex navigational artifacts. This work has been guided in large part by a distributed cognition theoretical framework (see section 2). Our design approach was inspired by observations of patient instructors who accompanied new students during training sessions and provided personally contextualized, "just-in-time" instructions for what to do and where to go next. To reduce the workload on support communities, our team considered how technologies could be designed to assist persons as they traveled or learned a new route and to enable trusted individuals to monitor (with appropriate privacy safeguards).

The socio-technical architecture shown in Figure 4 was designed to address the needs of mobile users traveling to and from a group home facility in a community setting [Sullivan, 2004]. This architecture leverages two emerging ubiquitous technologies: (1) mobile, wireless, location-aware personal digital assistants (PDAs) or cellular phones, and (2) mobile GPS technology now appearing as "standard equipment" on new public transit vehicles. Several commercial firms [Intuicom, 2003; NextBus, 2004] specialize in retrofitting existing bus fleets with such technologies to enhance fleet management and accountability. Because of the enormous cost associated with implementing new technologies throughout a public transportation system, our architecture represents a pragmatic strategy to focus on traveler-based software components that leverage existing and emerging transportation information infrastructures.

This architecture supports the following goals:

- direct support of the mobile user with personally relevant navigational tasks including "just-in-time" information for selecting a destination, locating the right bus, preparing to board, boarding the bus, signaling the driver where to get off, and disembarking;
- when needed, initiate or facilitate communications between the mobile user, support communities, and transportation system operators; and
- provide a "safety net" when something goes wrong.

Our collaborations with support communities reflect that their core values are "high touch" and not "high tech," because they desire better accountability and security safeguards for mobile users who have completed training and travel alone and are vulnerable if they fail to follow protocols [Booth, 2003]. This architecture provides a safety net normally only available through human "confederates" [Newbigging & Laskey, 1996] without the cost-prohibitive overhead of monitoring events that are not important.

This socio-technical architecture could be of particular relevance for those who require more training or confederate sessions than human resources would typically allow. We envision a service industry, similar to current residential emergency services [Lifeline Systems Inc., 2004], that could simultaneously monitor and support a number of *mobile users* as they travel. Currently such services only work in home settings. This approach would make in-demand vocational therapists and instructors available to assess, teach, and personalize technology solutions for those who need the most assistance and practice.

5.1 Exploring the architecture: implementing proof-of-concept prototypes

In order to explore the Mobility-for-All architecture we began implementing prototypes that demonstrated the feasibility of the various components shown in Figure 4. Before describing these system-building efforts in detail we briefly summarize in Table 2 each prototype and its relation to the architecture.

5.2 The Personal Travel Assistant

The Personal Travel Assistant prototype was developed in collaboration with a commercial end-user programmable software developer [AS, 2004] and mobile GPS instrumentation manufacturer [Intuicom, 2003]. This prototype instantiates two key synchronized architectural components (see Figure 5 and Table 2).

1. **Mobility Agents:** generate just-in-time prompts and detect breakdowns by using real-time telemetry data (i.e., location, speed, and direction) from buses and travelers.
2. **Support Community:** receives visual feedback of bus and client location data.

Table 2: Proof-of-concept prototypes developed to explore the architecture

Prototype	Description	Architecture Component
Personal Travel Assistant	Uses real-time GPS data from the bus fleet to deliver just-in-time prompts.	**Mobility Agents:** generate just-in-time prompts based on real-world data; detect breakdowns and adjust prompts **Support Community:** receives visual feedback of bus and client location data
Memory Aiding Prompting System (MAPS)	Provides a tool for support community to program scripts for the mobile user device user interacts with hand-held device to complete a task.	**Support Community:** end-user programming tool for script generation **Mobile User Devices:** audio-visual prompts for task support; *panic button* to summon caregiver assistance
Lifeline	Collects real-time task status from the mobile client and alerts the support community of potential problems.	**Data Servers:** stores user profiles and itinerary for use by mobility agents **Mobility Agents:** detects breakdowns and notifies support community **Support Community:** receives troubleshooting information including task status and history

Employing a user scenario to develop the prototype, the simulated traveler is Amy, a teen with developmental disabilities resulting in severe attention and memory deficits. Amy can be placed at a bus stop where a bus is approaching, and the demonstration sequence is "triggered" by selecting a destination option on her handheld device (Figure 5, left).

