The final, definitive version of this paper has been published in Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 59/1, December 2016 published by SAGE Publishing, All rights reserved.

Experimental Evaluation of Indoor Navigation Devices

Umair Rehman and Shi Cao
Department of Systems Design Engineering
University of Waterloo
Waterloo, Ontario, N2L 3G1 Canada

Augmented reality (AR) interfaces for indoor navigation on handheld mobile devices seem to greatly enhance directional assistance and user engagement, but it is sometimes challenging for users to hold the device at specific position and orientation during navigation. Previous studies have not adequately explored wearable devices in this context. In the current study, we developed a prototype AR indoor navigation application in order to evaluate and compare handheld devices and wearable devices such as Google Glass, in terms of performance, workload, and perceived usability. The results showed that although the wearable device was perceived to have better accuracy, its overall navigation performance and workload were still similar to a handheld device. We also found that digital navigation aids were better than paper maps in terms of shorter task completion time and lower workload, but digital navigation aids also resulted in worse route/map retention.

INTRODUCTION

Indoor navigation technologies are becoming an imperative area for research and development because people are readily using location-aware applications, and indoor environments are presumed to be the cornerstones for these applications (Coelho, Aguiar, & Lopes, 2011; Tony Costa et al., 2013). With the increasing prevalence of smart mobile devices, the application is also not limited to providing navigation aid but can benefit a wide range of domains (Jeong, Choi, Han, Suh, & Yeo, 2011). Industries such as retail, entertainment, healthcare, and manufacturing are all potential domains for location-aware applications (Tony Costa et al., 2013).

Few studies have examined human factors and usability issues regarding indoor navigation technologies. Part of the reason is that the technology itself is still being developed. Although human factors regarding outdoor navigation devices and interfaces have been investigated, the technologies (such as sensors) used in outdoor navigation devices are different and currently more reliable than indoor navigation devices (Pahlavan, Li, & Makela, 2002). There is a strong need to test and evaluate the human factors of indoor navigation technologies and devices (Brown & Pinchin, 2013). The current study therefore investigates indoor navigation technologies from cognitive ergonomics and human performance standpoints, because most previous studies related to indoor navigation focused on analyzing or improving localization techniques rather than human factors issues such as workload, comfort, and map retention (Mulloni, Seichter, & Schmalstieg, 2011).

Human factors evaluation of interface design plays an important role in determining the performance and usability of indoor navigation systems. Augmented reality navigation systems directly mark the target route in the real world with augmented images. It is expected to increase user engagement and reduce attentional effort in navigation tasks. Previous studies have tested AR and virtual reality interfaces, showing that AR localization was perceived to be more accurate and preferred by most subjects (Möller, Kranz, Huitl, Diewald, & Roalter, 2012). Later studies, however, uncovered some disadvantages of augmented reality implemented on handheld devices (Möller et al., 2014). Users have to hold the devices in an appropriate manner (specific orientation and position) for the applications to work properly. This requirement influenced critical usability components such as navigational accuracy and user satisfaction, and therefore it may hinder wider user adaptability of such AR applications.

Most existing studies implemented AR indoor navigation methods on handheld devices. There is a lack of studies testing and exploring wearable devices. Augmented reality implemented on wearable devices can have great values in a variety of industrial domains where navigational assistance is much needed. In this study, we examined a new AR indoor navigation prototype implemented on a wearable device (Condition 1) and on a handheld device (Condition 2), with a paper map as a baseline in comparison (Condition 3). We measured navigation performance, workload, and also map retention. Map retention concerns with users' ability to remember the route when the aid is unavailable. It is necessary to consider such situations, especially for users in extreme environment such as firefighting and combating. Previous studies have identified negative effects of navigation aids on route retention (Holmquist, 2005). As a result, we tested not only performance while using the navigation aids but also route retention after using the aids in the current study.

The novelty of this study includes the development of a new indoor navigation prototype for a wearable device that used augmented reality and image recognition for navigation (Figure 1). The same technology was also deployed on a handheld device (cell phone) and the user interface designed was uniform across both the devices. During navigation, augmented reality technology further assisted the subjects with directional information and audio assistance superimposed on the live video footage captured by the camera of the devices. This system required both accurate positioning and orientation; otherwise the augmented information could have caused confusion due to discrepancy in the real and augmented world.

