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Charles D. Baker
Governor

Karyn E. Polito
Lieutenant Governor

Stephanie Pollack
MassDOT Secretary & CEO

PERCEPT Indoor Navigation System for Visually Impaired: Beta Study

Principal Investigators
Dr. Aura Ganz
James Schafer
University of Massachusetts Amherst



Research and Technology Transfer Section
MassDOT Office of Transportation Planning



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16. Abstract Independent navigation through unfamiliar indoor spaces is beset with barriers for blind and visually impaired (BVI) individuals. A task that is spontaneous for people without disabilities has to be planned and coordinated with other individuals for the BVI population. Currently, there are no commercial systems that enable BVI users to independently navigate in indoor environments. The PERCEPT system (PERCEPT) is an affordable and accurate indoor navigation system for BVI users, developed by Prof. Ganz and her team at the University of Massachusetts 5G Mobile Evolution Lab. Using real-time localization and detailed navigation instructions that are automatically generated, PERCEPT enables BVI users to independently navigate through large indoor venues, as demonstrated in trials in Boston's North Station. An affordable and accurate indoor navigation system would (1) help BVI customers overcome barriers in navigating a complex MBTA transportation venue, to access the MBTA's subway and commuter rail systems; (2) strengthen MassDOT's and the MBTA's ongoing commitment to serve customers with disabilities; and (3) promote an equitable culture that serves all customers fairly. The project objective was to assist the MBTA to evaluate PERCEPT suitability for systemwide deployment. The study showed that (1) PERCEPT trial participants' feedback was positive; (2) the Bluetooth Low Energy infrastructure was robust and easy to maintain; and (3) the PERCEPT application was robust and could be remotely monitored.			
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PERCEPT Indoor Navigation System for Visually Impaired: Beta Study

Final Report

Prepared By:

Aura Ganz

Principal Investigator

James Schafer

Research Fellow

Electrical & Computer Engineering
University of Massachusetts Amherst
151 Holdsworth Way
Amherst, MA 01003

Prepared For:

Massachusetts Department of Transportation
Office of Transportation Planning
Ten Park Plaza, Suite 4150
Boston, MA 02116

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Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Executive Summary

This study, PERCEPT Indoor Navigation System for Visually Impaired: Beta Study, was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

Independent navigation through unfamiliar indoor spaces is beset with barriers for blind and visually impaired (BVI) individuals. A task that is trivial and spontaneous for people without disabilities has to be planned and coordinated with other individuals for the BVI population. Currently, there are no commercial systems that enable BVI users to independently navigate in indoor environments. The PERCEPT system (PERCEPT) is an affordable and accurate indoor navigation system for BVI users, developed by Prof. Ganz and her team at the University of Massachusetts 5G Mobile Evolution Lab. Using real-time localization and detailed navigation instructions that are automatically generated, PERCEPT enables BVI users to independently navigate through large indoor venues, as demonstrated in trials that were conducted at Boston's North Station.

Objective and Tasks

The project objective is to assist the Massachusetts Bay Transportation Authority (MBTA) to evaluate PERCEPT's suitability for systemwide deployment. To reach this objective, the research team accomplished all the tasks detailed in the proposal:

Task 1: Developed an in-app tutorial for the PERCEPT application. The tutorial explained to BVI users how to use PERCEPT. Up until this point, all study participants had received one-on-one training on how to use PERCEPT. During this beta study, each participant independently downloaded and used PERCEPT at North Station. The tutorial seamlessly transitioned the BVI participants into using all aspects of PERCEPT.

Task 2: Deployed Bluetooth Low Energy (BLE) tags in North Station. Using these tags, the PERCEPT app calculated the user's location in the venue. Given the user's location, PERCEPT provided the user with detailed navigation instructions from the current location to the selected destination. While BLE deployment from the prior North Station pilot covered the majority of the station, the team added a number of tags to cover areas that had been recently renovated.

Task 3: Developed an anomaly and crash analytics module used to optimize the operation and functionality of PERCEPT. The module monitored the tag infrastructure when participants were in the transportation venue, using the application and any operational or functional problems encountered by participants. This module generated an Issues Report, sent to PERCEPT cloud services, that included the types of issues encountered, along with a timestamp and location.

Task 4: Developed a human subjects protocol that was approved by the UMass Institutional Review Board. This protocol is required by UMass before conducting any human subjects trials.

Task 5: Prepared PERCEPT app for beta submission. The team prepared and submitted the PERCEPT application to Apple’s Test Flight platform, which was used to distribute the PERCEPT-beta application to the study participants. For Test Flight submission, researchers prepared the application description, screenshots of the application running, custom icons, and splash screens for each iPhone device. This Flight application was reviewed and approved by Apple.

Task 6: Issue resolution. Once the PERCEPT application was made available to beta participants, the research team monitored its deployment remotely, using the analytics module developed in Task 3. Any operational issues that occurred were resolved.

Task 7: Beta participant recruitment. The research team recruited 17 BVI participants from the following agencies: the National Federation of the Blind and the Visually Impaired Blind User Group. The recruitment was done through public meetings and cooperation with MBTA’s Office of System-Wide Accessibility.

Task 8: Reporting and presentation of research results. The authors prepared the final report, and monthly and quarterly reports, and presented their findings to the MBTA team throughout the study.

Deliverables

The team accomplished all the deliverables introduced in the proposal.

Deliverable 1: Implementation of in-app tutorial..

Deliverable 2: BLE tag deployment document that included BLE tag locations marked on North Station blueprints and a detailed table with description of each tag’s ID; deployed region in the venue; and description of the location in which it was deployed. All tags were deployed by MBTA staff according to the deployment document.

Deliverable 3: Implementation of the analytics module.

Deliverable 4: IRB protocol and related study documents that included questionnaires.

Deliverable 5: Implemented new PERCEPT App features, such as new rerouting mode and extended personalized wayfinding preferences.

Deliverable 6: Report that summarized user feedback, PERCEPT App usage, and tag maintenance.

Deliverable 7: Report that summarized recruitment efforts.

Deliverable 8: Monthly and quarterly reports, presentations to MBTA team, and final report.

Conclusions

In this project, the authors leveraged their expertise in the following research and development areas: localization, BLE tag deployment, navigation instructions generation, user interface design, experimental design, human subjects trials, development and testing of working systems, and software development for the iOS platforms and cloud services.

The proposed tasks and deliverables were all successfully completed. The authors concluded that the beta study itself was successful, due to the following observations:

- **The PERCEPT trial participants' feedback was very positive.** All participants mentioned that they will use PERCEPT if deployed at the MBTA. Note that in this study, the users independently downloaded and used the application instead of a controlled trial as in previous studies. Participants were able to independently install and learn how to use PERCEPT, and to navigate to the destinations in a complex station such as North Station. North Station is a challenging environment in which to navigate. It is large, open, complex, and can receive significant foot traffic during peak times. These facts showed the scalability of the PERCEPT application and its potential use by a large number of users in the MBTA.
- **The BLE infrastructure was robust and easy to maintain.** There was no malfunction or vandalism of the BLE tags. The tag batteries will drain about 18% per year, for a total of five years' battery life (there are tags with longer battery life). It was also shown that the tag replacement or addition effort was minimal. These facts are evidence to the scalability of PERCEPT and its applicability to systemwide deployment.
- **PERCEPT application is robust and can be remotely monitored.** There are two types of issues that were tracked: crashes in which a fatal error occurred and the application closed, and logical errors in which the application did not function as intended. Only a single type of each issue occurred early in the beta study. Both reports were identified through the analytics tools that were developed, and an updated version of the application was pushed to the participants.

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List of Acronyms

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1.0 Introduction

The World Health Organization reported that 285 million people are estimated to be visually impaired worldwide. Of those, 39 million are blind, and 246 million have low vision [1]. There is a recognized positive correlation between independent travel employment and issues of social equity. Independent navigation through unfamiliar indoor spaces is beset with barriers for blind and visually impaired (BVI) individuals. A task that is trivial and spontaneous for people without disabilities has to be planned and coordinated with other individuals for the BVI population. Although many improvements and aides are available to assist BVI individuals in outdoor settings, there has yet to be developed a reliable system that combines independence with accuracy and affordability for indoor navigation.

Currently, there are no commercial systems that enable BVI users to independently navigate in indoor environments using real-time localization and detailed navigation instructions that are automatically generated. There have been a number of research projects that aimed to help BVI users navigate in unfamiliar indoor environments [2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17]. However, none of these papers has introduced an automatic generation of detailed navigation instructions, which is necessary for a scalable and affordable indoor navigation system for BVI users.

The PERCEPT system, an accurate indoor navigation system for blind and visually impaired (BVI) individuals in buildings, introduced by the authors in Ganz, 2014 [18], was developed with the cooperation of the Massachusetts Orientation and Mobility division from the Massachusetts Commission for the Blind. Using the PERCEPT system [18] the user carries a smartphone that runs the PERCEPT application, which provides landmark-based navigation instructions to help the user navigate through indoor spaces to a chosen destination. PERCEPT includes three main modules: (1) the vision free user interface, using Android and iPhone accessibility features; (2) the localization algorithm; and (3) the navigation instructions algorithm. The user downloads the application from the PERCEPT server prior to his/her arrival at the indoor environment. The application flow includes the following steps: (1) start the application; (2) localize the user and determine current location; (3) select the destination using the accessible “vision-free” interface; and (4) receive audible detailed navigation instructions.

This report is organized as follows: Sections 2.1. and 2.2. provide an overview of the PERCEPT application that the authors developed and tested before this beta study and used in the MBTA North Station pilot study. These sections provide an opportunity to highlight the features developed during this beta study as described in Section 2.3. Study results are presented in Section 3.0. A discussion of implementation and technology transfer is provided in Section 4.0. Conclusions are in Section 5.0. Differences between the PERCEPT North Station pilot and the current beta study are provided in Table 1.1.

Table 1.1: Differences between North Station pilot and beta study

	North Station Pilot	Beta Study	Section Addressed	Task Addressed
Training	Manual: Hands-on training provided by research team.	Automated: Built-in tutorial provided in application.	2.3.3.1	1
Onsite Assistance	Research team was near the participant and readily available should concerns or issues arise.	Participant was independent.	2.3.3.1, 2.3.3.5	1 and 3
Smartphone	Controlled device provided by research team.	Personal device that can vary in model and configuration.	2.3.5	5
Application Usage	Only used during trial for maximum of three hours.	Used throughout five months of beta period.	n/a	n/a
Destination	A set of pre-selected destinations that participant was asked to navigate to, sequentially.	Participant's choice.	n/a	n/a
Evaluation	Off-line and manual: After the trial, a formal questionnaire was provided by research team.	Continuous and automated: Throughout five months of beta, participants provided qualitative feedback on experiences using app.	3.1	4 and 6
Analytics	Manual: Research team noted issues they observed, as well as those voiced by participants as they occurred during the trial.	Automated: Application monitored issues and automatically reported them.	2.3.4, 3.2	3 and 6
Environment	Commuter Rail and Subway	Subway, Commuter Rail, and Connector Tunnel	2.2.1, 2.2.2, 2.3.1, 2.3.2	2

2.0 Research Methodology

Chapter 2.0 describes the research methodology followed in the beta study, including descriptions of the PERCEPT application, the PERCEPT system, and the accomplishments in the PERCEPT beta study.

2.1 PERCEPT Application

The PERCEPT application (app) is currently exclusive to the iPhone platform. The majority of BVI smartphone users have an iPhone, due to Apple's exceptional accessibility features integrated into its platform. None of the BVI participants involved in the 70 trials previously conducted was an Android user. Mark Riccobono, president of the National Federation of the Blind, stated, "Apple has done more for accessibility than any other company to date." A PERCEPT Android application is possible, but would require additional time to develop and is outside the scope of this PERCEPT beta project.

The user carries an iPhone that runs the PERCEPT application, which provides detailed landmark-based navigation instructions that help the user navigate through indoor spaces to a chosen destination. The user downloads the application from the PERCEPT server before arrival at the indoor environment. The application includes the following steps: (1) start the application; (2) localize the user and determine current location; (3) select the destination using the accessible "vision-free" interface; and (4) receive audible detailed navigation instructions.

The following subsections describe the vision-free user interface, the user interaction, and a scenario of use.

2.1.1. Vision-free User Interface

The PERCEPT app, designed from the ground up to be accessible to BVI users, leverages preexisting accessible services and principles available in the smartphone. This design decision is important, because BVI users should be able to pick up and use the PERCEPT app as they would for any of the other applications they use, such as making a phone call, reading email, or browsing the Web.

PERCEPT leverages the iPhone's Voiceover accessibility service to provide the user with a vision-free accessible experience. Voiceover allows the user to interact with the iPhone through touch gestures on the screen and provides the user with audio-based feedback. Although the iOS operating system provides this accessibility service out of the box, it is up to the developer to ensure the application integrates seamlessly with Voiceover. Through the PERCEPT client application, the team designed a straightforward and simple layout so the user can easily maneuver through swipe or touch, and provided custom accessibility details to all user interface (UI) controls so that when the control is highlighted, it provides the user with an accessible understanding of the control.

