Informing the Design of an Automated Wayfinding System for Individuals with Cognitive Impairments

Alan L. Liu*, Harlan Hile*, Gaetano Borriello*, Henry Kautz†, Pat A. Brown‡, Mark Harniss‡, Kurt Johnson‡
*Department of Computer Science & Engineering, University of Washington, Seattle, WA USA 98195-2350
Email: {aliu,harlan,gaetano}@cs.washington.edu
†Department of Computer Science, University of Rochester, Rochester, NY USA 14627-0226
Email: kautz@cs.rochester.edu
‡Department of Rehabilitation Medicine, University of Washington, Seattle, WA USA 98195-6490
Email: {pabrown@u.washington.edu,mharniss@u.washington.edu,kjohnson}@u.washington.edu

***Abstract*—Individuals with cognitive impairments are often prevented from independently living, working, and fully participating in their community due to wayfinding concerns. We conducted two user studies of a mobile wayfinding aid designed to support such individuals. The first study examined usability issues related to wayfinding outdoors. The results were positive overall, but showed that the directions we used were at times too low-level, requiring strict adherence to the route and therefore highly precise message timing. The second study examined the use of landmarks to provide directions at a higher-level, as a way to overcome the limitations of the directions we were using. We found that certain types of landmark-based directions were significantly easier to follow, but individual performance varied across most direction types. The findings from both studies show that individuals with cognitive impairments would benefit from a wayfinding system that is capable of supporting customizable and adaptable direction selection.**

I. Introduction

People with cognitive impairments prefer to live and function as independently as possible. When they cannot navigate safely and independently, the burden on caregivers and community services increases and the opportunities to act independently and participate fully decrease. As part of a larger effort to construct technology aids for this purpose, we conducted two user studies examining the potential of a mobile device to support individuals with cognitive disabilities in wayfinding. The design of this wayfinding application for our unique target user base has been a continuing, iterative process involving design, prototyping, and evaluation. The process began with a participatory design phase to elicit design requirements from end-users as well as their caregivers and job coaches, who are involved with training and aiding individuals with cognitive impairments. Following this initial design phase, we developed and studied a prototype used in an indoor environment [1]. Building upon the insight and feedback that we received from that study, we have conducted two more user studies, both reported here. All of our studies use the Wizard-of-Oz approach, where participants interacted with the prototype while its behavior was controlled remotely by a researcher. We used this method so that potential users could walk through a realistic experience of using a wayfinding system without all parts of the system being fully implemented.

The first user study that we describe in this paper examines issues raised by the indoor study that might be exacerbated in an outdoor environment, such as the effort needed in identifying complex visual features in images on a small screen, difficulty making correct turns at less structured outdoor pathways, and safety issues such as dealing with traffic. The second study examines the use of landmarks to provide "high-level" directions as a way to overcome some of the limitations of the types of directions we have used up to this point, which tended to require strict adherence to a route and therefore highly precise message timing. Based on our findings from our studies, we have developed a framework for automatically generating directions. By using a Markov decision process (MDP) as the model for choosing appropriate directions, we can customize directions to accommodate individual health conditions, direction preferences, place familiarity, and wayfinding error behavior. In addition, MDPs provide a way to continuously adapt to the user, so that customizations can be adjusted over time.

II. Related Work

Researchers have designed infrastructure [2], algorithms [3], and novel technologies for localization [4], [5] to support wayfinding systems, but focused less on evaluating user interfaces for delivering directions. An exception was [6], where researchers evaluated potential users' ability to follow one set of static directions placed in an environment using QR codes.

Our work has emphasized user interface issues gathered through feedback from members of the target user-base. In a prior study, a diverse set of participants were guided through three indoor routes using different combinations of interface modalities (text and audio, text and images, and all three) [1]. Despite the challenge of navigating through an unfamiliar and somewhat generic indoor environment, all participants were able to follow directions to their destinations. Though users were able to use all types of modalities to find their way indoors, they varied in their preferred modalities, suggesting that customization and adaptation should be important considerations. The first study described in this paper replicates this work outdoors and adds a baseline condition.

This outdoor study uncovered some drawbacks to the types of directions we used, so we examined the use of landmarks as a complementary way of giving directions. Studies have shown that landmarks are the predominant way of producing wayfinding directions for people without disabilities [7] and that they can help older people by reducing the cognitive load required to wayfind [8], however until recently integrating landmarks into wayfinding directions has not been practical. Because of advances that promise to provide scalable and ubiquitous access to landmark information [9], we chose to conduct the second study in this paper that examines the usability of landmarks, to see whether those findings also apply to people with cognitive disabilities.