Figure 1. The figure describes how the two navigational devices would be physically operated for indoor navigation. The wearable device on the right (i.e. Google Glass) works as a head mounted display where the information is received on the augmented reality screen focused on the pupil of the right eye. The smartphone on the left needs to be positioned in an upright position for appropriate orientation.

After the development of the technical solution, an experiment was devised in order to assess all imperative aspects of this indoor positioning system from human factors and performance standpoints. This experiment took into account user-based evaluations alongside performance and workload measures. Diagnostic, summative, and formative forms were all exercised in order to ensure a comprehensive analysis. It was very important to ascertain how accurate the users perceived the devices to be and how much contextual information they retained after using the navigation aid. The test of route retention was important because it reflects to what extent users rely on the navigation aids and what happens if the assistance devices are removed or not available. Through the experimental analysis, we assessed different indoor navigation aid devices on the basis of perceived accuracy, comfort, subjective workload, efficiency (traversal time), and route retention error.

METHOD

Participants

Twenty-seven adults (15 males and 12 females), all of whom were University of Waterloo students, participated in this study. None of the participants had used mobile navigational aids in indoor environments; however all were well aware of mobile navigational aids and had experienced them in outdoor environments. The majority of the participants stated that they were confident in navigating in indoor environments. All had normal or corrected-to-normal visual and auditory acuities.

Tasks and materials

The indoor navigation system prototype developed in this study used image recognition technique as a way to achieve indoor localization. It functions by matching the live video feed images from the camera of the device against a database map of previously collected 3D panoramic images. The system would know the position of every image in the database, and therefore the position of the device could be localized after matching camera images to database images. Using the nearest image allocation procedure, the system can pinpoint the user's position at any given time. Directional information including both visual arrows and voice guidance was implemented as navigation assistance (Figure 2).

Figure 2. Screenshot of the indoor augmented reality navigation aid application while being assessed at the test location. The augmented arrow and text are visual instructions displayed on the screen of the devices. The application also provides voice instructions that tell the user the same instructions as visible on the screen. The same interface was deployed on both digital devices used in the experiment.

In order to implement this prototype, first we needed to 3D scan the test environment. We used Metaio creator (www.metaio.com) to scan the test location (Games Institute at University of Waterloo). The Metaio Creator was also used to add the augmented arrows and audio guidance on the 3D map of the test environment. Three distinct routes (Figure 3) were formulated and optimized for the experiment to ensure that navigational instructions were added at the most appropriate places. Once the user interface was properly designed, it was deployed on both a handheld device (Samsung S5-Android Cell Phone) and a wearable device (Google Glass). The wearable device was equipped with a built-in camera, a head mounted display, and a speaker that allow image recognition as well as both vision and voice based navigation aids. The third navigational device was the paper map, which was a CAD (computer-aided design) version of the floor plan.
The tasks required the participants to navigate through the test location and find specific books located on different shelves using different types of aids. Such tasks are typical representations of indoor navigation.

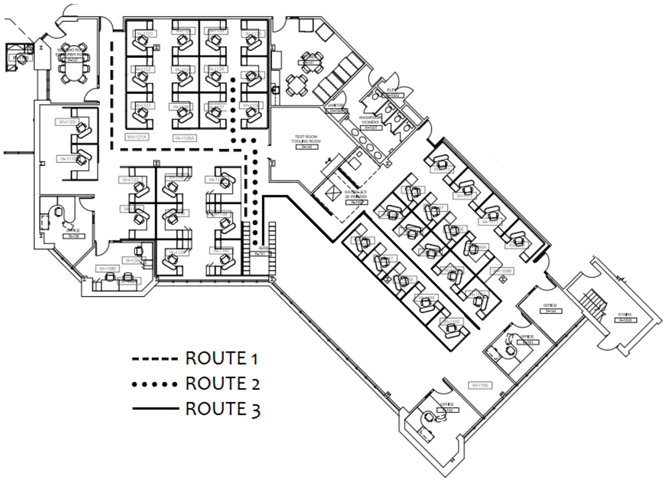


Figure 3. Three distinct routes used in the experiment. The three test routes are highlighted on the floor plan of the test location. The users used a blank version of the same floor plan to draw the trajectories after the completion of the experiment as a way to measure route retention. A blank floor plan was also used in the paper map condition.