The three main screen touch gestures for Voiceover are as follows.

- **Tap.** A user touches any point on the screen, and the accessibility service provides voice feedback to the UI control that the user is touching. When the control is touched, it reaches a particular state present for accessibility called “focused,” and a black box surrounds the UI control (Figure 2.1). When a UI control is focused, Voiceover will read the accessible description for the control. The UI control stays focused until the user focuses on another control. Touch provides a spatial exploration experience to the user so he or she can understand what is displayed on the screen, and once a user becomes familiar with the application, the user can use this gesture to quickly select controls on the screen.

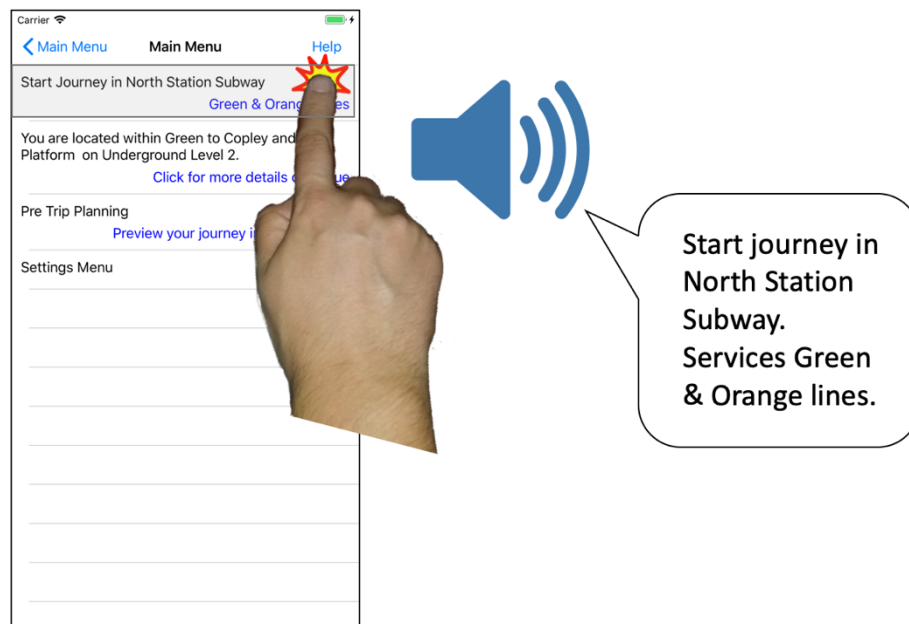


Figure 2.1: Voiceover accessibility touch gesture

- **Swipe.** By swiping in any direction on the screen, the user can move the focus from the current control to the adjacent control that is in the direction the user swiped (Figure 2.2). This provides a quick and efficient way to navigate linearly through the UI without having to touch all around the screen to search for the UI control. Additionally, the user can perform the swiping gesture anywhere on the screen without needing to know how UI is laid out. Performing a swiping down gesture at the top of the screen is going to provide the same result as swiping down on the bottom of the screen.

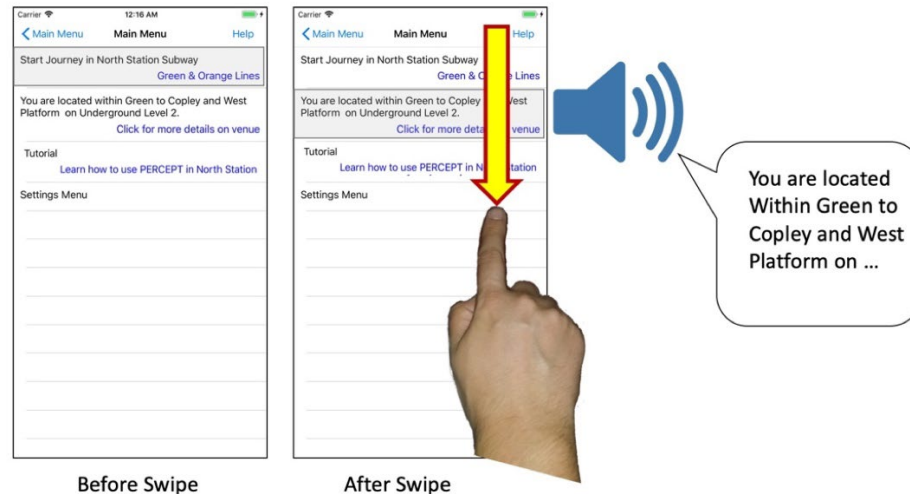


Figure 2.2: Voiceover accessibility swipe gesture

- **Double-Tap:** Without voiceover, touch would usually be the way one would click on buttons or select text boxes to enter information. In order to perform this action with Voiceover enabled, the user would first focus on the UI control and then the user would perform a double-tap gesture anywhere on the screen with a single finger (Figure 2.3).

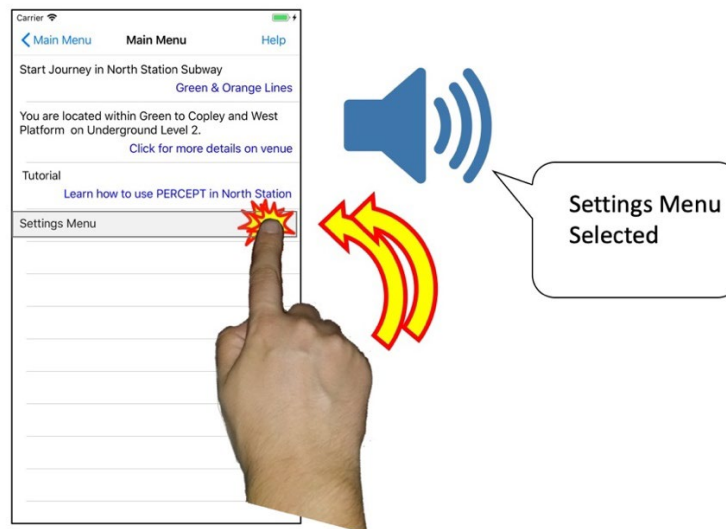


Figure 2.3: Voiceover accessibility double-tap gesture

2.1.2. User Interaction

The PERCEPT app provides the user with detailed turn-based navigation instructions from the current location to the chosen destination. The app flow includes the following five pages.

- **Main Menu page** provides a high level understanding of where the user is located.
- **Select a Destination page** provides a list of destinations to which to navigate.

- **Instruction page** provides detailed navigation instructions in easy-to-digest steps.
- **Venue Description page** provides a high-level description of the venue.
- **Personalized Wayfinding Preferences** provides the user with choices on how to traverse between floors.
- **Help Menu** overlays on top of each page and provides the user with shortcuts to quickly access features within the app.

Detailed descriptions of the functions of each page are as follows.

Main Menu page. When the user opens the PERCEPT app and is brought to the main menu, the app begins scanning for transmissions from PERCEPT BLE tags located nearby. The PERCEPT localization algorithm (Appendix H) uses these transmissions to calculate the location of the venue and announces the result to the user. Following the venue detection, the localization algorithm will calculate the floor and region within which the user is located. This information is both visualized and announced to the user through the UI. All three states of the main menu, scanning for tags, determining the venue, and determining floor and region, are depicted in Figure 2.4.

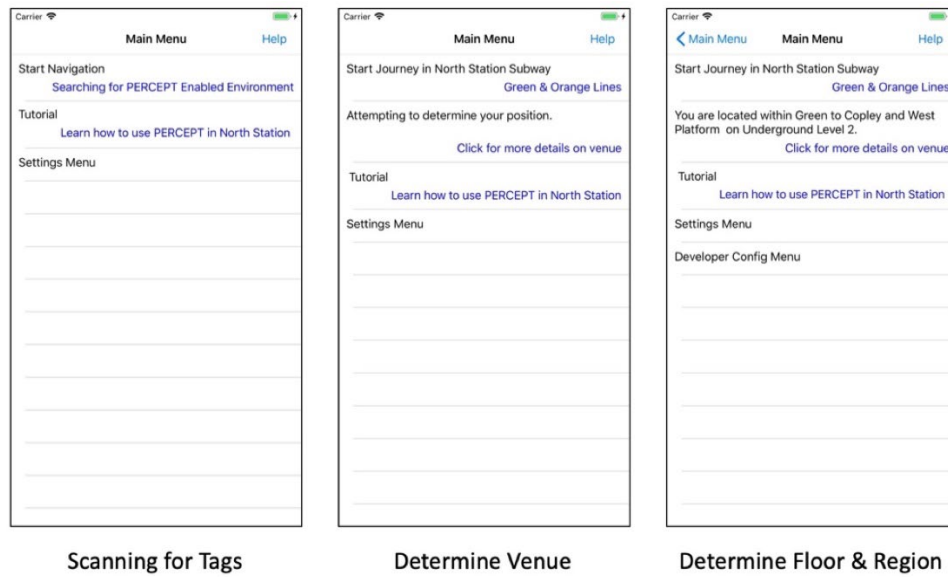


Figure 2.4: Real-time states for Main Menu

Select a Destination page. With the venue is detected, the user can select the Start Journey option from the Main Menu page and is then brought to the Select a Destination page. This page provides the user with a list of destinations within the venue, ordered alphabetically. The user selects the destination and is then brought to the navigation instruction screen.

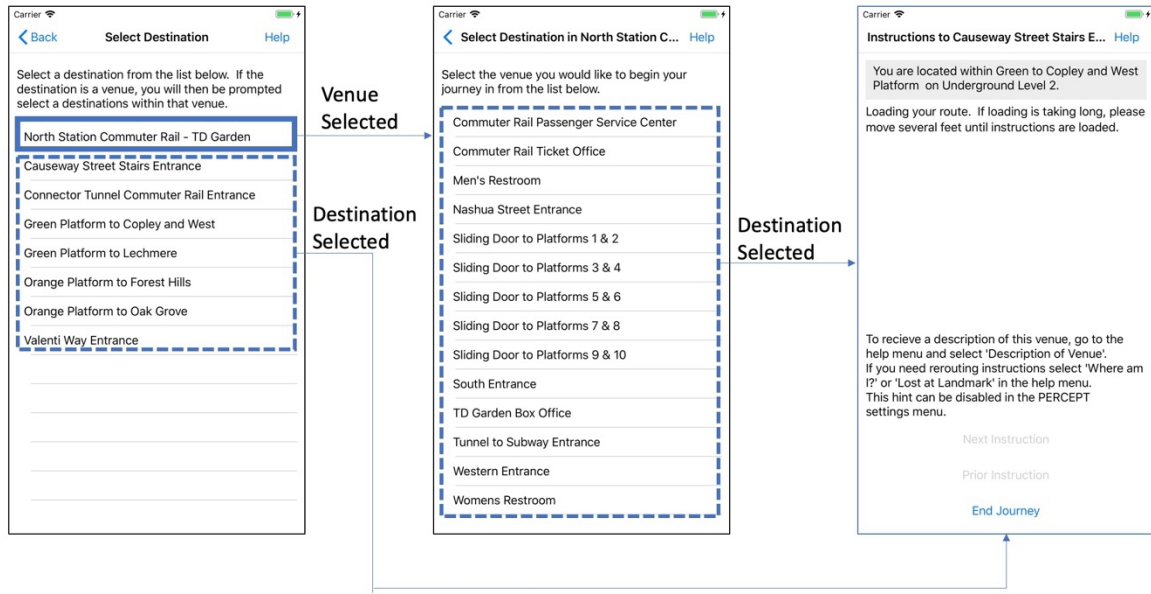


Figure 2.5: Select Destination flow

Instruction page. Once the user has selected the destination, the Instruction page (Figure 2.6) is displayed. The user is presented with step-by-step detailed navigation instructions based on the destination selected and current location within the venue. If the user's location has not yet been determined, this page will indicate to the user that it is determining the location and will prompt the user to move a couple of steps in any direction if the user is in a weak coverage area for PERCEPT localization.