As the system runs, real-time GPS data is wirelessly transmitted every two to three seconds from buses on the street to a networked server within a transportation management office. Virtual bus agents [Repenning & Sullivan, 2003] remotely access this data stream and update bus locations on a map display (Figure 5, right). Once the user selects a destination, the handheld computes state changes based on events triggered by GPS updates to the virtual display.

At a higher level, Amy's mobile phone generates visual and auditory prompts triggered by real world events. Prompts are given to "get ready" for her approaching bus, "please board now" when the bus stops at her location, "please pull the stop cord and prepare to get off" as the bus approaches the destination stop, "please get off" at the destination stop, and finally, "don't forget your backpack." By comparing location and movement information from Amy's Personal Travel Assistant with GPS data from buses in her vicinity, Mobility Agents can unobtrusively monitor and detect if Amy has missed her bus or mistakenly boarded the wrong bus so that personal heuristics can be used to remedy the situation. In the former case, Amy may be instructed to wait for the next bus, while in the latter case, a transportation official or her caregiver may be notified to help resolve the problem (as described in section 5.4).

This initial prototype instantiates two key architectural components that link a mobile user with her support community, and demonstrates how intelligent, agent-based technologies can create meaningful attention and memory prompts from a real-time data stream available in GPS-enabled bus fleets. Conceptually, these technologies support computationally mediated communications between the transportation system, caregiver communities, and mobile user.

Figure 5: Agent-based prototype showing a mobile prompting device synchronized with display of real-time bus system

5.3 Memory Aiding Prompting System: Personalizing Task Support.

The emphasis of the Personal Travel Assistant prototype was the development of mobility agents that help travelers manage the complex transportation system. Mobility agents help overcome a major obstacle that prevents people with cognitive disabilities from participating in their community. While this addresses an important part of the problem, traveling on public transportation is rarely an end in itself, but is rather a necessary means to an end. Transportation is typically a subtask of an overarching activity (e.g., going to work). To explore the broader usage of prompting systems and especially the personalization of such systems, we have developed the Memory Aiding Prompting System (MAPS).

Figure 6: An initial prototype environment for programming a mobile Personal Travel Assistant

MAPS was developed to explore issues related to the programming and use of prompting systems such as the Personal Travel Assistant. This prototype instantiates two interrelated architectural components (see Figure 5 and Table 2):

1. **Support Community:** end-user programming tool for script generation
2. **Mobile Client:** audio-visual prompts for task support; Panic Button summons caregiver assistance

Our approach is to design prompting systems that can provide a set of *scripts* that are tailored to support complex tasks. Scripts are comprised of atomic attention and memory prompts with task-specific audio-visual stimuli and feedback. They are organized into finite state sequences with state changes triggered by the traveler's actions (e.g., selection from a menu, movement, etc.) or external events in the traveler's environment (arrival of a bus, passage of time, etc.).

Figure 6 shows a prototype caregiver configuration environment [Carmien et al., 2003] that is used to program the handheld prompter. The process of creating or editing a script consists of selecting image and sound pairs and inserting them into a script. Once the script is completed the caregiver loads it on to the prompter for use by the client. The configuration environment employs shared repositories so that vocational counselors and caregivers with varying abilities can share scripts and templates using a collaborative, participatory design process [Fischer & Sullivan, 2002b]. The design of the script editor presents interesting challenges of *meta-design*, a process for creating new media and environments that allow users to act as designers [Fischer, 2003b]. In most applications of meta-design, the designer is the end-user. In this application domain, we are designing systems to empower caregivers so they can design systems for use by yet another person (a traveler with cognitive disabilities) within a dynamic environment.

One key design parameter in a scripting sequence is the granularity, or specificity of a particular prompt (i.e., some users, more than others, will need a task to be specified with a greater number of steps). When users are learning to travel independently, the prompting granularity may be extremely fine with frequent prompts and feedback. As the traveler gains experience, granularity may become less frequent in order to be less intrusive and still provide the proper level of support for the traveler. Since the script design task is conducted by one or more caregivers who generally have little professional technical training, the design environment must provide powerful multi-media tools to organize and tailor attention and memory aides, while at the same time reducing the complexity of creating, storing, retrieving and sharing script components.