Design and measures

The experiment used a within-subject design. The independent variable was the type of navigation aid device, including three conditions− paper map, cell phone (handheld), and Google Glass (wearable).The dependent variables included subjective workload ratings using NASA-TLX (raw overall score), perceived accuracy, contextual retention error, and efficiency (i.e., traversal time or task completion time). Each dependent variable was individually measured for the three navigational devices. The testing of each device used a different route, and there were a total of three routes (Figure 3). The pairing between devices and routes was balanced across subjects.

In order to measure unprepared route retention performance, the participants were asked to draw all the three trajectories only after completing all the three routes. Since the order of experiencing the three devices were balanced, the carryover effects should be controlled.

Distance errors resulting from participants' map drawing were used to quantify the contextual route retention error. The three target routes (Figure 3) had the shortest distance to their destinations, and therefore any extra distance drawn by the participants means error. We compared the ground truth (i.e., target routes) on the map with the routes drawn by the participants, by superimposing both of them on a single map. The additional distance drawn by the participants was recorded as map retention distance error. In order to determine which device was most efficient, we recorded the time taken by each subject to complete a single route (traversal time) for each device and calculated the average that represented the efficiency for each device. A set of subjective ratings for perceived accuracy was obtained through a questionnaire (5-point Likert scale) conducted after the experiment. The questionnaire also included subjective evaluation questions for wearability comfort, usability control comfort, and display comfort ratings (5-point Likert scales) and subjective workload (raw NASA-TLX, without the weighting procedure).

Procedure

First, the participants read the information letter that described the details of the experiment, and then they filled the consent form and the pre-experiment questionnaire. Short practice for about 5 minutes was provided for the participants to get familiar with the devices. Most participants had not used Google Glass before, so we gave them adequate time to adjust themselves with the navigational technology until they felt fully confident to initiate the formal experiment. From here on they were instructed to navigate using the three aid devices (wearable, handheld phone, and paper map) to shelves located at the test location to find three books (one for each route). They were instructed to find each book as quickly as possible. The experimenter shadowed and timed the participants. Once the participant completed testing the three devices, they were asked to fill the post-experiment questionnaires. In the end, they were given a blank map and were requested to draw the three trajectories as they remembered during the experiment to measure the route retention performance.

RESULTS

Repeated measures ANOVAs (analysis of variance) were conducted to examine the effects of navigation aid type, and pairwise comparisons were conducted (with Bonferroni correction) to compare the three types of aids (i.e., wearable, cell phone, and paper map).

The effect of aid device type on traversal time (task completion time) was significant, $F(2, 52) = 10.494$, $p < 0.001$, $\eta^2 = 0.288$. No significant difference was found between the wearable (106 s) and cell phone (113 s) conditions ($p = 1.000$), but both of them had significantly shorter completion time than the paper map (249 s) condition (p values ≤ 0.01) as shown in Figure 4(a).

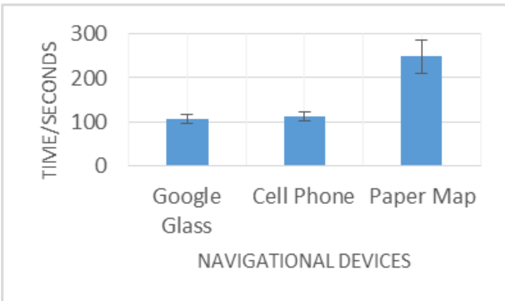
The effect of aid device type on perceived accuracy was significant, $F(2, 52) = 14.386$, $p < 0.001$, $\eta^2 = 0.356$ as shown in Figure 4(b). The wearable aid was perceived to be more accurate (4.4) than both cell phone (3.7) and paper map (3.1) conditions (p values ≤ 0.001); no significant difference in perceived accuracy was found between the cell phone and paper map conditions ($p = 0.197$).

Similarly, the effect of aid device type on NASA-TLX overall workload score was significant, $F(2, 52) = 30.422$, $p < 0.001$, $\eta^2 = 0.539$. No significant difference was found between the wearable (20.8) and cell phone (27.3) conditions ($p = 0.254$), but both of them had significantly smaller overall workload than the paper map (53.4) condition (p values < 0.001) as shown in Figure 4(c).