Our study results showed that individuals with cognitive impairments would benefit from a wayfinding system that is capable of supporting customizable and adaptable direction selection. This can be achieved by using a decision-theoretic approach where system actions are chosen based on knowledge of a user model. In many ways this is similar to the path planning problem in the robotics community. Various techniques for path planning under uncertainty have been developed by that community [10], which we can apply toward creating an automated wayfinding system. A key concept in this context is the Markov decision process (MDP), which provides techniques for generating navigation plans even when observations and the outcome of navigation actions are uncertain [11]. For example, partially-observable MDPs have been used to assist persons with dementia through tasks such as hand-washing [12]. The framework we propose at the end of the paper builds upon on these techniques to model uncertainty in whether a person will follow the guidance provided by our system, but to simplify our model and reduce the state space necessary to solve our MDP, we rely only on observable action results.

III. Outdoor Route Study

Our indoor study showed that images with overlaid arrows, combined with text and audio messages, could be used by people with cognitive disabilities. The goal of this user study was to study the effect that the outdoor environment has on:

1) The usability of images: Visual features tend to be less uniform and more complex outdoors, so recognizing photos might be more challenging for users, especially recognizing details (including text) on a mobile device screen outdoors (*e.g.*, due to size, glare, etc.). Changes in weather and season can affect the appearance of environmental features. Would participants have issues with photos that were taken in a different condition?

2) Turn precision: In our indoor study, some participants had trouble with arrows that directed them to turns that were not at 90° angles. Outdoors, paths may wind and not meet at precise four-way intersections, so we investigated whether participants could make correct turns given the lack of precise angles of paths and intersections.

3) Finding a precise location: Indoors, most rooms are labeled and ordered by number. Could the prototype's set of directions guide someone to an unlabeled building entrance? How accurate must the wayfinding system's estimate of a user's location be?

Fig. 1. Sample images used in the interface. *Clockwise from top-left:* plain photographs, directional symbols, photographs with highlighted areas (e.g. room number), and photographs with overlaid arrows.

4) Outdoor distractions: In a more dynamic environment, a user has more varied distractions from pedestrian and traffic activity, which could make paying attention to directions from a device harder to maintain.

5) Baseline vs. prototype: We also included a baseline condition to compare with the prototype, giving us insight into how a just-in-time system affects how our target users find their way to new locations. Specifically, we wanted to find out what methods of wayfinding were currently used (*e.g.*, written, verbal, or map directions) and why they preferred that method. We also wanted to observe any problems users encountered and whether the prototype improved confidence and comfort while wayfinding compared to methods used during the baseline data collection.

A. Methodology

The interface consists of a client program running on a HP iPAQ handheld that delivers directions and prompts to the user. Both directions and prompts consist of a subset of images, audio, and text messages. Images are photos, arrows and other generic symbols, photos with overlaid arrows, and photos with an outlined area (see Figure 1). Text are brief messages displayed in large font. The text and audio messages used the same wording. Users can choose to use headphones or the built-in speaker to hear the audio.

The client is remotely controlled by the *navigation wizard*, a person who determines what to display and play based on the participant's location and heading. To simulate location and orientation sensors, we use a *location wizard*, a person who follows study participants and transmits their location and orientation to the navigation wizard in real-time using a simple map-based GUI. Both wizards use WiFi-enabled Tablet PCs to communicate. Study responsibilities are divided between two wizards (in addition to other observers) in order to more effectively operate the multi-modal simulations.

TABLE I
ROUTE STUDY PARTICIPANT DEMOGRAPHICS. *CE:* CEREBRAL ENCEPHALOPATHY, *TBI:* TRAUMATIC BRAIN INJURY, *DS:* DOWNS SYNDROME.

Participant	Gender	Age	Primary Health Condition
1	Male	41	TBI
2	Female	23	DS
3	Female	30	DS
4	Male	44	DS
5	Male	27	CE
6	Male	47	TBI

The study involved every participant walking through three routes of differing complexity. We chose routes that traversed through different parts of the campus in order to minimize any learned familiarity, and varied the order of routes presented to each participant. For the "baseline" case, participants were asked to choose the mode they would typically use to find their way to a novel location (*e.g.*, map, written directions, or verbal guidance). Participants used the prototype for the other two routes. Researchers followed each participant and took notes, obtained feedback from the participant, and provided assistance when the participant chose to use verbal directions or became confused or uncomfortable.

Six participants were recruited from a pool of adults with cognitive impairments who were receiving employment services from a community-based rehabilitation provider (see Table I for participant demographics). Participants 3-6 had participated in the previous indoor study, but had little familiarity with the outdoor routes or recollection of the prototype. Although there was a wide variation in participants' health conditions, higher-level functional abilities such as navigation often vary widely between any two individuals with cognitive impairments due to their unique set of abilities and disabilities. This variation provided the opportunity to investigate trends and highlight individual differences that affect landmark understanding among potential users with cognitive impairments.