5.4 Lifeline: Supporting independent travel with unobtrusive supervision and assistance

Lifeline allows caregivers to remotely and unobtrusively monitor a traveler's activities and offer assistance when needed. Figure 7 shows the Lifeline prototype that explores navigation tasks beyond the public transportation system. In this scenario Amy uses MAPS to help her navigate through a complex building as she delivers mail. When a script is executed on the handheld device, the script or plan is registered with Lifeline. As a result, Lifeline will expect a certain sequence of steps. Associated with each step are constraints that define abnormal conditions (e.g., time limits, location boundaries, rapid temperature changes, etc…). As the script is being executed, status changes are sent to Lifeline. Lifeline continuously displays the client's current status, including current script description, a list of steps in the script with expected and actual times, and the traveler's location. This prototype explores three elements of the architecture (see Figure 5 and Table 2) that together provide a vital tether between the traveler and caregiver:

1. **Data Servers:** stores user profiles and itinerary for use by mobility agents
2. **Mobility Agents:** detects breakdowns and notifies support community
3. **Support Community:** receives troubleshooting information including task status and history

Initial interviews at assisted living facilities indicate that caregivers are optimistic about the potential of mobile prompting systems and the prospect of increased independence for their travelers; however, optimism is also tempered by a significant concern about safety. "What happens when it breaks?", "What if they leave it [their hand-held device] on the bus?" are common concerns raised by caregivers.