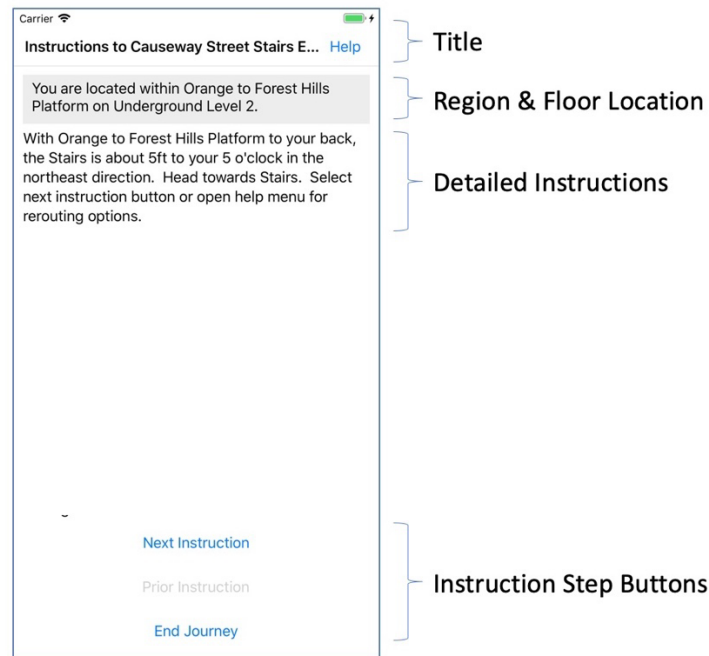


Figure 2.6: Instruction user interface

The Instruction page includes four parts:

1. **Title bar.** Includes “Instructions to {Destination Name},” which acts as a reminder to the user as to what the user selected as the destination.
2. **Region and Floor Location bar.** Dynamically updates the user location (region and floor) as the user moves throughout the venue.
3. **Detailed Instructions bar.** Provides instructions in easy-to-digest steps.
4. **Instruction Step button bar.** The user controls the pacing of the instructions by using the Next Instruction, Prior Instruction, or End Journey buttons. If the user is on the first step of the instruction, the Prior Instruction button is disabled but remains visible in the UI. The same is for the Next Instruction button, when the user is on the last step of the instruction.

Help Menu. The user can access the HELP menu from the application’s instruction page by shaking the iPhone. This shake will prompt the help menu overlay and provide the user with the option to use the Where Am I feature (Figure 2.7). This feature is used for rerouting the user when lost or disoriented by providing orientation to the nearest landmark, followed by detailed navigation instructions to the selected destination. Section 2.2.4. provides a more detailed description of this rerouting feature.

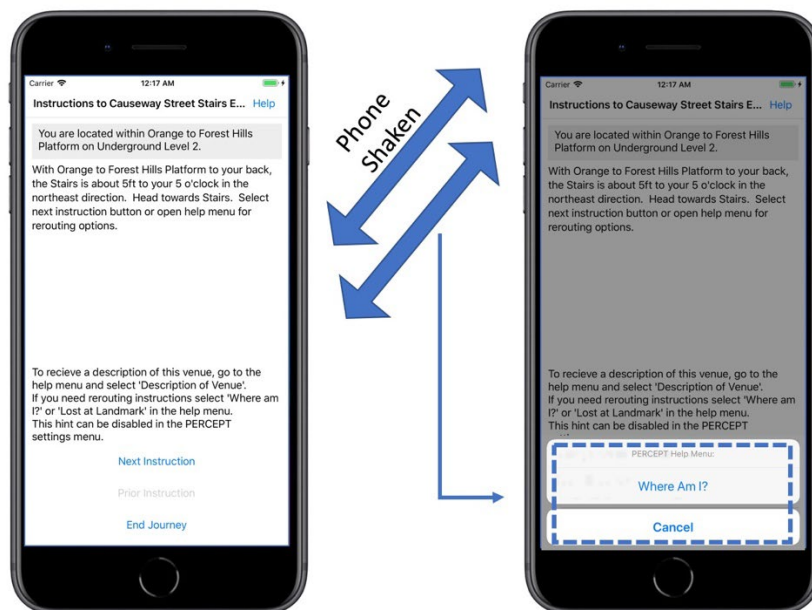


Figure 2.7: Shaking phone opens PERCEPT Help Menu

Venue Description page. Once the venue is detected, the user can navigate to this page from the Main Menu by selecting Click for More Details on the Venue. This page (Figure 2.8) includes two parts:

1. The top part provides the user with the region and floor the user is located in the venue.
2. The bottom part conveys a detailed description of the venue.

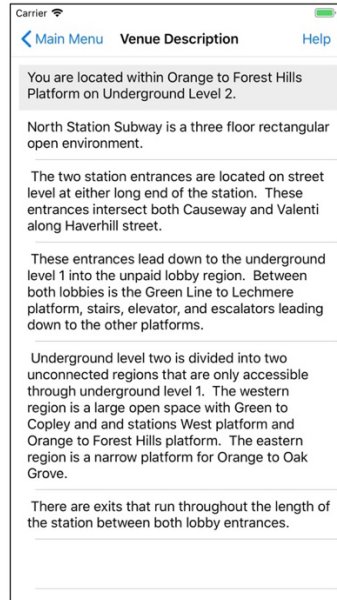


Figure 2.8: Venue Description page

Personalized Wayfinding Preferences. The Preference page is accessible at any time from the Main Menu by selecting the Settings Menu option. Once selected, the user is provided with a choice of options for navigating between floors. The user is presented with the following options: stairs, elevator, escalator, and shortest route (default). The shortest route takes the user through the most direct route to the destination, whether it be using an escalator or a stairway (Figure 2.9).

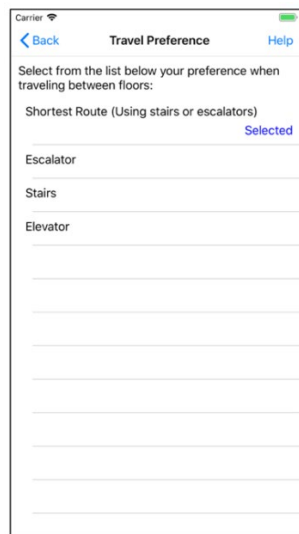


Figure 2.9: Floor Traversal Preference page

2.1.3. Scenario

The following scenario illustrates how the PERCEPT system worked in MBTA's North Station, prior to the 2018 completion of renovations to North Station included in the beta study. Figure 2.10 depicts the layout of all three floors of the North Station subway, including the street-level entrance and two underground levels.

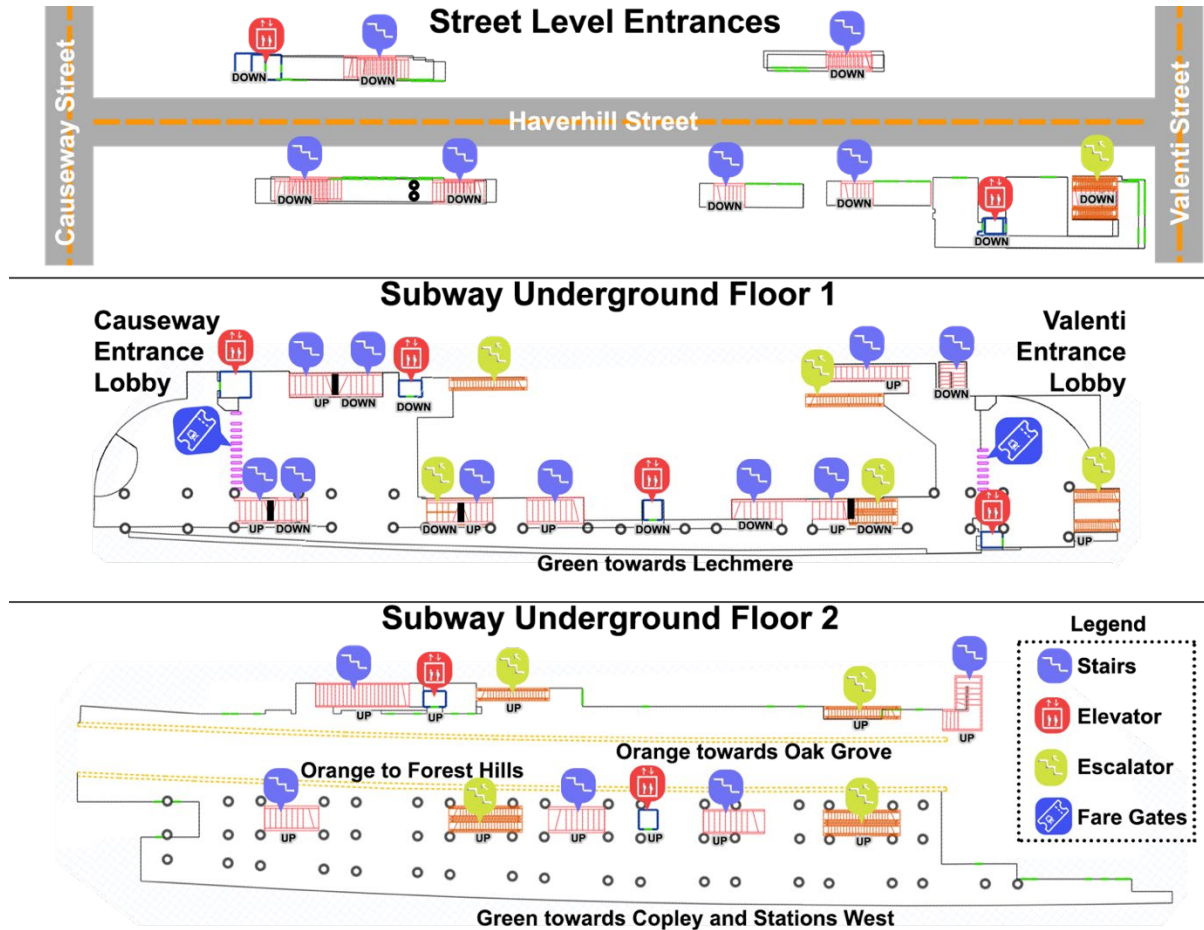
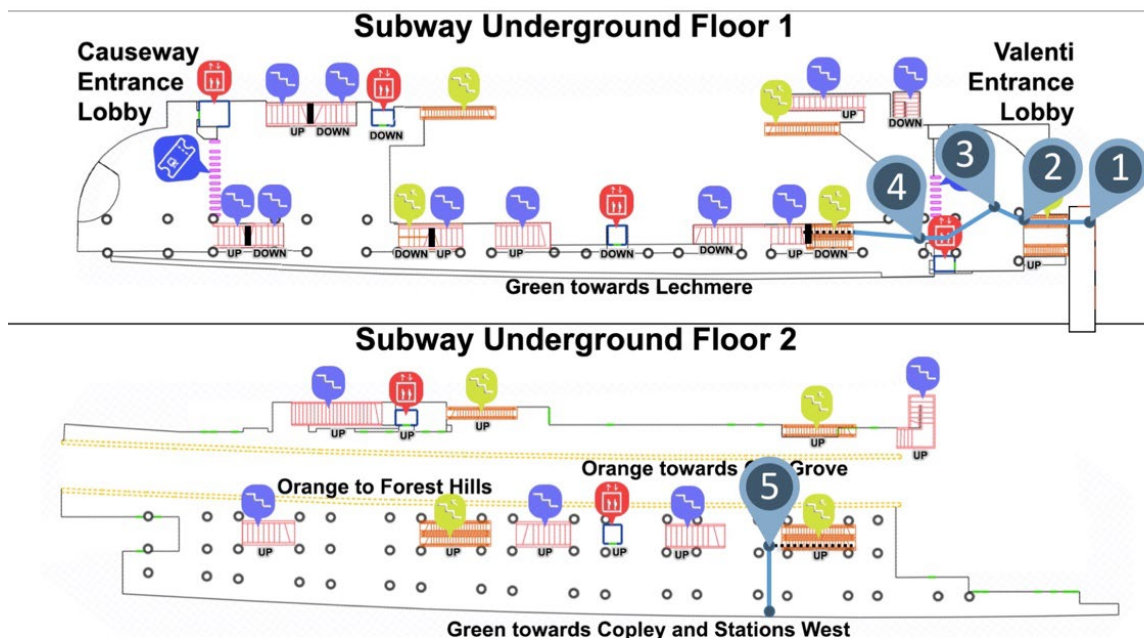


Figure 2.10: North Station subway layout

Figure 2.11 depicts the layout of the North Station commuter rail, which resides on the main floor of the TD Garden.

3. **Lost in Unpaid Lobby (Marker 3).** Kara follows the instructions but becomes disoriented along the route and is now unsure where to go. She shakes the phone to bring up the Help Menu and selects the Where Am I option. The app then responds with the rerouting instructions: “You are currently in the Southern Unpaid Lobby region. You have been traveling northeast. The fare gates unpaid side is located 25 feet to your 11 o’clock in the northwest direction. Head toward fare gates unpaid side and go through the fare gates. Select the next instruction button.” Kara follows the rerouting instructions and is back on track and heading toward her destination.
4. **Paid Lobby to Lower Platforms (Marker 4).** Once through the fare gates, Kara selects the next instruction button and the app responds: “With the Fare Gates to your back, there is escalator to your 12 o’clock direction. Walk across to the escalator to your 12 o’clock direction, heading northwest, 50 feet away. Take the escalator down. Select the next instruction button.”
5. **To Green Platform to Copley and West (Marker 5).** At the bottom of the escalator, Kara selects the next instruction button and the app responds: “Your current location is: Escalator, With the escalator to your back, turn left, walk straight ahead, heading southwest, until you reach the Green Platform to Copley and stations west, 40 feet away. You will face the track. You have reached your destination: Green Platform to Copley and stations west. Select End Journey to end the journey.”