B. Results

While all but one participant struggled to complete their baseline route, they had few to no issues following directions given by the prototype to navigate. Participants had noticeably less trouble transitioning between steps when using the prototype.

1) The usability of images: Participants did not have trouble viewing photos most of the time, although it was more problematic when they had to pick out details in photos without distinctive visual features. Participant 1 was not able to match a destination room inside a building to a photo with that room's number highlighted. Participant 5 was not able find some landmarks by photo and thought that it might have been too sunny to see the screen clearly.

Inconsistencies due to changes in season, weather, lighting conditions, and other influences did not cause any observable impact on participants' wayfinding. In a notable example of such inconsistency, brightly colored poles that were the most visible aspect of a photo had been removed from a path. Participant 6 was the only person to note some of the inconsistencies, pointing out that a trash can had moved and that some plants and trees were in different stages of blooming.

2) Turn precision: Because outdoor paths are typically less constrained than indoor paths, we were interested in seeing whether atypically oriented arrows (*e.g.*, slight turns) would cause problems for users. We did not observe any wrong turns caused by such arrows, however there were times when the overlaid arrow was ambiguous. One intersection where two nearby paths both went off to the right caused some participants to take a different path than the intended one.

3) Finding a precise location: Even with a person as the location wizard, there were still times when location errors caused directions to be sent too early or late to participants. Participant 2 passed the doors to a destination before the interface prompted her to turn and enter it. Confused because she could not turn at her location, she became frustrated.

4) Outdoor distractions: We noticed that some participants focused their attention on the device and reduced their awareness of the environment. Some participants had to be reminded to watch for traffic even in the baseline scenario, but this was an even greater concern when participants were using the wayfinding device. However, on the positive side participants did not exhibit signs of being overwhelmed by crowds or noise.

5) Baseline vs. prototype: In addition to a reduction in wayfinding errors, we noticed that participants had less trouble making decisions and initiating action when using the device. Participant 2 demonstrated the most difficulty initiating each step in her baseline navigation trial. She consistently stopped at the end of each step and waited for a verbal prompt (*e.g.*, "What does the next step say?") before proceeding. Participant 3 also had difficulty knowing when to proceed to the next step. For both, the device provided the necessary prompts to move to the next step without the need for additional prompting by the accompanying researchers.

C. Summary

The results from the user study showed that while just-in-time directions can provide a large benefit over current wayfinding practices available to people with cognitive disabilities, there are still issues to address. Relying on photos with overlaid arrows had several drawbacks. The system would need highly accurate knowledge of the user's location in order to present photos that align to the user's perspective, otherwise turns could be missed. Also, the user's perspective does not always contain distinctive visual features, so matching the photo to the environment can become a cognitively high-effort task that takes attention away from the surroundings. For these reasons, we next examine using landmarks as a complementary approach to providing directions for users and situations where our current types of direction may not be ideal.

IV. OUTDOOR LANDMARK STUDY

In our second user study, we wanted to better understand whether there were aspects of landmarks that could affect the

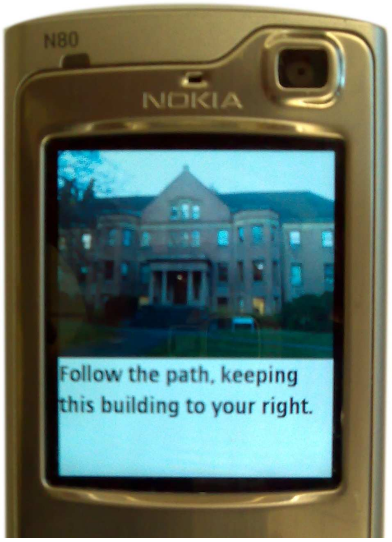

Fig. 2. An example of the client in the landmark analysis study.

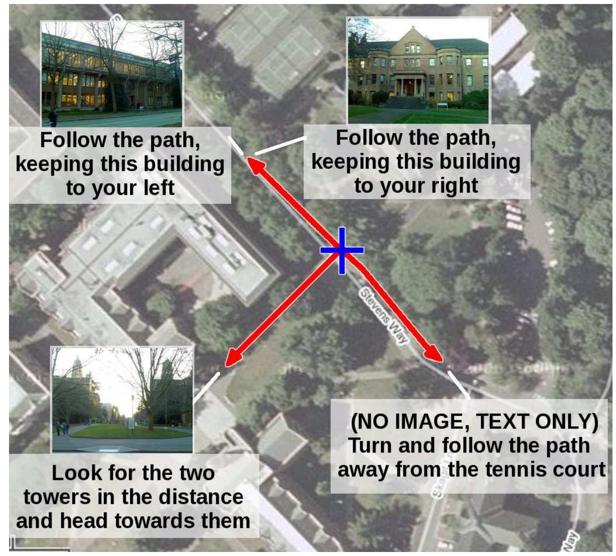

Fig. 3. The landmark analysis study set-up. A user starts at one location marked by the blue cross and is asked to follow different directions to different destinations. Example directions and expected destinations are shown.