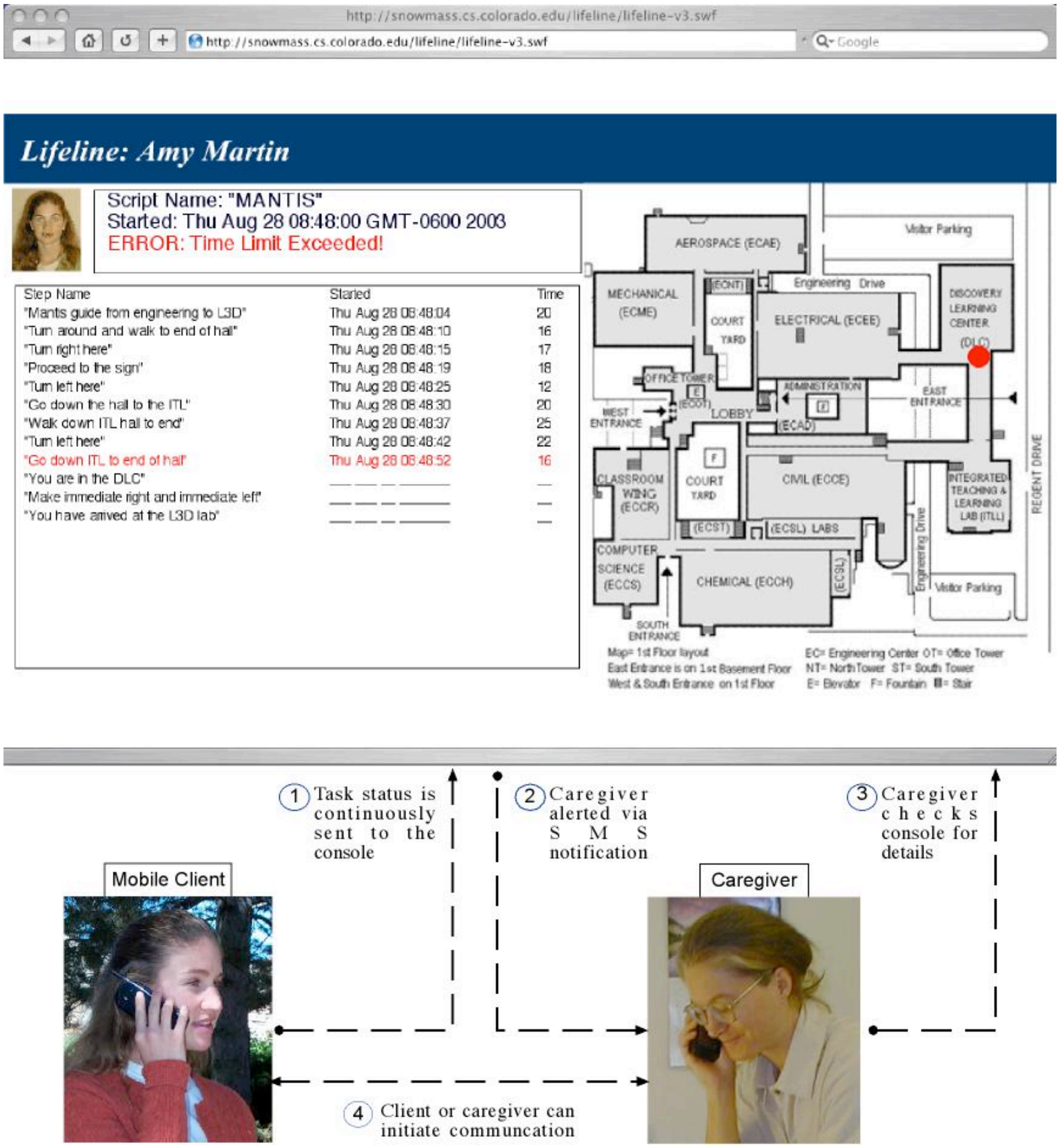

Figure 7: Lifeline prototype showing the flow of information in a distributed socio-technical support system

To address the problem of caregiver trust we are exploring the concept of *human errors* [Reason, 1999] and *breakdowns* [Fischer, 1994] that require some intervention. The detection of errors and breakdowns is complex since they can arise from multiple events and sources. Breakdowns can be caused by human errors, but also system errors such as wireless network instability or inadequate battery power. In the current prototype we employ two simple methods for signifying and detecting breakdowns. Travelers can *signify* a breakdown and summon caregiver assistance with a "panic button" if they perceive something is wrong. Unfortunately the traveler may not be cognizant of being off track. Lifeline can *detect* simple breakdowns such as when task steps exceed an expected time threshold as defined using the script editor or when the handheld device stops sending status data to the server due to a lost network connection or low battery power. In these cases the Lifeline server notifies the caregiver via Simple Message Service (SMS). The caregiver can then explore the nature of the breakdown.

Through this approach, the power of distributed cognition is leveraged in context-aware socio-technical systems [Carmien et al., 2003; Carmien & Gorman, 2003] that integrate ubiquitous computational and human support for guided situated action [Suchman, 1987]. Our prototype demonstrates the technical feasibility of creating a remote support system, but it does not address the real question of whether such a system can effectively be used by caregivers and travelers to cooperatively accomplish tasks.

6 ASSESSMENT

For any socio-technical system to be successful, community-based assessment must begin at the design stage and continue to be integrated throughout the project. Over a two-year period, we have built essential relationships with organizations that prepare those with cognitive disabilities for independent living, transportation organizations, and local school districts, which have facilitated a number of pilot studies and the initial design of the prototypes. This effort has set the stage for a more systematic and thorough study of the design, deployment, use and integration of these technologies into the lives of individuals with disabilities.

The Mobility-for-All research project is a unique opportunity to create fundamental understandings regarding the extent to which the community of individuals with cognitive disabilities can benefit from innovative technologies and live more independently by having a more effective and efficient means to using public transportation.

Our assessment studies will create a fundamental understanding of how:

- people with cognitive disabilities perceive and use information in travel tasks using mobile handheld devices [Gorman et al., 2003];
- non-technical caregivers can utilize configuration environments to personalize assistive technologies [Carmien, in Press] (see Figure 6); and
- caregivers can be supported in providing remote real-time assistance [Carmien et al., 2003] (see Figure 7).

Social assessment opportunities: This research ultimately will be judged by the opportunities for independence and societal inclusion it provides to those who would otherwise be left behind. To this end, we will assess the following hypotheses concerning benefits of our proposed socio-technical environments:

- the ability of a traveler with cognitive disabilities to learn a new route with fewer directly supervised sessions than is required without the system;
- the ability to learn more complex routes (longer duration or more transfers);
- the ability to navigate on a new route with fewer errors;
- the ability to detect and recover from errors; and

- the ability to remotely assess and assist a user in unforeseen circumstances.

These advantages will be compared and contrasted with existing problems identified in the use of public transportation by individuals with cognitive disabilities.