Note: Markers 1–5 represent the navigation steps.

Figure 2.12: User navigation journey in North Station

2.2 PERCEPT System

The PERCEPT navigation system design and deployment process is illustrated in Figure 2.13 and comprises the following modules: digital representation, BLE deployment, user localization, navigation and reorientation instruction generation, and region announcement.

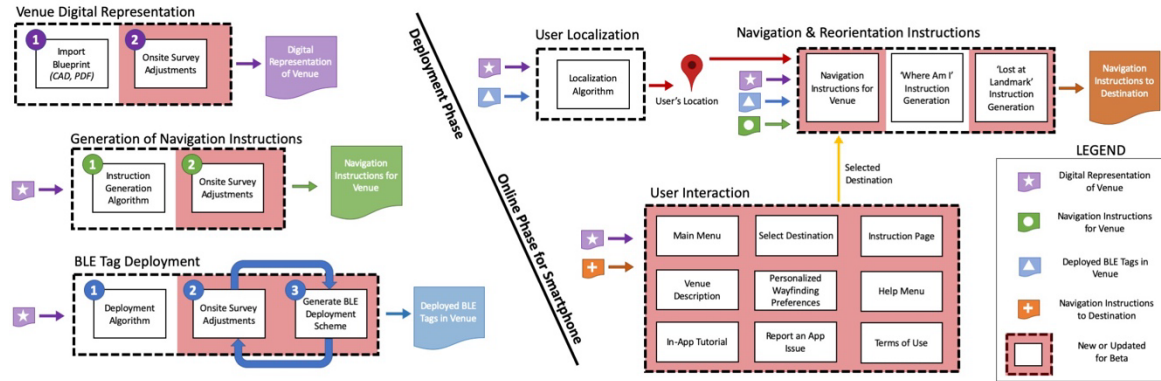


Figure 2.13: PERCEPT system diagram

2.2.1. Digital Representation

To generate the PERCEPT systems's detailed navigation instructions, a virtual representation of the physical space must be created using a suite of specialized tools and algorithms created in the lab. The research team used a construction blueprint of MBTA's North Station terminal to generate an initial spatial representation of the station. For the algorithm, the authors require a digital representation that comprises numerous layers of information, such as landmarks, regions, navigation graph, accessibility features, and temporal events. Because the blueprint did not contain all of this information, an onsite survey of the venue was completed to determine multimodal sensory information that includes tactile, audible, olfactory, and situational information required for the detailed navigation instructions algorithm. Any future renovations or changes in the physical environment will require future onsite surveys and modifications to the digital representation.

2.2.2. Bluetooth Low Energy (BLE) Tag Deployment

The team deployed the Smart Beacon SB16-2, manufactured by Kontakt.IO. This tag was selected due to the following factors:

- Battery life of five years
- Replaceable battery
- Small footprint (15mm x 55mm x 56 mm) and form-factor that allows the tag to blend in with the environment
- Cost: \$19 (for larger quantities, the cost is lower)

Each BLE tag has three identifiers:

- **Serial** is used to uniquely identify each manufactured tag. This value is set when the tag is manufactured and cannot be modified.

- **Major** is a configurable ID that is used to indicate the subway station in which the tag is being deployed. Each subway station has a unique assigned number, and in the study, the North Station commuter rail's major ID is 3, the subway is 4, and the connector tunnel is 15.
- **Minor** is a configurable ID that is used to uniquely identify a tag assigned to a specific location in a station. The ID number starts at 1 and increases by one for each subsequent tag. By having a reconfigurable ID, one can swiftly replace a malfunctioning or vandalized tag with a new tag with same major and minor IDs. Since they match, the PERCEPT app will continue to function with the new tag without any updates necessary.

Once the tags are received, they undergo several steps to be prepared for deployment.

- **Configuring tag IDs.** The major and minor ID for each tag is configured to reflect a tag deployed in a specific location within a subway station. The Kontakt.IO app, provided by the manufacturer, is used for this step.
- **Labeling tag.** Each tag is labeled with its serial, major, and minor ID so the installer can quickly identify each tag.
- **Adding mounting adhesive.** Two strips of 3M VHB foam adhesive are added to the back of the tag for mounting. This adhesive adheres on a wide array of surface materials (e.g., plastic, metal, and concrete) and on curved surfaces such as columns. The adhesive was selected to avoid drilling into surfaces. When applied with high heat, the adhesive can be removed without damaging the surface.

Figure 2.14 depicts the top and bottom view of the tag and includes visuals of the serial, major ID, minor ID, and mounting adhesive.

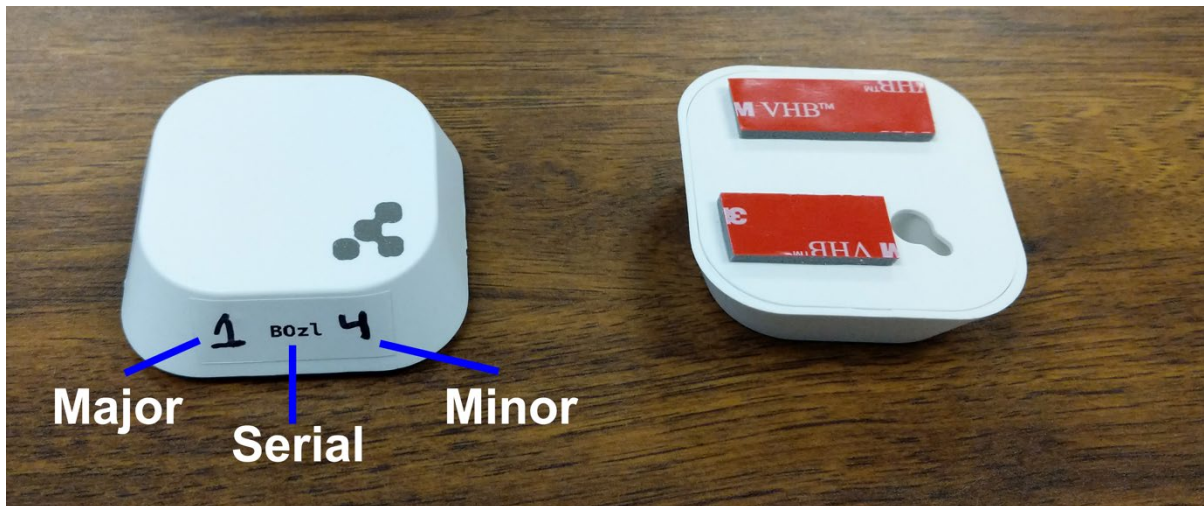


Figure 2.14: Top and bottom perspective of the BLE tags

The optimal tag deployment algorithm developed (Appendix H) minimizes the number of tags while ensuring that every zone in the venue is covered by at least three tags. After the tags were deployed, the venue was surveyed and adjustments made. The adjustments are usually required due to the fact that some tags cannot be deployed in spots determined by the

deployment algorithm, and the building materials differ in each venue, a fact that influences the signal propagation properties.

2.2.3. User Localization

The user is localized in specific zones (e.g., entrances, platforms) in the venue using the received signal strength indicator from multiple BLE tags that are deployed in the venue. The localization algorithm developed is documented in Appendix I.

2.2.4. Navigation and Re-orientation Instruction Generation

The user receives instructions through two modes: (1) detailed landmark-based navigation instructions generated by the PERCEPT navigation instructions generation algorithm introduced in Appendix I, and (2) in case the user is lost, he/she selects Where am I and will receive a detailed description of the surrounding landmarks, the distance to the landmark, and the orientation relative to the user's orientation (Appendix I).

2.2.5. Region Announcement

The region announcement is an accessible feature provided on each page of the PERCEPT application. Each venue is divided up into regions such as entrances, platforms, and lobby areas. Figure 2.15 depicts the regions for the commuter rail, where each dotted line area is a region within the venue. As the user moves throughout the venue and transition into a new region, this feature will accessibly inform the user of the new region entered. Moreover, this added context can reinforce to the user that the user has reached the correct platform or entrance within the venue and can help the user build a high-level map of the venue while walking around in the space.

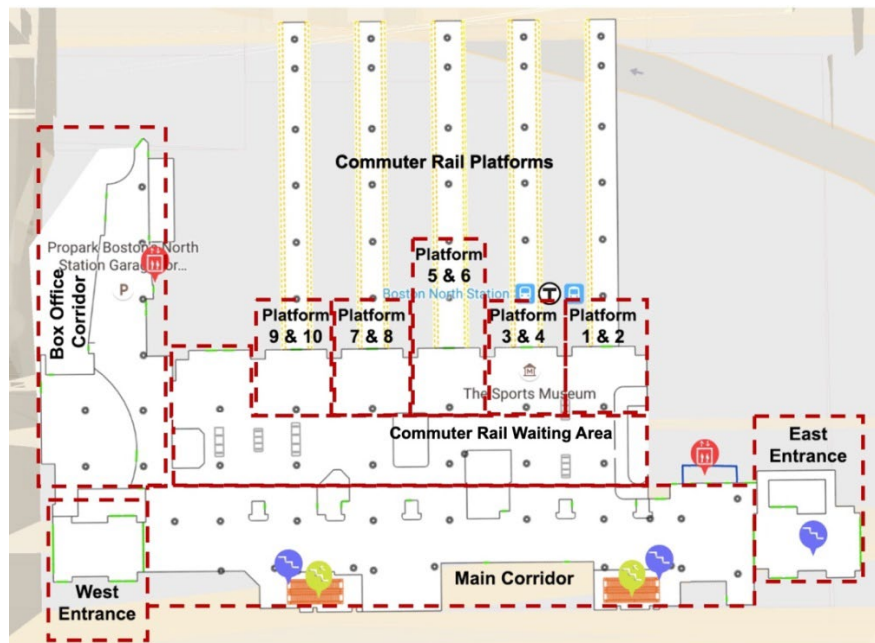


Figure 2.15: Regions of North Station commuter rail

2.3 PERCEPT Beta

This section describes the accomplishments in the current beta study. Figure 2.16 contains a diagram of shaded modules that were changed or added during the beta study. The following modules were updated: the digital representation and instruction generation; the BLE deployment; user interaction; analytics module; and PERCEPT Test Flight submission.

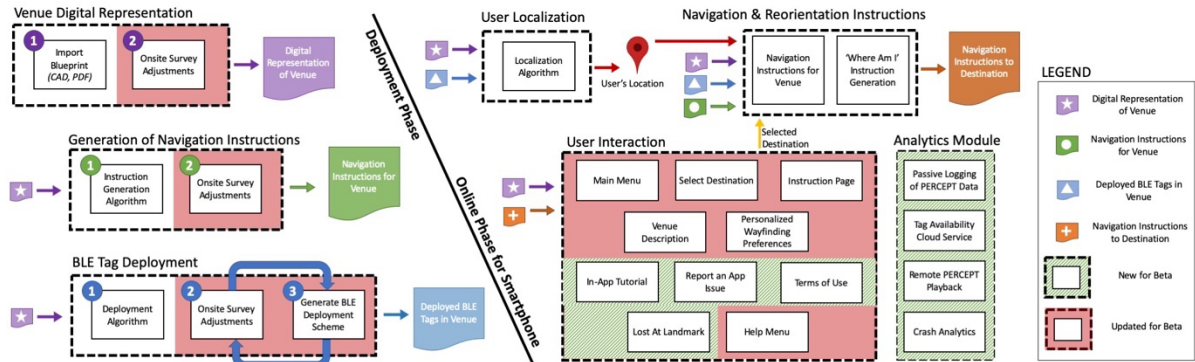


Figure 2.16: Beta accomplishments

2.3.1. Venue Digital Representation and Instruction Generation (Task 2)

The following changes were made to the digital representation for this project, due to the recent renovations in in the MBTA's North Station commuter rail and subway stations and the addition of the connector tunnel:

- Commuter Rail
 - The escalator next to the Western Entrance that leads to Legends Way was removed, and a wall was installed in its place.
 - The Western Entrance that leads to Legends Way was closed to the public. This entrance was removed from the list of destinations, and if the user were to enter this lobby for this entrance, the user would be reminded that the entrance is closed.
 - A new southern entrance that faces Causeway Street was added. This entrance and lobby were added to the virtual representation and set as a new destination.
 - The connector tunnel was opened to the public. The entryway to the tunnel was added to the virtual representation.
 - The TD Garden box office was moved from next to the southern entrance to next to the entryway to the connector tunnel. The virtual representation was updated to include the new location of the box office.

- Connector Tunnel
 - This was an entirely new area that was composed of two floors. The street-level floor connects to the TD Garden Commuter rail and has a small area that has an escalator, stairway, and elevator leading to the floor below. On this underground floor is a long hallway that extends from the stairways, escalator, and elevator to the entrance to the subway, with an elevator halfway through the hallway that leads up to Causeway Street.
- Subway
 - The entrance to the connector tunnel was added when opened to the public. This entrance is located on Underground Level 1, Causeway Street unpaid lobby region.