usability of directions for this population. Could our users recognize landmarks on a mobile device? What kinds of landmarks might likely to be known and usable by a system? Are there landmarks that are easier or harder to recognize in general, or are useful landmarks heavily dependent upon the individual? Do users "plan" farther when given a landmark rather than a turn-by-turn direction such as the ones used in our previous studies? Thus, we designed a repeated measures study in a realistic setting, our university campus, to explore multiple dimensions of landmark directions. Directions were classified along dimensions informed by empirical findings on the cognition of geographic space [13]:

Landmark type: Typical landmarks used in directions include buildings, sculptures, roads, etc. Landmark information could be derived from Graphical Information System (GIS) databases or the Web, where geotagged collections of landmarks are populated by web users (*e.g.*, Google Earth, Flickr). Sometimes there are multiple landmarks to choose from at a location, so we wanted to learn whether our users would be more successful at recognizing certain types of landmarks.

Uniqueness of the landmark: Unique landmarks often have names and might be photographed, while generic landmarks that our users might recognize without photos include bus stops, roads, parking lots, etc. While a unique landmark might be less ambiguous, if a user is unfamiliar with it, he or she may have to rely on recognizing its visual features. On the other hand, generic landmarks may be more commonplace and familiar, but without associated photos, variations in their appearance might make them difficult to recognize.

Landmark distance: Landmarks that are far away from a user's current location may be more useful for longer-range directions, as they may be visible for a longer duration as a user is moving. Also, their location with respect to the user's location do not change as quickly, thus minimizing any problems that could occur due to location inaccuracy. However, there is also a chance that there might be more obstructions that block the view of a distant landmark.

Orientation in relation to user: Landmarks may be in front of, behind, or on the left or right of a user. Intuitively, users should recognize landmarks that are directly in their view more quickly, but there are situations when no such landmark exists.

Alignment of landmark to path: Landmarks can be used as a goal for a user to move toward, to move away from, to cross (a road, for instance), or to keep alongside the user's side.

Perspective of photo: A landmark might be photographed from near the user's location, containing context surrounding a landmark to aid in recognizing it. However, the landmark itself may not as apparent as it might be in a close-up photo or a more "canonical" shot that emphasizes the distinctive features of the landmark.

For the study, we ported the application that ran on the iPAQ to a Nokia N80 mobile phone with 802.11 (WiFi) (see Figure 2). The new platform is capable of vibration feedback, a frequently requested feature to alert the delivery of a direction. It also provided a smaller form factor as well as button input capability. The latter allowed us to introduce a "Help" button to the study, which study participants were informed that they could press to request help rather than directly ask a researcher for help during the study. While we did not implement any functionality in the button, we used it to observe whether participants could remember to request help, and if so, under what circumstances. We also used it as a basis to later discuss what kinds of help they would want in a real situation navigating own their own.

A. Methodology

We recruited 9 participants[1] with cognitive impairment through a University research center and an outpatient re-

[1]As an example of how real the problem of wayfinding can be, a tenth participant was recruited for the study but due to difficulties in wayfinding, could not reach our campus.

TABLE II
LANDMARK STUDY PARTICIPANT DEMOGRAPHICS. *MS:* MULTIPLE SCLEROSIS, *TBI:* TRAUMATIC BRAIN INJURY, *MD:* DUCHENE'S MUSCULAR DYSTROPHY.

Participant	Gender	Age	Primary Health Condition
1	Female	60	Post-stroke
2	Female	40	MS
3	Female	28	TBI
4	Male	21	Asperger's
5	Male	57	MS
6	Male	30	Asperger's
7	Male	21	MD
8	Male	51	MS
9	Female	60	MS

habilitation clinic. Participants ranged in age from 21–60 (mean 41) with 4 women and 5 men (see Table II for more demographics).

Researchers met with the participants and explained the goals of the study, showed the interface used, and led them to 4 locations on a university campus. At each location, participants were tasked with following 5 separate directions that used surrounding landmarks; see Figure 3 for examples of directions at one such location. The order of locations was varied and the order of directions at each location was randomized. Participants were encouraged to talk aloud, while researchers shadowed and tracked navigation errors, participant confusion, etc., that were part of a set of predetermined categories of observable behaviors. At the end of the outdoor portion of the study (1–2 hours in duration), a semi-structured interview was conducted that asked whether they liked different aspects of the directions, what made directions easy or hard to follow, and other features they would like such as a "help" mode.