6.1 Phased development and evaluation

We believe it is necessary to develop and assess our prototypes in naturalistic settings [Hutchins, 1994], but as we go beyond the proof-of-concept stage, there is a dilemma regarding how to engage in participatory design with caregivers when the technology is still too immature to test with real travelers with disabilities. We believe that it is possible to overcome this "boot strapping" problem with a phased approached, which is summarized in Table 3. Our current development and assessment activities fall into the *phase 1* and early *phase 2* stages and are now described below.

Table 3: A multi-phased development and evaluation methodology

	Phase 1 **empirical studies & proof-of-concept prototypes**	**Phase 2** **usability studies in controlled settings**	**Phase 3** **in-situ system and user testing**
key issues	identify system architecture and components needed to support mobile travelers and caregivers build proof-of-concept prototypes and gather feedback from user community and domain experts	assess technical sufficiency of components identify technologies needed for routine and emergency scenarios usability assessment of system components build caregiver trust	technical verification and validation of the deployed mobile architecture usability of the deployed architecture
assessment approach	evaluate existing transportation systems and learning strategies develop travel scenarios using non-deterministic simulations of travelers and system failures (see 6.2 below)	caregivers designing non-trivial prompting scripts on devices in laboratory tasks (see 6.3.1 below) persons with disabilities using prompts on handheld devices in non-trivial laboratory tasks (see 6.3.2 below) caregivers designing travel prompts caregivers remotely supporting simulated travelers caregivers remotely supporting travelers without disabilities persons with disabilities using prompting systems in supervised travel tasks.	user studies with caregivers remotely supporting cognitively disabled travelers in real world travel tasks

6.2 Phase 1: Using interactive simulations for early assessment

The Personal Travel Assistant prototype (see Figure 5) is an interactive simulation. Virtual buses move along their routes based on real-time bus location data. One or more simulated travelers can move through the transportation system. The simulated travelers' goals and actions (e.g. which destination the traveler chooses, when the traveler gets on and off the bus) are controlled in real time through inputs to the system from a real user. The prototype has proved to be a well-suited substrate for early assessment as well as participatory design of the system.

The ability to control the simulated user's behavior dynamically has enabled us to conduct participatory design sessions with caregivers in the form of "what if" games for various travel scenarios. We can discuss appropriate system responses for different scenarios like:

- what if the traveler gets on the wrong bus?
- what it the traveler forgets to get off the bus?
- what if the traveler changes destinations mid-route?

With the simulation, caregivers can act as "surrogates" for the simulated users, and assess the system's behavior in a realistic setting. However, we recognize that this simulation does not represent real-world travel conditions (e.g. potential distractions the traveler will encounter), which can only be understood by testing the system in the real world. Nevertheless, the interactive simulation has facilitated excellent feedback from caregivers that would not have been possible without the prototype.

6.3 Phase 2: Using controlled user testing to test basic usability issues

The research problems associated with the design and implementation of an effective script editor system are multi-leveled and range from basic research in cognitive psychology, to system-level issues in interface protocols, HCI, user modeling and error event discovery algorithms. Although there are "best practice" traditions in the field of assistive technology [Epstein, 2001], little research has been done in the fields of image recognition for users with cognitive impairments and appropriate verbal structure of prompts. We have done preliminary studies in these areas and will design and conduct more extensive experiments to investigate these issues in the context of traveling.

We have conducted two pilot assessment studies with MAPS, in order to evaluate the usability of the handheld device and the script creator. These studies involve multi-step tasks unrelated to travel, but that adequately assess basic usability issues in a safe setting. These pilot studies have also allowed us to test and refine our experimental method and data-gathering technique to prepare for future rounds of more robust user studies. Both studies were video and audio recorded, and were finished with a brief structured interview with the participants.

6.3.1 Pilot Study 1: Teachers use script editor to create a complex script

Participants. Three special education teachers participated in this study. They were chosen randomly from a pool of teachers that have expressed interest in participating in the Mobility-for-All project.

Task. The teachers were asked to write a script for making cookies (a common task taught to teens with disabilities to develop life skills). The number of steps (42) and the large number of images and prompts comprising the steps were a good approximation of a typical use of the script creator. The teachers selected from pictures and audio prompts that were already loaded into the system.