The changes were made and a new set of navigation instructions were generated for each venue. Figure 2.17 depicts the current layout of all three floors of the North Station subway, including the street-level entrance and two underground levels.

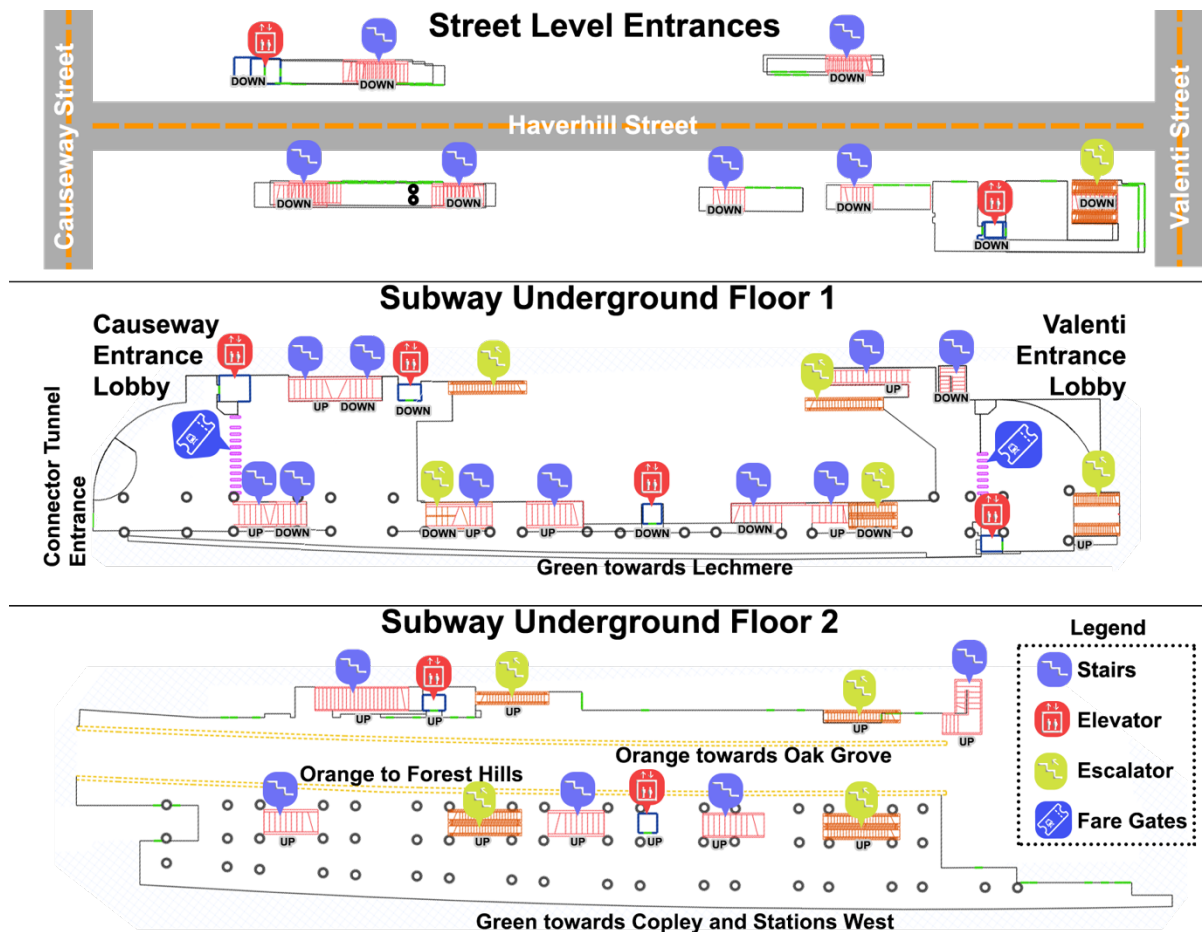


Figure 2.17: North Station subway layout

Figure 2.18 depicts the current layout of the North Station commuter rail, which resides on the main floor of the TD Garden.

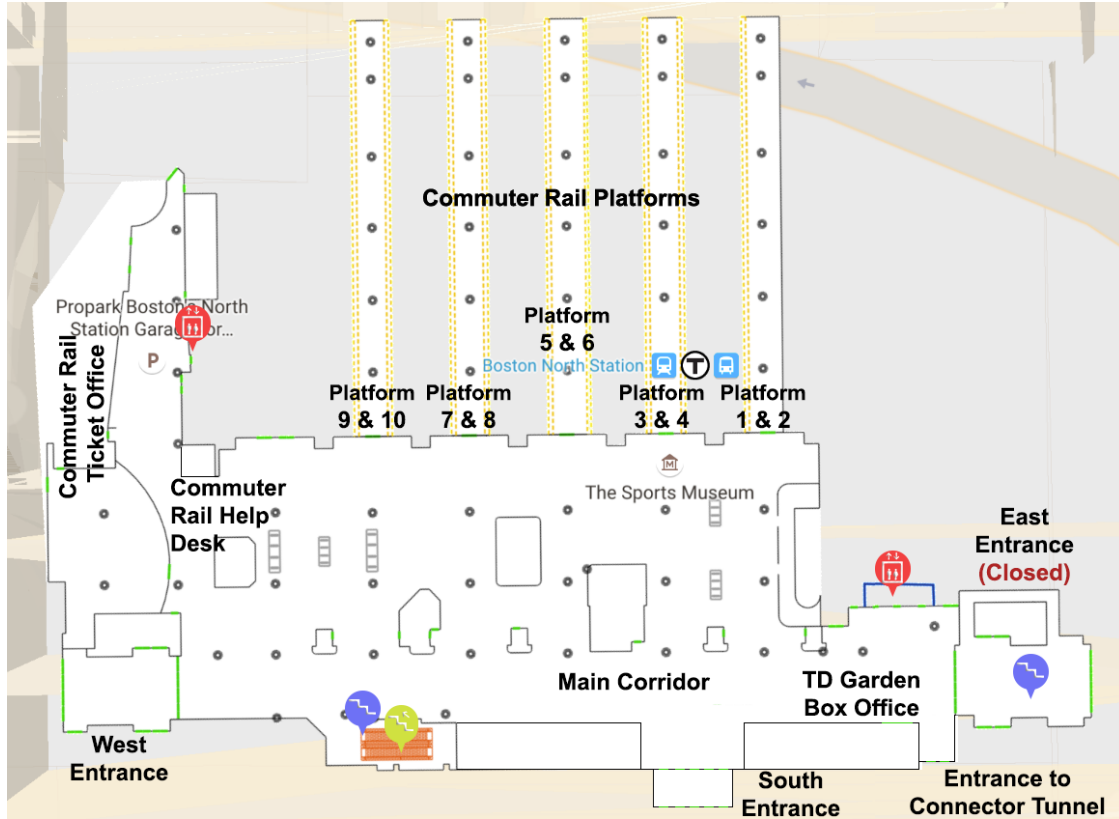


Figure 2.18: North Station commuter rail layout

Figure 2.19 depicts the layout of the North Station connector tunnel that was newly opened during this project and connects the subway and commuter rail through a tunnel underground.

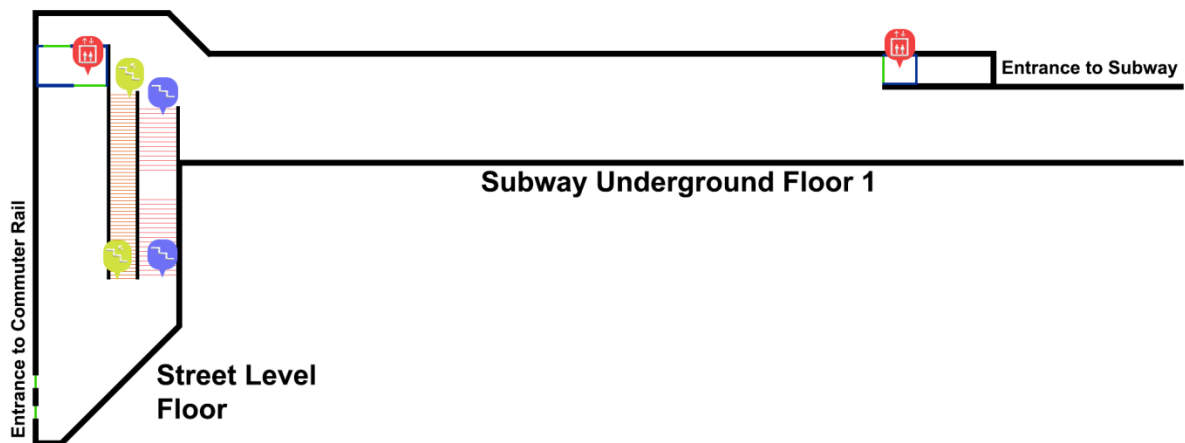


Figure 2.19: North Station connector tunnel layout

2.3.2. BLE Tag Deployment (Task 2)

To ensure full coverage of the renovated and new areas described previously, the team deployed additional BLE tags (Task 2). A total of 42 tags were installed: 11 in the commuter rail, 18 in the subway, and 13 in the connector tunnel. Table 2.1. depicts the number of tags per area in the original deployment and the additional tags deployed for the beta project.

The deployment document for North Station can be found in Appendix A. Timothy Avelino, supervisor for the Building and Station Maintenance department, oversaw this installation.

Table 2.1: Summary of station tags

Date	Detail	BLE Tag Count			
		Commuter Rail	Connector Tunnel	Subway	Total
Original deployment	Tags Installed Count	75	0	148	223
Beta deployment	Tags Installed Count	11	13	18	42
	Total Deployed Count	76*	13	166	255

*10 of the original tags in commuter rail were removed during construction.

2.3.3. User Interaction

This section describes updates to the user interaction for the beta. These updates include: the in-app tutorial; terms of use; extended Personalized Wayfinding Preferences; Lost at Landmark; Report an App Issue; extended PERCEPT Help Menu; and indicating Bluetooth permission and enabled state.

2.3.3.1. In-App Tutorial (Task 1)

The in-app tutorial is available by selecting the Tutorial option from the Main Menu page. Once selected, the user is provided with a list of all available venues (e.g., the commuter rail and subway). After selecting the venue, the user selects his or her starting location within the venue. Then the user needs to select the destination, and the system provides the detailed navigation instructions. The flow for the tutorial is depicted in Figure 2.20.

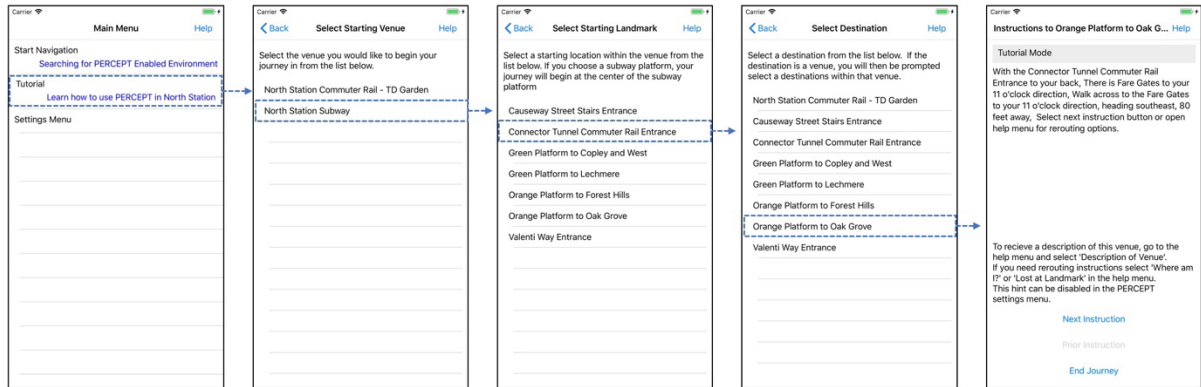


Figure 2.20: Flow of tutorial mode

Additional accessible tutorial content has been added to all pages in the PERCEPT app. This content is broken into three types:

- **Hints.** These are concise bits of information that guide the user to perform a specific action on the page. Figure 2.21 provides an example of a hint.
- **Accessible Prompts.** These are added accessible cues so that the vision-free interface provides more context to the user. For example, when in the Settings menu and the user focuses on the Floor Traversal Travel Preference, the voiceover would say, “Floor Traversal Travel Preference. Double tap to select.” With the customized accessible prompt, the voiceover now also announces the current preference and says, “Floor Traversal Travel Preference. Preference set to Shortest Route. Double tap to select” (Figure 2.22).
- **Explanation:** These are detailed tutorials that describe the page’s purpose and enumerates all the available actions the user can perform. Each page’s explanation is available through the PERCEPT Help Menu. Figure 2.23 depicts the explanation page for each page in the PERCEPT app.

Together, these three types of tutorials provide the user with layers of assistance in using the PERCEPT application.