In order to focus on landmarks and reduce the number of factors in the study, arrows were not overlaid on directions.

B. Results

We collected and labeled 180 observations of participants following the set of directions. Participants correctly followed directions 150 times. Several factors are likely to have played a part in the 30 times participants incorrectly followed the directions. Misunderstanding the direction (*e.g.*, mistakenly walking toward rather than away from a landmark) was noted in 13 observations. Misinterpretation due to direction ambiguity (*e.g.*, walking toward a street that bordered campus rather than an on-campus road several meters away) was noted in 15 observations. Participants showed signs of confusion (*e.g.*, circling around, pacing) 16 times, though that did not always result in choosing an incorrect path. Despite being confused or unsure, participants requested help only 11 times.

Because we recruited people who had not participated in our earlier studies, we ended up with different representation of health conditions. Unlike participants in our previous studies, these participants were not as likely to confuse their left and right sides, suggesting that they may have had a higher capability for wayfinding. However, they had other difficulties that shows the need for a wayfinding system that can support a range of individual wayfinding capabilities.

Directions using photos taken from the participant's perspective were less likely to lead to difficulties and were not involved in any incidences of misinterpretation caused by ambiguity (χ^2=2.8409, df=1, p<0.01). We initially thought that users would have difficulty clearly seeing the features of a landmark when the photo was in perspective, given a mobile phone's limited screen size. In a close-up photo, landmark features occupy more of the screen at the expense of the surrounding context. The results and participant comments suggest that this additional context was key to increasing the understandability of directions, because it lessened the cognitive effort required to identify landmarks.

Participants made fewer errors when directions featured a road or sculpture (χ^2=8.6154, df=1, p<0.01) rather than a building or miscellaneous landmarks (*e.g.*, parking lot, flagpole). They also made fewer errors when tasked with walking toward rather than to the right/left or away from a landmark (χ^2=12.1333, df=4, p<0.05). While we chose landmarks that had distinctive features, we believe that landmarks such as buildings, not photographed in perspective, were more challenging for participants to clearly identify. This was highlighted in several sessions, when a participant would focus on finding the reference landmark first, then forget where the direction told him/her to go in relation to it, or vice versa.

> ***P6:*** *The first step... was to have the instruction of turning to the left or whatever, so because of that I focused. That was my priority, and hence I didn't always go to the second step on the process.*

When a referenced landmark was located behind them, 6 of the 9 participants went the wrong way at least once. Even though they were reminded that the directions could reference landmarks anywhere around their location, participants commented that they expected to have landmarks in their field of view, and missed things such as a flagpole because it was behind them and taller than they expected.

> ***P1:*** *If I wasn't facing in a particular direction, like I wasn't sure about the flagpole. I thought about it and twirled around a bit... I thought that in the direction that I'm looking, that's where it's going to be, so I just looked there.*

Our qualitative observations and participant feedback illuminated some more issues to consider:

Effort vs. time: Individuals with MS often experience fatigue and our participants with MS mentioned that one of their concerns when traveling is knowing about the effort needed to complete a route. Specifically, they noted that they might carefully plan a route that includes rest stops, or choose longer but easier routes versus shorter, more difficult routes (*e.g.*, with lots of stairs) in order to conserve their energy. The system has the potential for minimizing such effort, and also providing routes that include wheelchair or ramp access for those in wheelchairs or prefer not to take stairs.

> ***P8:*** *I mean I could go, I would go [along a] shorter*

[length route] if I had to do two flights of stairs maybe, as opposed to, like a longer [length route] if I had to go five flight of stairs or so.

Pre-existing knowledge of places: Some participants were familiar with the campus or surrounding area, while others were not. We did not use any place names in the study, but noticed that once some participants recognized a landmark, they would often mention it by its name. By using more familiar landmarks in directions when possible, the system could lessen some of the cognitive effort needed by a user when identifying visual features in a photo. In some cases, it may not even be necessary to present a photo, or even detrimental if it makes a user hesitate and verify the landmark's location.

> ***P8:*** *I couldn't see it because it was obscured by the Safeco building. I think that is what [that building] used to be called and so it is now. I just knew where that was but I'm not sure I would have spotted it among the trees.*

Cardinal directions: Some participants were aware of their orientation with respect to the cardinal directions (north, south, east, west). In some situations, referring to those directions might have been easier or less ambiguous to them.