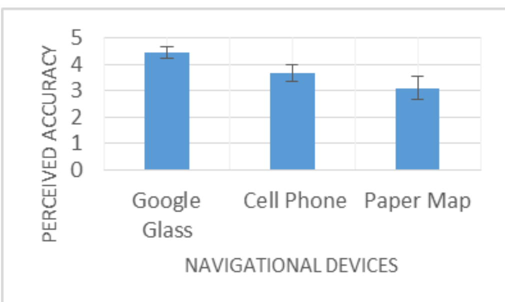
The effect of aid device type on map retention distance error was also significant, $F(2, 52) = 7.669$, $p = 0.001$, $\eta^2 = 0.228$. No significant difference was found between the wearable (1.6 m) and cell phone (1.6 m) conditions ($p =$

1.000), but both conditions had significantly larger retention error than the paper map (0.6 m) condition (p values ≤ 0.005) as shown in Figure 4(d).

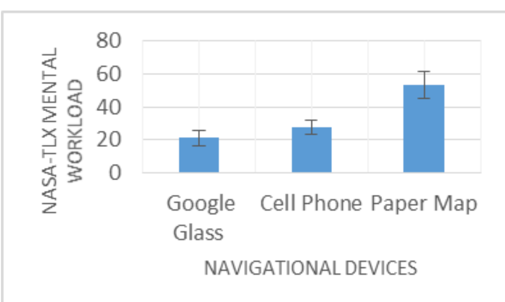
No significant effect was found on the wearability comfort ($p = 0.055$, $\eta^2 = 0.106$), usability control comfort ($p = 0.178$, $\eta^2 = 0.064$), and display comfort ratings ($p = 0.441$, $\eta^2 = 0.031$).



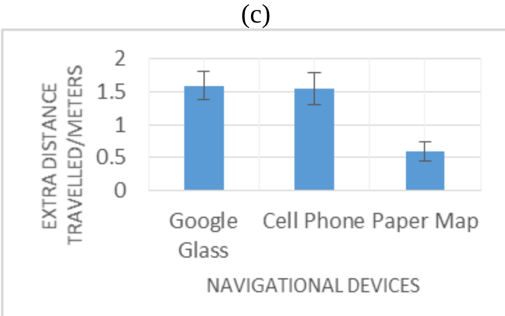
(a)



(b)



(c)



(d)

Figure 4. Effects of navigation aid device type on traversal time (a), perceived accuracy (b), NASA-TLX overall workload rating (c), and route retention error (d). Error bars represent 95% confidence interval.

DISCUSSION

In this experiment, the wearable device (Google Glass) was perceived to have the best accuracy. A potential explanation for this would be that the camera of the wearable device was located at a higher position than the handheld cell phone; the high position gave it a wider view for image recognition resulting in better localization. The camera of the cell phone was usually held at mid-body level, and therefore the perceptibility for image recognition was not ideal. Also the head-up display made the augmented reality experience more intuitive. The virtual representation of directional instructions on the camera feed was directly concentrated on the pupil of the eye, and the camera also moves naturally with head movement. This feature enhanced the navigational experience of the wearable device as its interface became more focused and adaptive. As a result, the wearable device provided the shortest navigation time on average, though not significantly different from the cell phone condition. The traditional paper map, however, was a very slow medium for directional assistance. It took participants almost twice as much time as the Google Glass and the cell phone conditions mainly because of the time required to mentally understand the map and then translate it to the contextual environment.

No significant difference was found on subjective comfort ratings (wearability comfort, usability control comfort, and display comfort) between different devices. This is possibly because each individual device had certain pitfalls that influenced the participants' experience. The cellphone had to be kept at a certain position and orientation in front of the head for the augmented information to match the real-world perspective. The glass did not have this issue because the head-up wearable display could move as the head. But adjusting the glass for proper visibility was very meticulous especially for people wearing frame glasses, and sometimes the Google Glass application had technical difficulties due to slower processing speed and shorter battery life. For the paper map condition, the floor plan was not easily explicable because the paper map had too much information so that discerning the area of interest became challenging.