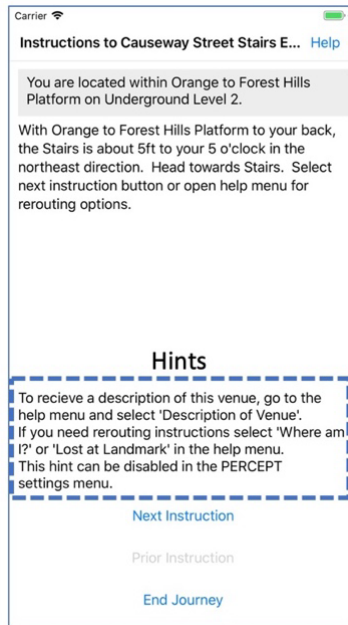


Figure 2.21: Hints example

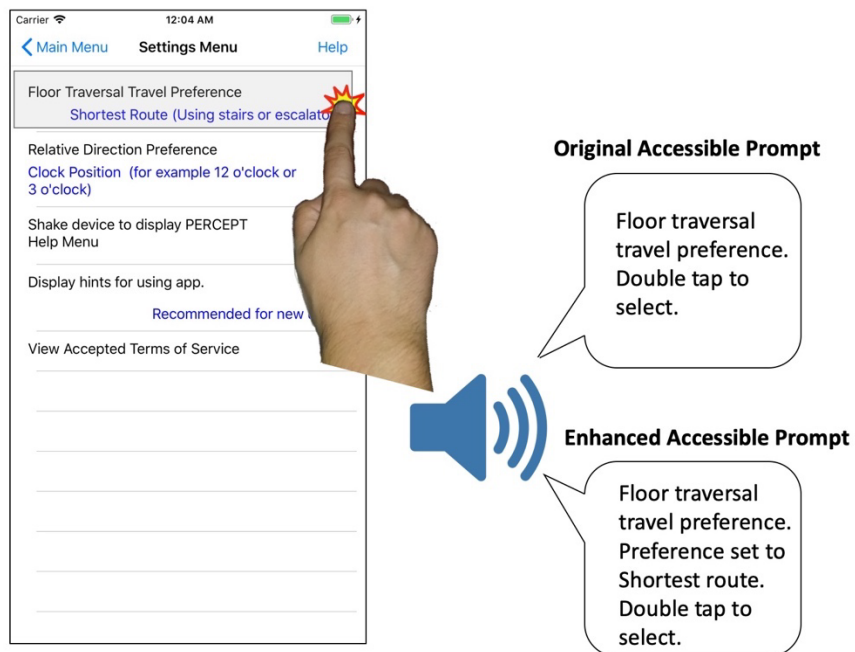


Figure 2.22: Accessible prompts example

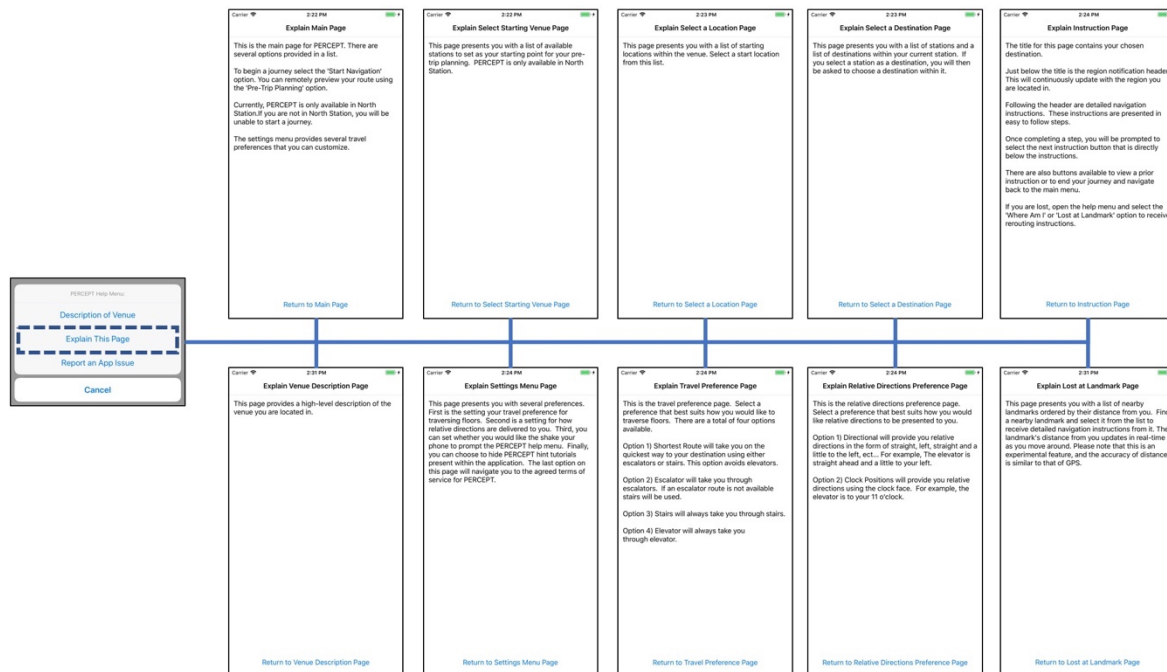


Figure 2.23: Explanations for each application page

2.3.3.2. Terms of Use (Task 4)

The Terms of Use page is presented to the user upon opening the PERCEPT app for the first time. The user can only access the PERCEPT app should the user read and agree to these terms. Once the user agrees to the terms, the user is brought to the Main Menu page, and the application stores the accepted terms state of the user, so the user is no longer prompted to read and accept the terms on future uses of the application. However, if the user does not agree to the terms, he or she will be informed that the app will be unavailable unless the user agrees, and the user will be presented with the Terms of Use page when opening the app until this is the case. Figure 2.24 depicts the flow for the Terms of Use page.

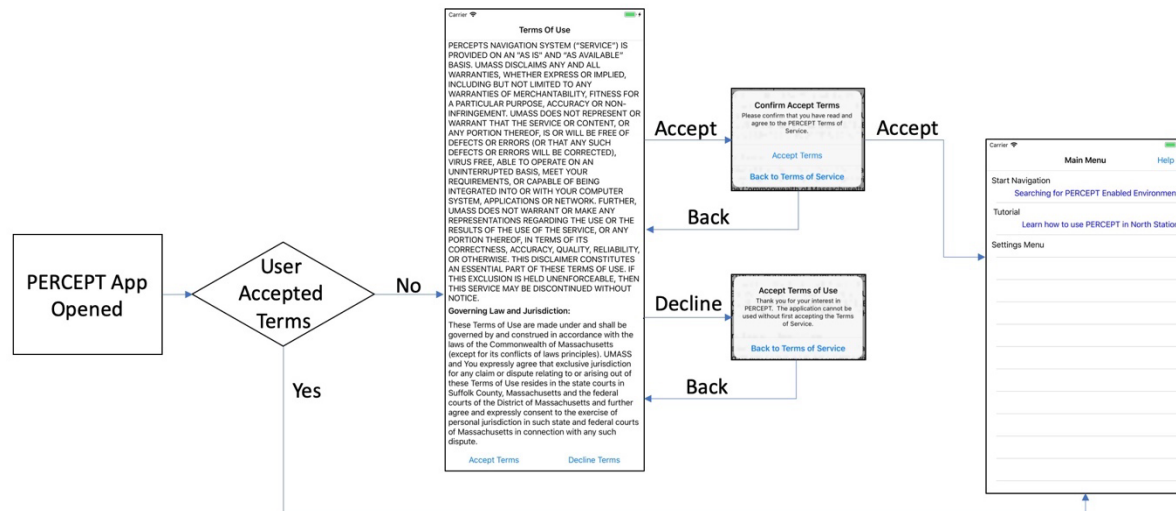


Figure 2.24: Terms of use flow

This page was created for the beta (**Task 4**). The PIs utilized content for the terms of use that was created by the UMass Legal Department. This was then revised by the MBTA Legal and Safety Department under the direction of PC David Block-Schachter. The Terms of Use are included in Appendix G.

2.3.3.3. Extended Personalized Wayfinding Preferences (Task 6)

Based on feedback provided by participants, the personalized wayfinding preference was extended so that users can further customize their PERCEPT experience. The Preference page is still accessible at any time from the Main Menu by selecting the Settings Menu option, but users are now brought to a Settings Menu page (Figure 2.25), which is displayed with the following options:

- **Floor Traversal Preference.** Original preference described in Section 2.1.2.
- **Relative Directions Preference** (Figure 2.26). Provides users with a choice on whether they want their relative directions presented directional or in a clock face (default).
 - Directional directions: provides a more traditional relative direction in the form of straight, left, and right. Example: “The elevator is straight ahead and a little to your left.”
 - Clock face directions: Example: “The elevator is to your 11 o’clock.”
- **Shake device to display PERCEPT Help Menu.** Provides users with the option to disable “shake phone” gesture that would prompt the PERCEPT Help Menu. There are two ways to prompt the PERCEPT Help Menu, either by selecting the Assist button on the top right corner of the current page or by shaking the device. This preference provides the user with a simple toggle switch. By toggling the switch off, the PERCEPT Help Menu can only be prompted through the Assist button. The default value for this is the switch toggled on.
- **Display hints for using app** (Figure 2.27). Provides users with the option to hide hints that are placed throughout the app. Throughout the PERCEPT app are hints that act as mini-tutorials or reminders for different features available on a certain page. As

users become more familiar and adept with the PERCEPT app, they may not want to have these hints anymore, and by toggling this preference off, all the hints are hidden.

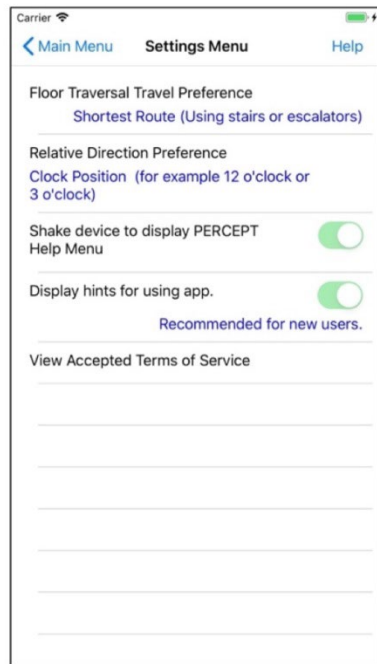


Figure 2.25: Settings Menu interface

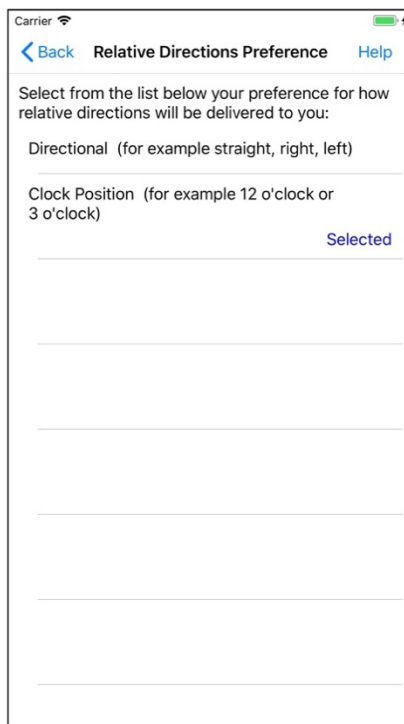


Figure 2.26: Relative Directions Preference interface

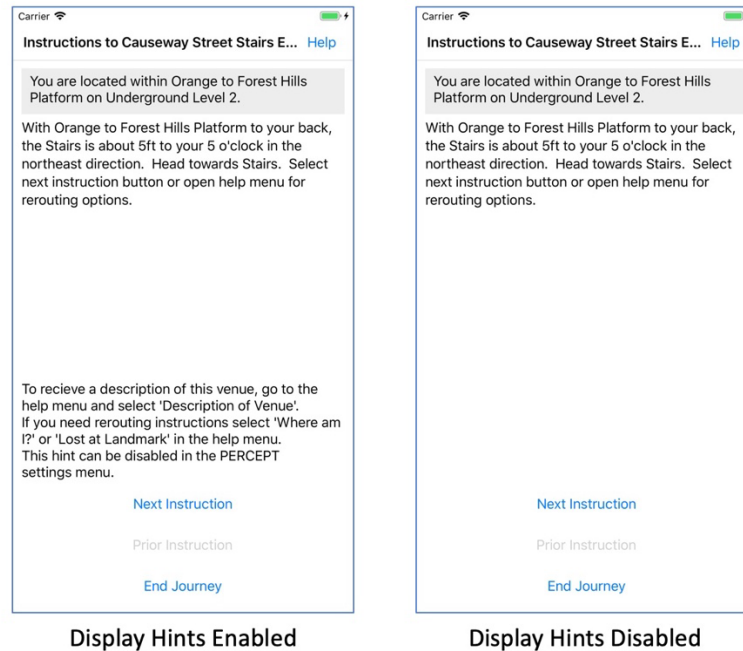


Figure 2.27: Example of Instruction page with hints enabled and disabled

2.3.3.4. Lost At Landmark (Task 6)

This is an additional reorientation feature available to the user from the PERCEPT Help Menu by selecting the Lost At Landmark option. This page provides the user with a list of nearby landmarks and their approximate distance from the user. These distances are updated in real time as the user moves throughout the venue. The landmarks in the list are ordered by their initial distance from the user. As the user moves throughout the venue, the landmarks in the list will maintain their initial order, making it easy for a BVI user to navigate and keep track of the user's place within the list.