Level of detail: Some participants did not think of the route in terms of following path segments. Instead, they would interpret directions literally. For example, unless a crosswalk was mentioned in the direction, they would cross the street from their starting location. Other participants interpreted the directions as general guidelines, so they remained on paths or chose alternate but equivalent paths that they knew would reach the same destination. The system needs to provide appropriate directions to individuals on either side of this spectrum to avoid potentially dangerous situations while also not bogging down the user with too many short-range directions.

Error detection: When participants went in the wrong direction, some checked as they moved and realized their mistake, but others committed to their choice and did not reevaluate it. The common behaviors we observed when participants could not find a landmark were repeatedly turning in place or taking a "best-guess" and moving in that direction.

> ***P2:*** *I actually considered asking for clarification using the help button... But I didn't, because there's something about momentum that once you start moving, it's way easier to keep moving than it is to make everything stop.*

Help: Many participants did not press the Help button on the phone during the study. Besides not wanting to "make everything stop," it is possible that they could not decide when they needed help. As one participant noted, such an event often causes some level of stress and impedes problem-solving and meta-cognition. However, if the system were able to determine that help was needed, the kinds of help that participants suggested included revealing more detail about the landmark via text or animated zooming, providing a different set of directions, or calling another person. Calling another person was widely considered an action that would be taken as a last resort, but potentially necessary at times when totally lost.

> ***P4:*** *It would give you the direction in a different way... You could have a GPS function and a person [elsewhere] to find out where you are and then, when you press the help button, it will call a certain person who knows that area. They would be able to see where you are located and maybe look on the map to help you to find where to go?*
> ***P5:*** *I know it's around here someplace, so should I take a left or a right? That would be one level, the other level would be I'm on campus but I have not a clue where I'm going...*

Device issues: The vibration notification was a welcome feature to study participants, although if a user was not holding the device (e.g., when the device was resting on a wheelchair tray) then its usefulness would be diminished. Most participants said they could view the text on the screen without trouble. Unexpectedly, overcast conditions caused more problems for viewing the screen than sunny conditions, because the screen would reflect the cloud cover and could not be easily moved to shield away from the source of the glare. Under these conditions more care needs to be made in selecting landmarks, potentially including the use of animation (as was suggested) to zoom in on the visual features of the landmark that a user could look for.

Situational issues: While participants might have preferred or been successful with certain types of directions, several mentioned that their situation could have a significant impact on how they wanted the system to behave.

> ***P2:*** *For me when I'm on a big relapse, I wanna know how to get to where I need to go as quickly and as easily as possible.*
> ***P6:*** *I think who cares, you know, I just went. But if I wanted clarity... because I was really nervous about finding a place... it depends upon how well I know the area, how comfortable I feel being in the area...*

C. Summary

These results suggest several considerations when choosing the appropriate landmark and its photo representation when providing directions to help guide individuals with cognitive impairment. Nearby landmarks that are in the user's path should be preferred, and should be shown with a photo of the landmark from the user's current view. Identifying a landmark can be a cognitively challenging task, and if an individual does not find the landmark immediately, they may become stressed or confused, making it even more difficult for them to perform the problem-solving necessary in navigating. The best photos are the ones that lower such cognitive effort by providing features that are evident to the particular individual.

While certain types of directions did not match the majority of our users' expected usage model, many directions elicited more varied responses. Only 4 of the 20 directions were misunderstood by more than 2 participants, while 7 directions were misunderstood only by a single participant. These findings suggest that the ability to adapt the photo selection algorithm to individual users is a crucial requirement for the system.

V. Design Implications and Next Steps

Our studies have shown a need to support both customization and adaptation in a wayfinding system. Supporting customization involves incorporating individual users' health conditions, preferences, ability to handle detail, error behavior, safety concerns, and place familiarity, among others. Adaptation involves adjusting system behavior when initial customization is not sufficient, because of changes to the situation, due to user stress or energy levels, the environment[2], or users' own preferences.

Current navigation systems are limited in their ability to support customization and adaptation. For example, Global Positioning System (GPS) navigation devices give users the ability to choose between quickest and shortest routes, but every user that chooses the same route will receive the same type of direction, without regard to user preference. GPS devices also do not adapt based on user behavior – if a user does not wish to follow the device's proposed route, the device may create a new route, but the next time the user is traveling to the same destination, the device will revert back to the original route. Because GPS units do not have alternative methods for delivering directions, they cannot produce different levels of help that a user may desire. Finally, current devices do not support incorporating landmarks into directions, despite the utility of landmarks in pedestrian wayfinding.

To produce a wayfinding system that better supports the needs of individuals with cognitive impairments, we must enhance the user model that control the system's routing and message delivery. We are developing a system to automatically generate customized directions. The central piece of the system is to develop a decision-theoretic framework for choosing appropriate directions and adapting to user success over time. The system will automatically generate directions that previously required manual creation. We are also incorporating a landmark selection system that can retrieve photos of landmarks based on criteria that represent what is best suited for the individual user, such as a photo that shares the same perspective or highlights a visual aspect that the user tends to recognize more easily.