6.3.2 Pilot Study 2: Students use multi-modal handheld prompter to perform a complex task

Participants. This study included six high-school students with moderate cognitive disabilities. Several of the students had communication disabilities and several students had slight physical disabilities, such as poor coordination and slight visual acuity impairment. The participants were chosen with the assistance of the teacher, on the basis of having cognitive impairments (DSM-IV classified as 40-80 IQ), and age (between the ages of 16 and 21).

Task. The participants were given the task of assembling a balsa wood glider. Each student was given a handheld prompter that was loaded with an eight-step script of images and voice prompts for assembling the glider. We planned for each participant to complete a single trial. Our main focus for this study was to validate that the basic input and output devices of the interface (touch screen, display and audio output, panic button) could be learned and used with proficiency.

6.3.3 Findings from pilot studies

Although they needed minor assistance during the task, both teachers and students were successful in completing their different tasks in a single trial. Our study showed that not only could non-technical caregivers build complex scripts, but that individuals with cognitive disabilities were able follow script directions on a handheld device and ask for assistance using the panic button successfully. Thus only minor interface design changes were made to both the script editor as well as the handheld device.

7 RESPONSIBLE SOCIO-TECHNICAL DESIGN AND HCI CHALLENGES

Even when transportation systems are designed to serve the 95th percentile of a population, they will be of no use to a large number of people within a large population [Norman, 1988]. Even more unfortunate, when transportation systems are built this way, they may not serve those who are most dependent on them, such as the physically or cognitively disabled and elderly. Our methodology challenges conventional approaches by responsibly designing systems that support 5-7% of the population who have the greatest difficulties while traveling. Our hypothesis is that such systems would not only result in a more inclusive system, but will provide information architectures upon which to build systems that are more usable for mainstream travelers as well.

Public transportation environments present unique research opportunities to investigate more global HCI issues with mobile ubiquitous computing architectures, wearable computing systems, personalization and user modeling techniques, and universally accessible interfaces for complex systems. Specific HCI research challenges include:

- **No single perspective can yield a satisfactory solution.** The unique needs and abilities of our users must be juxtaposed with the complexity and constraints of modern public transportation systems and emerging technologies, making collaborative, participatory partnerships essential [Arias et al., 1999; Arias et al., 2000; Fischer, 2000; Schuler & Namioka, 1993]. Such practices are not an additional step or afterthought, but a catalyst to inform, enhance, and possibly transform existing practices of all participants [Fischer & Sullivan, 2002b].
- **Complex socio-technical systems cannot be designed and evaluated in the laboratory alone** [Nardi, 1997]. Problems such as people falling asleep or buses not running on time are likely only to be seen in the world, and not in the laboratory. Since a "proxy group" (the caregiver community) is articulating the needs of a non-verbal user community, new approaches must ultimately be tested, evaluated, and refined in-the-world with real users.
- **There are no "silver bullet" technologies that can or should replace caregivers**. Socio-technical systems can be designed to (1) intelligently augment and assist the overworked support community; (2) provide new mobility and independence options for an under-represented population; and (3) augment memory, focus attention, and offer assistance contextualized to suit the mobile user [Fischer, 2001a].
- **Personalization and user modeling techniques are critical**. As architectural components are refined and deployed, personalization and user modeling [Fischer, 2001b; Riecken, 2000] will increasingly become an important research area. Technologies must be developed that (1) permit support communities to easily configure mobile systems to suit the unique "universe of one" abilities of each person and (2) allow systems to intelligently "adapt" to each users abilities and learning styles through use.
- **Context-aware, ubiquitous computational environments are necessary.** Because of communication and computational demands, the mobile user cannot carry a single device that has all information necessary to know where to go and what to do next. This provides an ideal research environment to study how personally relevant information can be extracted from distributed information spaces [Repenning & Sullivan, 2003; Weiser, 1993] and how context-aware environments [Dey et al., 2001] and architectures can be used to create distributed support systems [Carmien et al., 2003; Carmien & Gorman, 2003].
- **Intelligent, mobile prompting systems are essential and challenging components**. We have started technical explorations to conceptualize how location-aware mobile prompting systems can be configured and personalized to serve as a digital assistant in dynamic "open environments" [Carmien et al., 2003]. We are also analyzing early PDA research projects

[Isaac, 2003] and commercial technologies [Ablelink, 2003] to better understand the promise and limitations of current technical approaches.