This page (Figure 2.28) helps the BVI user get familiar with the surrounding landmarks and build a mental map of the venue.

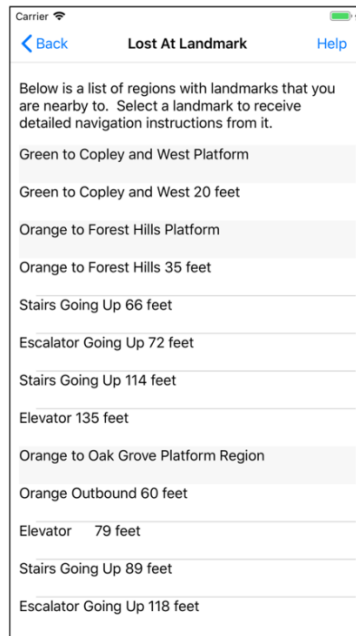


Figure 2.28: Lost at Landmark page

The Lost at Landmark page is a new PERCEPT reorientation feature developed for this beta study, based on feedback collected from participants.

2.3.3.5. Report an App Issue (Task 3)

This feature provides the user with the ability to report an issue to the Principal Investigators by selecting the Submit an Issue option from the PERCEPT Help Menu (Figure 2.29). The user is then prompted to leave a brief message describing the issue and then to select the Submit button. Once the Submit button is selected, a report is made that includes the brief issue message, smartphone type, operating system version, and a log for the application since it had started. This feature was added for this beta study and is a part of the crash analytics module for **Task 3**.



Figure 2.29: Submit an Issue interface

2.3.3.6. Extended PERCEPT Help Menu (Task 6)

The functionality of the Help Menu was expanded upon to provide the user with a list of shortcuts so the user could access from any page within the app. The options available to the user include the following.

- **Explain This Page.** Provides the user with an accessible explanation of the current page.
- **Report an Issue.** Provides the user the ability to report an issue experienced within the application.
- **Description of Venue.** Provides the user with a high-level description of the venue within which the user is currently located. Participants requested that this feature be added to the Help Menu.
- **Mute Announcements.** PERCEPT provides accessible announcements when transitioning to a new region within the station. Participants requested the ability to mute or unmute these announcements.
- **Where Am I.** Original rerouting feature in PERCEPT Help Menu. This option is only available when the app is on the Instruction page.
- **Lost At Landmark.** Provides orientation of surrounding landmarks to user. This option is only available when the app is on the Instruction page.

Participants provided feedback to have the Help Menu be prompted through clicking a button and not just by shaking, and also to add an option to disable the shake prompt. The team added a personalized preference to disable the shake feature and added a Help button to the top right of each page within the application (Figure 2.30). The user can access the Help Menu anywhere within the application by either selecting the Assist button that is conveniently placed to the right of each page's title on the top of the screen or by shaking the device.

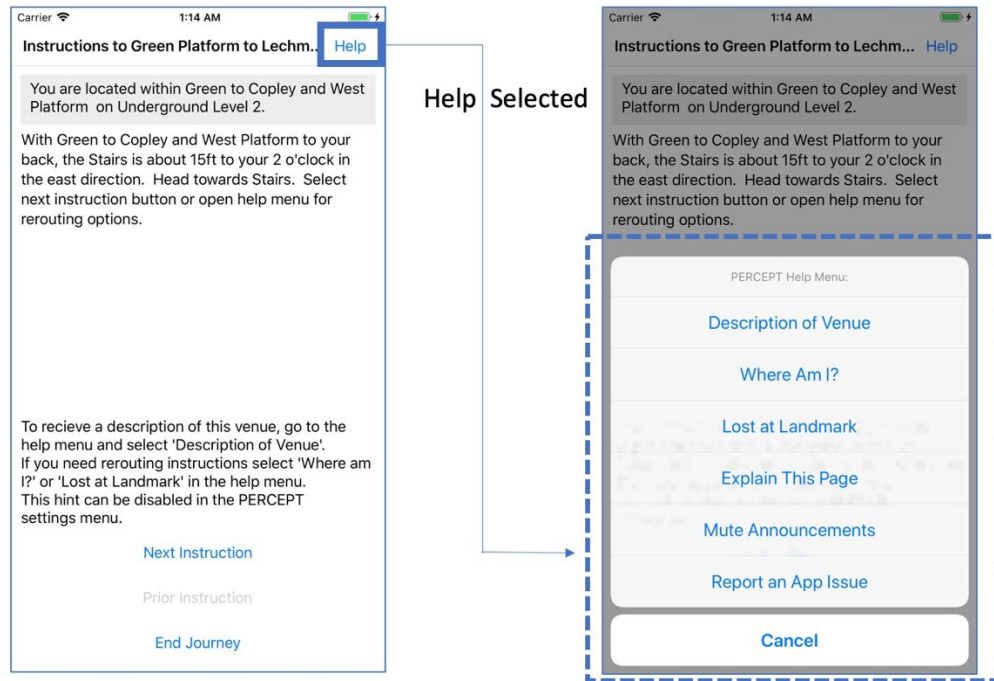


Figure 2.30: Prompting Help Menu through Help button

2.3.3.7. Indicating Bluetooth Permission and Enabled State

A participant shared the experience of being unable to use the PERCEPT app to navigate to any destination in North Station. The app was unable to identify that the user was in North Station. After consulting with the participant and looking at the data provided by the analytics, it was determined that the participant's Bluetooth was turned off on the participant's iPhone. The participant was unaware that Bluetooth was needed for PERCEPT. A new service was created that now detects whether or not Bluetooth is turned on. If Bluetooth is turned off, the user is informed on the Main Menu page (Figure 2.31). It was decided to take this feature one step further and to also inform that the localization permission is blocked for the PERCEPT app. When the PERCEPT application is opened for the first time, a user is prompted to allow PERCEPT to access the user's location. Should the user not allow access, PERCEPT also will be unable to localize. The service to detect the Bluetooth also detects if the permission is blocked. If it is blocked, the user will be informed of the need to accept the permission (Figure 2.31).

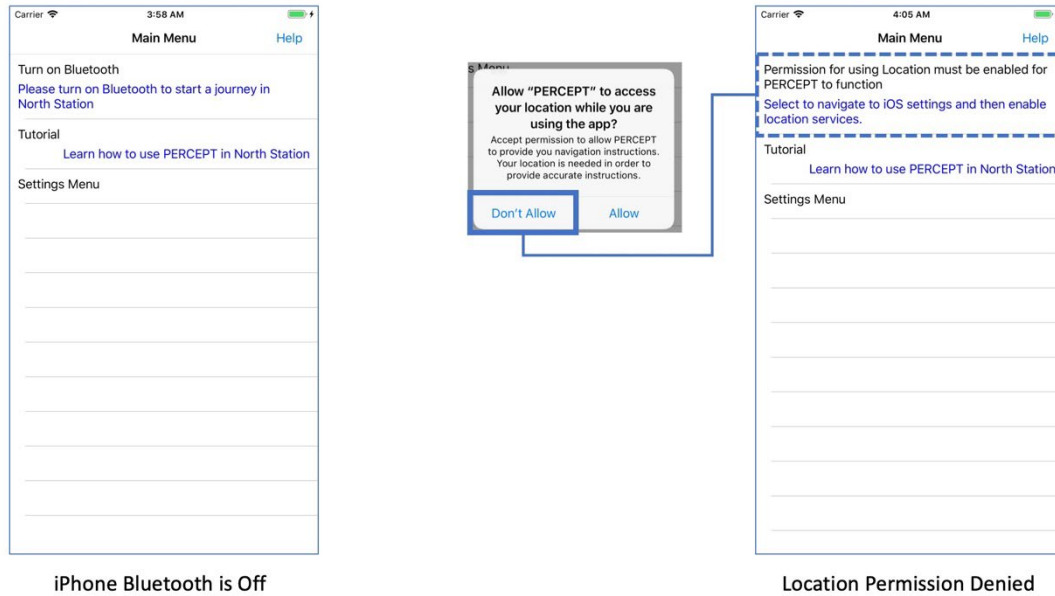


Figure 2.31: Bluetooth off and in Location Permission Denied state

2.3.4. Analytics Module (Task 3)

The developed analytics modules for PERCEPT provide passive monitoring of BLE tags in North Station and system software. The following subsections describe each part of the analytics module: passive logging of PERCEPT data; tag availability cloud service; remote PERCEPT playback; and crash analytics.

2.3.4.1. Passive Logging of PERCEPT Data (Task 3)

The PERCEPT application passively logs application-related data while the app is open. The logged data does not contain any identifying information for the user, and should the user switch to another app while using PERCEPT, the logging is paused. Each participant agreed to the capturing of this information as it was outlined in the beta study consent form signed in order to participate (Appendix D). When the app is first opened, it creates a random ID for the user. The logged data is approximately 10 Kb in size for every 10 continuous minutes of application use. In contrast, a standard MP3 song stored on the iPhone takes 3,500 Kb of space. The PERCEPT app logs all transmissions in a local database, and after a user finishes using PERCEPT, the log will be queued to be uploaded to the Web services. Once a log is in the queue, it will wait until an Internet connection is available to upload the logs to PERCEPT cloud Web services.

Three types of data are logged:

- **App Usage.** A list of all the actions the user performs in the application. The log attempts to store any action the user has taken with a timestamp. These actions include personal preferences that were set in the app, starting a journey in North Station with a specific destination, using the rerouting features, and starting a pre-trip planning journey.

- **Location Usage.** The app logs each calculated location of the user throughout North Station. The location is calculated using the BLE-based localization algorithm.
- **BLE Tags.** When the user is in North Station, the user will receive transmissions from the BLE tags deployed within the subway environment. The app will log these transmissions' signal strength, major and minor ID of the tag, and timestamp.
- **Report App Issue.** This is an optional data field that is only populated if the user reports an app issue within the app's Help Menu.

This collected data is used to analyze the BLE tag system health and to debug issues users are experiencing by remotely recreating their experience.

2.3.4.2. Tag Availability Cloud Service (Task 3)

The tag availability cloud service processes the log of BLE tags collected by PERCEPT users. The information can be used opportunistically to gauge the health of the BLE deployment. The service keeps track of the last instance a transmission from each BLE tag is received. Using this information, the team can query the service to identify the BLE tags that have no logged transmissions from a specified date. Moreover, the team can then query to identify if transmissions were received by tags neighboring the unresponsive tag. This will prompt an onsite visit to verify if the tag is functional.

2.3.4.3. Remote PERCEPT Playback (Task 3)

The playback function was developed in order to replay the remote logs generated by the study participants. By replaying their experience, the team could better identify issues each user experienced, through visually replaying the user interface that the user was experiencing and running the playback through the debugger for a granular understanding of the application state. For remote playback, the team created a developer version of the PERCEPT application that has all the features of the version the study participants used, plus the addition of playback available as an option in the Main Menu. Once the playback option is selected, the user is navigated to a list of all available playback sessions stored on the scenario. Each scenario is labeled by timestamp, operating system (OS) running on the iPhone, and an issue message if the scenario was tagged with one. Once a scenario is selected, the user will be prompted to replay the scenario with user actions. If the user selects yes, the UI will not accept any input from the developer and play back the scenario exactly as it unfolded for the user. However, if the developer selects to replay the scenario without user actions, they can navigate the UI themselves.

2.3.4.4. Crash Analytics (Task 3)

The team integrated the Microsoft App Center diagnostics and crash analytics platform into the PERCEPT client application. This provides the ability to remotely monitor any issues from within the application and collect some application usage statistics. There are two parts to this platform:

- **Client Software Development Kit (SDK).** The SDK is integrated into the PERCEPT client application. The main feature of the client SDK is the reporting of crashes. Should PERCEPT crash due to a fatal error, this will generate a detailed report of the

error and log this information until it can be sent remotely. In addition to crashes, this SDK can generate reports for handled errors. A handled error is an error that occurs within PERCEPT but from which the app can recover. Finally, the SDK monitors what type of iPhones are being used, OS version, when the application is used, and for how long.

- **Web Portal.** This is an administrative portal that provides a comprehensive historical view of all application crashes, handled errors, and usage statistics. All the information can be aggregated by issue type, time, smartphone, OS, and users in order to understand if the crash is global or more specific to a phone or user. A sample issue report is depicted in Figure 2.32.