The NASA-TLX results showed that navigation using the paper map caused the highest workload. The participants had to analyze where they were on the map with respect to the environment and also identify their target location; then they need to constantly analyze the surrounding for potential clues. All this yielded a heavy toll on the time taken to complete the experiment and raised participant dissatisfaction. The workload values in the wearable and cell phone conditions were very similar since neither was a cognitively strenuous exercise. Another key aspect we wanted to evaluate was route retention in case the user had to navigate the same routes without the assistive devices. We concluded that the wearable device and the cell phone performed poorly in this regard as the retention errors were larger than the paper map condition. When using the digital devices for navigation, participants get used to simply following the navigational instructions and are not actively processing the surrounding environmental information. In contrast, when using a paper map, the participants have to analyze the environment alongside the map in order to navigate successfully. Automated navigation aids resulting in worse map retention performance could become a problem when they become dysfunctional, especially for users in critical situations like rescue workers or fire fighters. A potential solution could be to develop adaptive automation aid system that could balance the need for navigation aid and the need for map retention. Future studies are needed to identify better design solutions.

In summary, the wearable device was perceived to be more accurate, but objective performance and subjective workload results showed that the wearable device condition was not significantly different from the handheld cell phone condition. This result might be explained by the fact that the current experiment was conducted in a relatively simple indoor environment and used relatively short routes. Since the wearable device (Google Glass) has very limited battery life, and the 3D scan for the image recognition purpose is also time consuming, it is a limitation that we do not have better technologies right now for a larger scale test. Based on the current results, we conclude that augmented reality indoor navigation implemented on the wearable device was neither worse nor better than the cell phone implementation. However, we still expect that a wearable implementation would be preferred when it is tested for a longer duration in a more complex environment, when holding a cell phone in front of the head becomes tiring. The current preliminary study would form the basis for future research using technologically superior wearable devices with better battery life and higher computational powers, testing and evaluating more advanced augmented reality indoor navigation prototypes in more complex scenarios.

ACKNOWLEDGEMENT

The authors would like to extend their sincere appreciation to the members of the Games Institute for their repeated support and appreciation throughout this research. This work was partially supported by an NSERC Discovery Grant (RGPIN-2015-04134).

REFERENCES

Brown, M., & Pinchin, J. (2013). Exploring Human Factors in Indoor Navigation. In *The European Navigation Conference*. Retrieved from http://www.researchgate.net/profile/Michael_Brown45/publication/258728932_Exploring_Human_Factors_in_Indoor_Navigation/links/00b49528e2abb7acac000000.pdf

Coelho, P., Aguiar, A., & Lopes, J. C. (2011). OLBS: Offline Location Based Services. In *Next Generation Mobile Applications, Services and Technologies (NGMAST), 2011 5th International Conference on* (pp. 70–75). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6081997

Holmquist, J. (2005). *Navigation aids in route training: Increase navigation speed, decrease route retention?*. University of Central Florida.

Jeong, G.-M., Choi, W.-S., Han, G. Y., Suh, D.-K., & Yeo, J.-Y. (2011). Paradigm Shift and the State of the Art of LBS in the Advent of Smartphone. In R.-S. Chang, T. Kim, & S.-L. Peng (Eds.), *Security-Enriched Urban Computing and Smart Grid* (pp. 251–258). Springer Berlin Heidelberg. Retrieved from http://link.springer.com/chapter/10.1007/978-3-642-23948-9_28

Möller, A., Kranz, M., Diewald, S., Roalter, L., Huitl, R., Stockinger, T., … Lindemann, P. A. (2014). Experimental evaluation of user interfaces for visual indoor navigation (pp. 3607–3616). ACM Press. http://doi.org/10.1145/2556288.2557003

Möller, A., Kranz, M., Huitl, R., Diewald, S., & Roalter, L. (2012). A Mobile Indoor Navigation System Interface Adapted to Vision-based Localization. In *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia* (pp. 4:1–4:10). New York, NY, USA: ACM. http://doi.org/10.1145/2406367.2406372

Mulloni, A., Seichter, H., & Schmalstieg, D. (2011). Handheld augmented reality indoor navigation with activity-based instructions. In *Proceedings of the 13th international conference on human computer interaction with mobile devices and services* (pp. 211–220). ACM. Retrieved from http://dl.acm.org/citation.cfm?id=2037406

Pahlavan, K., Li, X., & Makela, J.-P. (2002). Indoor geolocation science and technology. *Communications Magazine, IEEE*, *40*(2), 112–118.

Tony Costa, Sarah Rotman Epps, Thomas Husson, Julie A. Ask, Peter Sheldon, Carlton A. Doty, … Andia Vokshi. (2013). *Indoor Venues Are The Next Frontier For Location-Based Services*. Retrieved from https://www.forrester.com/Next+In+Tech+Indoor+Positioning/fulltext/-/E-RES82781?docid=82781