A. Framework for generating directions

Our studies have produced much evidence that users are best served with tailored directions. We have turned to representing the problem of choosing directions using the Markov decision process (MDP) framework. MDPs are defined by $state$ and $action$ sets and one-step $transitions$. States have associated $rewards$, and a solution to an MDP is a $policy$ that maps states to actions in order to maximize expected reward. A key aspect of MDPs is that they can be used as a framework for learning and adaptation – transition probabilities may be approximated at first and then updated given observed behavior. Techniques for solving MDPs have been shown to enable the generation of navigation plans in robotics, and we believe they apply well to our problem of choosing directions along a route for an individual with cognitive impairment that maximizes the chances of success.

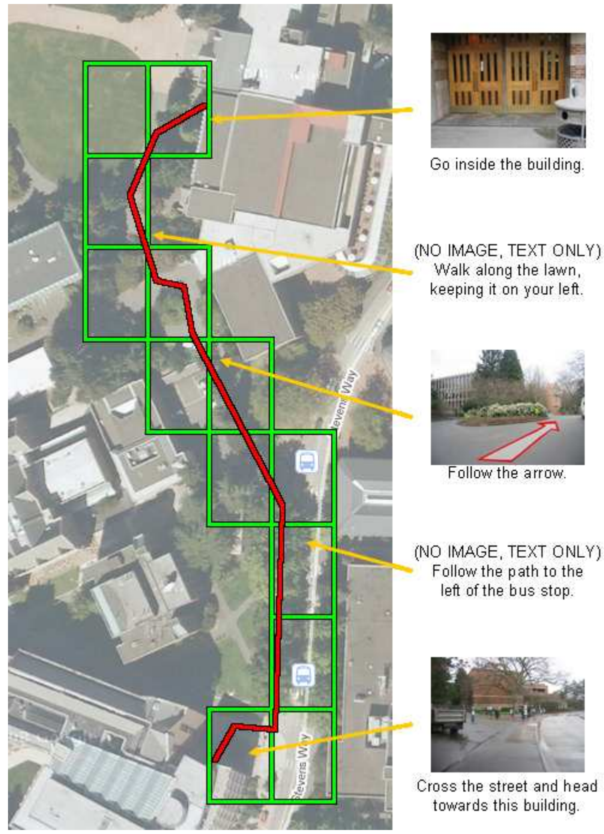

Fig. 4. An example route showing various types of directions selected assuming a user follows each direction correctly.

To illustrate how an MDP might represent the problem of generating directions, consider a scenario where a person wants to get from one building to another (see Figure 4). The states in the MDP would include the user's location, orientation, velocity, current direction given by the system, and a window of history that summarizes whether the user has been generally successful or having difficulty following the directions. The actions of this MDP encode the directions that the wayfinding system could give, such as a landmark-based direction or a lower-level direction such as a turn message. Transitions represent the next state that the user would be in if the system were to provide a direction. The probabilities would be initially populated by our user study observations and customized for each individual. A positive reward would be given in states where the user has reached the desired destination, a negative reward would be given in states where the user has not, and a very large negative reward could be given in states deemed "unsafe" situations, such as ones where

[2] In our landmark study, a large statue that had not been moved for decades was taken down for repairs. Such changes are difficult for any system to predict, but should be handled by producing alternate directions to avoid a breakdown in wayfinding.

the user might cross traffic while confused.

B. Landmark selection system

Automatically generating landmark based directions requires selecting an appropriate landmark and an image of that landmark (text and map directions could also be used). The landmark selection system we are using leverages existing collections of geotagged images to retrieve suitable images of landmarks [9]. Images are annotated with the location where they were taken and the landmark they contain. This makes it possible to select an image from the database that relates to the user's current location and intended direction, for example, to select an image of the building they should walk toward in a perspective close to their current position. Additional aspects of the image database make it possible to choose landmarks by popularity (number of images in the database) and to choose a quality representative view from the possible choices. These images can also be augmented with arrows, and the database can contain landmarks without images, falling back to text-only instructions when necessary. Our user studies will inform this system about how to choose the best landmark images for the average user, and our adaptive system can provide parameters to make customized landmark choices.

C. User interface design considerations

Even if the model is extensively customized for a user, there will still be times when it might not produce the correct direction or route for a user. For instance, a user might become more familiar with an area, a path might be blocked off due to construction or a landmark might change. Design considerations that we can include in the system include a knowledge of areas that users are familiar with, several levels of user- or system-initiated help ranging from giving a different direction type to contacting a caregiver, and safety warnings about traffic. We will thoroughly evaluate our design with potential end-users under realistic conditions. Our next study plan includes a comparison of a non-customized system to one that has been customized either through past observations (with returning study participants) or via interview or short pre-trial evaluation.