- **Designing "dual-use" technologies is important to widespread adoption.** Early in our research, we observed that "dual-use" technologies often achieve better adoption and are less expensive because they serve larger audiences. Just as "curb cuts" serve persons in wheelchairs as well as parents pushing strollers or bicyclists, we believe mobile architectures and technologies can be designed with potential to be adopted to larger audiences such as the out-of-town visitor or non-native speaker.

8 FUTURE WORK

The prototype systems developed in the Mobility-for-All project provide interesting "objects-to-think-with" for evaluation as we progress toward our goal to design socially inclusive human-centered transportation systems. Future project plans include:

Connecting other members of a mobile community. While we have focused on the needs of travelers with cognitive disabilities, our collaborations have revealed that the network of caregivers who support these travelers might benefit from similar platforms. For example, mobile systems might automatically track associates on duty so they can lend help or check on each other in community settings. This provides opportunities to explore how dynamic, knowledge-based infrastructure technologies can make travel safer and more socially stimulating. For example, a computational "travel agent" might easily summon and direct a nearby associate where to go when a client faces a crisis in the community. Similar technologies might also facilitate a spontaneous meeting of travelers, trainers, or associates by routing them through a common bus stop on an itinerary.

Communication-augmentation systems. Our architecture could also support essential dialogs between mobile users, support communities, and transportation system operators. Future prototypes will explore how mobile devices could be designed to communicate personal needs to transportation system operators so they can better serve their customers. We also envision a simple "panic button" that easily initiates person-to-person communication between mobile users and support communities in times of fear or uncertainty.

Multi-level error detection, recovery, and emergency notification systems. Our architecture must be designed to gracefully handle both system and user failures and provide a safety net when unexpected or unusual events occurs. This requires a level of reliability and robustness not normally seen in mobile devices and services. For the mobile phone user, dead batteries or "roaming out of the cellular network" may be an inconvenience. For the mobile traveler who is unsure where to go and unable to communicate effectively, these situations are considerably more serious and require immediate intervention. Rather than wait for an error to occur, our mobile systems could collect performance data and detect subtle anomalies that precede error states. This could both provide better service and valuable design data for system improvements.

A "virtual bus" stop. We have started collaborations with the University of Colorado/BP Visualization Center to create a prototype bus stop in a virtual "cave" environment to explore how regular mass transit users traveling without mobile technologies could use "core technologies" from our Mobility-for-All project.

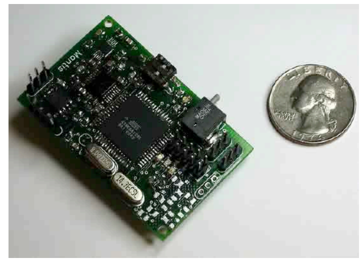

Figure 8: Prototype MANTIS remote sensor

Creating "Smart" environments. The Lifeline prototype (Figure 7) is being designed to interface with a prototype *ad hoc* sensor network [Han et al., 2003 to appear 2003] which will have both a sensory and dynamic computational capability (Figure 8). This technology is being developed by another University of Colorado research team [Han, 2003] and represents a growing trend of ubiquitous computing devices and sensors that could significantly augment the capabilities of personal mobile devices with navigational information where GPS coverage is not available, and local information such as environmental temperature and humidity and distributed services, including network connectivity, data storage, and computational services.

9 CONCLUSIONS

Creating human-centered public transportation systems represents both a challenging research problem and opportunity of tremendous social significance. The effective design of personalized, mobile architectures has the potential to enrich the lives of those who must rely on public transportation, while addressing problems of national significance [TRB, 2001]. This research also supports exploration in a number of intriguing HCI issues. In sum, this research (1) addresses the needs of an under-represented and often non-vocal sector of society within the context of a technically complex system; (2) requires the participation of disparate design communities for a common goal; (3) changes methods and practices of participants, and could influence the way future HCI designers and engineers are educated; and (4) has the potential to improve public transportation systems for everyone through the adoption of universal architectures and prototypes that promote universal access.

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