VI. Conclusion

As part of an ongoing project to design a functional wayfinding system for people with cognitive disabilities, we have conducted two user studies that informed our understanding of how this user population might need customized and adaptable directions. Our first study showed that individuals with cognitive impairments can follow a set of image, audio, and text directions outdoors. Based on the results of the first study, we decided to examine the use of landmarks as a way to provide "high-level" directions as a way to overcome some of the limitations of the types of directions we have used up to this point, which require strict adherence to a route and therefore highly precise message timing. While certain types of directions seem to be more intuitive and easier to understand in general, we observed quite a large variation in how individuals wayfind. We are using these findings to iterate on our design and focus the next steps of the project that involve representing the problem as a Markov decision process (MDP). By using MDP as the model for choosing appropriate directions, we can customize directions to accommodate individual health conditions, direction preferences, place familiarity, and wayfinding error behavior. In addition, MDPs provide a way to continuously adapt to the user, so that customizations can be adjusted over time.

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References

[1] A. L. Liu, H. Hile, H. Kautz, G. Borriello, P. A. Brown, M. Harniss, and K. Johnson, "Indoor Wayfinding: Developing a Functional Interface for Individuals with Cognitive Impairments," in *Assets '06: 8th ACM SIGACCESS Conference on Computers and Accessibility*. ACM, 2006, pp. 95–102.

[2] S. Carmien, M. Dawe, G. Fischer, A. Gorman, A. Kintsch, and J. F. Sullivan, "Socio-technical environments supporting people with cognitive disabilities using public transportation," *ACM Transactions on Computer-Human Interaction*, vol. 12, no. 2, pp. 233 – 262, Jun 2005.

[3] D. J. Patterson, L. Liao, K. Gajos, M. Collier, N. Livic, K. Olson, S. Wang, D. Fox, and H. Kautz, "Opportunity knocks: a system to provide cognitive assistance with transportation services," in *Proceedings of the 6th International Conferenceerence on Ubiquitous Computing*, 2004.

[4] D. Burke, S. Leeb, R. Hinman, E. Lupton, J. Burke, J. Schneider, B. Ahangar, K. Simpson, and E. Mayer, "Using talking lights to assist brain-injured patients with daily inpatient therapeutic schedule," *Journal of Head Trauma Rehabilitation*, vol. 16, no. 3, pp. 284–91, 2001.

[5] S.-K. Tsai, "Wader: a novel wayfinding system with deviation recovery for individuals with cognitive impairments," in *Proceedings of the 9th International ACM SIGACCESS Conferenceerence on Computers and Accessibility*. ACM, 2007.

[6] Y.-J. Chang, S.-K. Tsai, and T.-Y. Wang, "A context aware handheld wayfinding system for individuals with cognitive impairments," in *Assets '08: Proceedings of the 10th International ACM SIGACCESS conference on Computers and accessibility*. New York, NY, USA: ACM, 2008, pp. 27–34.

[7] A. J. May, T. Ross, S. H. Bayer, and M. J. Tarkiainen, "Pedestrian Navigation Aids: Information Requirements and Design Implications," *Personal Ubiquitous Computing*, vol. 7, no. 6, pp. 331–338, 2003.

[8] J. Goodman, P. Gray, K. Khammampad, and S. Brewster, "Using Landmarks to Support Older People in Navigation," in *Proceedings of Mobile HCI 2004*, ser. LNCS, S. Brewster, Ed., no. 3160. Springer-Verlag, Sep. 2004, pp. 38–48.

[9] H. Hile, R. Vedantham, A. Liu, N. Gelfand, G. Cuellar, R. Grzeszczuk, and G. Borriello, " Landmark-Based Pedestrian Navigation from Collections of Geotagged Photos," in *MUM 2008: Proceedings of ACM International Conferenceerence on Mobile and Ubiquitous Multimedia*. ACM Press, 2008.

[10] S. Thrun, W. Burgard, and D. Fox, *Probabilistic Robotics*. MIT Press, 2005.

[11] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*. MIT Press, 1998.

[12] J. Boger, G. Fernie, P. Poupart, and A. Mihailidis, "Using a POMDP Controller to Guide Persons With Dementia Through Activities of Daily Living," *the Adjunct Proc of the Fifth International Conference on Ubiquitous Computing (UBICOMP), Seattle, WA*, 2003.

[13] R. Kitchin and M. Blades, *The Cognition of Geographic Space*. I.B.Tauris, 2002.