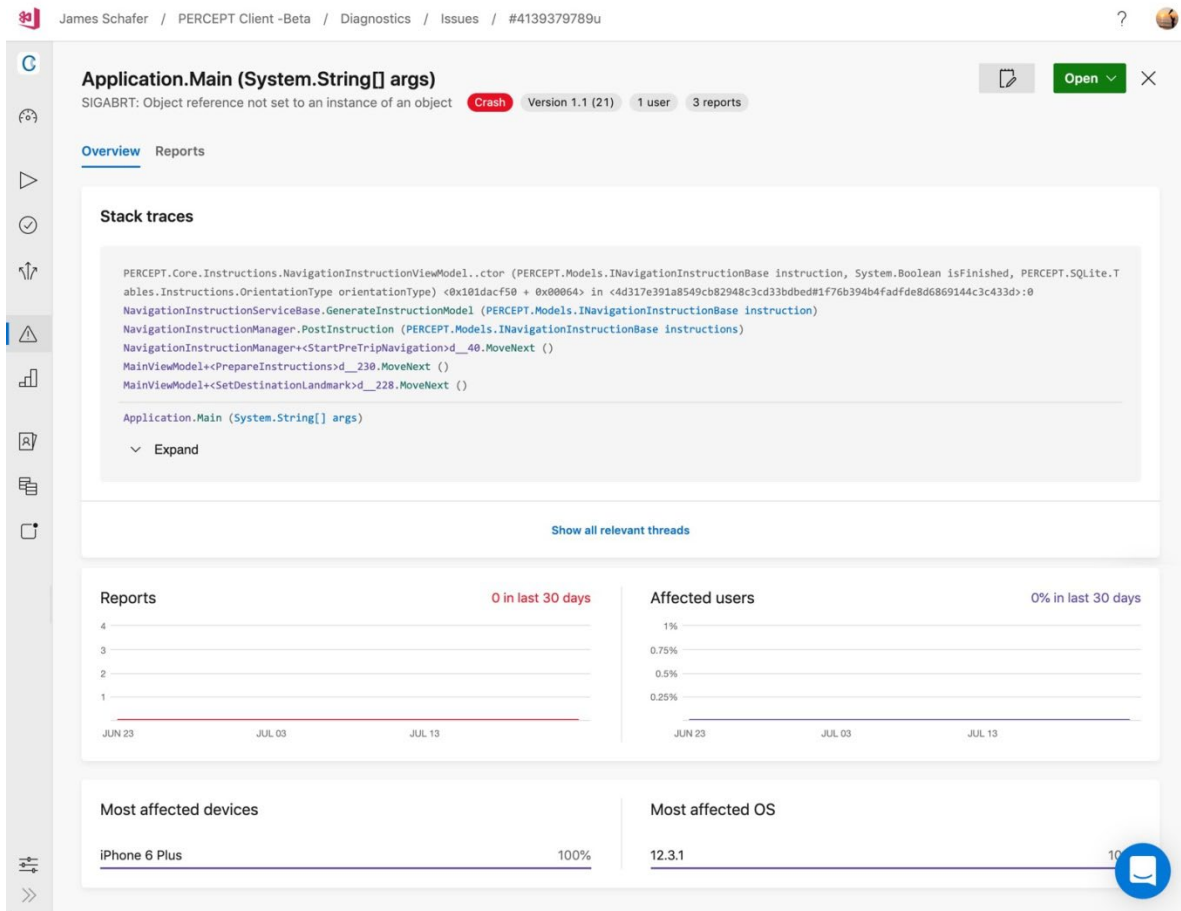


Figure 2.32: Example of issue report provided by crash analytics Web portal

2.3.5. PERCEPT Test Flight Submission (Task 5)

Upon completing Tasks 1 through 4, the research team prepared and submitted the PERCEPT application to Apple's Test Flight platform. This platform facilitates distributing the PERCEPT beta application to the enrolled participants. The following was accomplished in order to prepare the app for Test Flight:

- Generated a release build package for the application. This is similar to an .EXE file on a Windows system that is used to run or install an application.

- Thorough integration testing was conducted for the release build of the application. Each part of the application was tested, and this was performed both in the lab and onsite. Any issues encountered while testing were resolved.
- Custom app icons were created for the app (Figure 2.33).
- Custom splash screens were created for the app (Figure 2.34). A splash screen is the first screen displayed when opening an application.

The release build was then submitted to Test Flight to be reviewed by Apple. Once approved, the research team then shared the application with beta participants through an email link (Figure 2.35). Only beta participants authorized by the research team were able to download this application through the link. The link is a one-time use, and the team has the authority to revoke usage at any time should the app be used by someone who is not the enrolled participant. Upon the completion of this beta study, the PERCEPT application will be removed from Apple's Test Flight platform and be unavailable for use by beta participants.



Figure 2.33: PERCEPT app icon



Figure 2.34: PERCEPT app splash screen

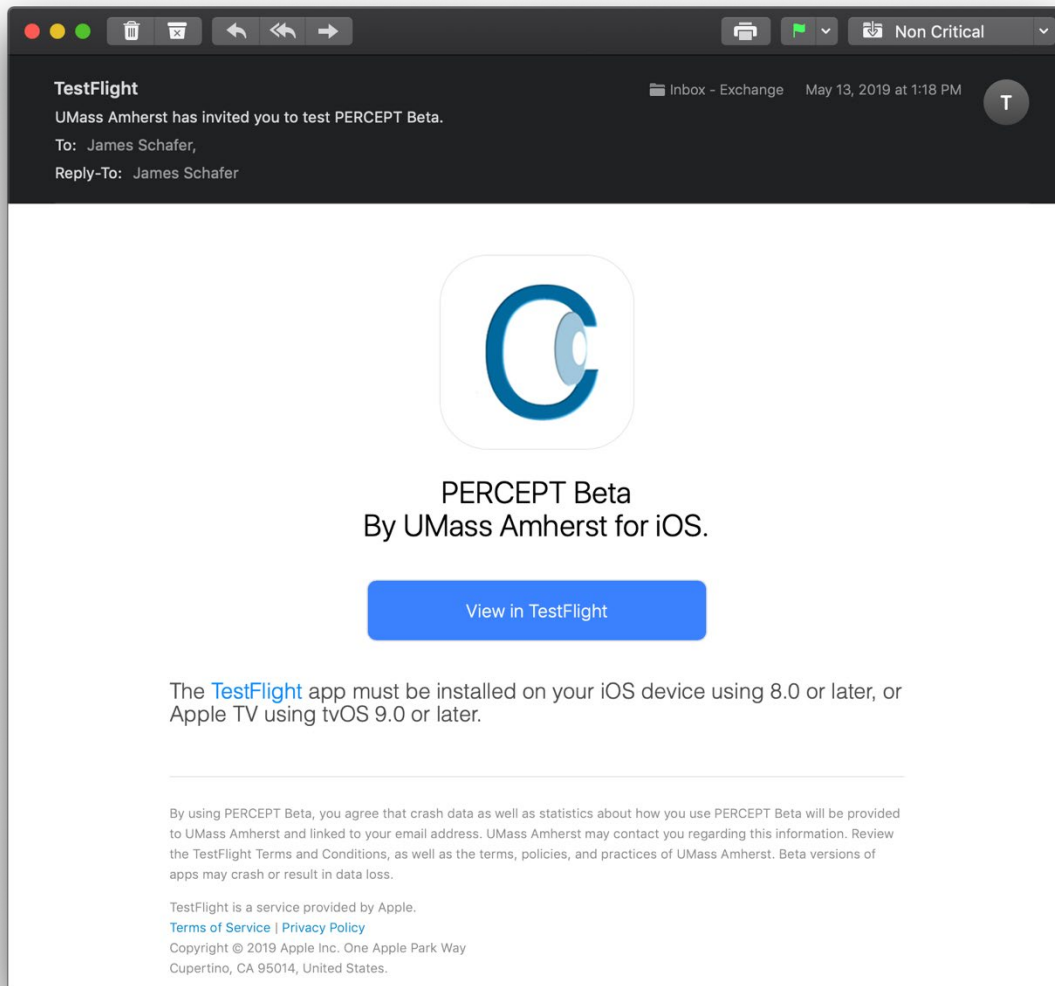


Figure 2.35: Email invitation to PERCEPT beta

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3.0 Results

Chapter 3.0 summarizes the results of human subjects testing and the various analytics collected covering usage and crashes, BLE tags, and trip count per destination.

3.1 Human Subjects Testing (Tasks 4, 6, 7)

The goal of the human subjects trials was to obtain BVI participant feedback on the PERCEPT application that was independently downloaded and used and that included the new features the team integrated during this beta study. This section discusses the IRB protocol, recruitment procedure, trial enrollment and participation, and summary of user feedback.

3.1.1. IRB Protocol (Task 4)

This study was approved by the UMass IRB; the IRB protocol is a part of **Task 4**. The principal investigators worked with PC David Block-Schachter to draft the documents used for the protocol. These documents can be found in the Appendices:

- Letter of Advertisement (Appendix B)
- Participant Screening Questions (Appendix C)
- Consent Form (Appendix D)
- Beta Questionnaire (Appendix E)
- IRB Submission Form (Appendix F)

3.1.2. Recruitment (Task 7)

Participants for the beta were recruited in one of three ways:

- The MBTA sent an email to its BVI patrons. Laura Brelsford, assistant general manager for MBTA's System-Wide Accessibility, orchestrated the participant recruitment email campaign using the IRB approved letter of advertisement. Six participants joined the study.
- The research team contacted participants from prior studies who requested to be informed of future studies and enrolled six of these participants.
- The principal investigators presented PERCEPT research to BVI organizations, the National Federation of the Blind, Greater Springfield chapter, and VIBUG in Cambridge. Five additional participants were recruited from these presentations.

The principal investigators continue to seek participants for the study.

Eligibility. As mentioned in the IRB protocol, all participants in the beta study must fulfill the following requirements in order to participate:

- Legally blind or visually impaired
- 18 years of age or older

- No further complications with physical or mental disability
- Received orientation and mobility training from COMS
- Own an iPhone 4S or newer

3.1.3. Trials Enrollment and Participation (Task 6)

Candidates who fulfill the eligibility requirements are given a UMass IRB-approved consent form. If they sign the consent form, they will be enrolled as participants in the study. Enrolled participants will have the following experience.

- **Install PERCEPT App:** After signing the consent form, participants will receive an email with a one-time link that authorizes the download of the PERCEPT application. Only authorized users can install the PERCEPT app on their smartphone. The application is set to expire when the study is completed on Sept. 30, 2019. Once expired, participants will no longer be able to open the application on their device.
- **Familiarize with PERCEPT:** Participants are encouraged to familiarize themselves with the PERCEPT app at home first by using the pre-travel planning feature to explore routes in North Station. Built into the application pages are tutorials and explanations that can familiarize participants with the use of the PERCEPT app. The participant can go through this process as many times as needed in order to become comfortable with using PERCEPT.
- **PERCEPT usage in North Station:** Participants will evaluate the PERCEPT app at a date and time that is convenient for them. When participants arrive at North Station, they will open the app and select a destination from a list of available destinations in North Station. Participants will then follow these detailed navigation instructions from their current location in order to reach the chosen destination.
- **Post-usage questionnaire:** Participants will provide feedback and experience using a qualitative questionnaire (Appendix E). This will be conducted either in person or over the phone at a scheduled time that is convenient for participants. Participants are asked to score their agreement with specific statements related to their experience during the trial. The score follows a Likert scale, from 1=Strongly Disagree to 7=Strongly Agree, and 4=Neither Agreeing nor Disagreeing with the statement. Should participants choose to continue using the PERCEPT app past the initial trial, follow-up post-trial questionnaires will be scheduled every month.

3.1.4. Summary of Participant Feedback (Task 6)

The statements included in the post-usage questionnaire (Appendix E) are provided in Table 3.1. Individual participant scores and the average score for each statement are provided in Table 3.2. One of the participants' feedback was not included, since the participant could not use the application because Bluetooth was disabled. This person will return for additional trials.

Table 3.1: Post-trial questionnaire statements

ID#	Statement
A	It is easy to learn how to use the PERCEPT system.
B	It is easy to use the PERCEPT system.
C	It is easy to follow the tutorial.
D	The PERCEPT app user interface is clear.
E	The PERCEPT system provided sufficient re-orientation information when lost.
F	I am confident when navigating North Station.
G	PERCEPT gives me the confidence to use public transportation independently.

Table 3.2: Post-trial questionnaire using Likert Scale scores

(Likert scale ranges from 1=Strongly Disagree to 7=Strongly Agree, and 4=Neither Agreeing nor Disagreeing with the statement.)

	Statement ID#						
ID#	A	B	C	D	E	F	G
P8	6	6	5	5	3	5	5
P11	7	7	n/a	7	7	6	7
P5	5	5	5	6	4	4	5
P2	6	6	n/a	6	5	7	6
P6	7	4	4	7	6	5	6
P14	6	5	6	6	5	5	5
AVG	6.17	5.50	5.00	6.17	5.00	5.33	5.67

Impression Questions. The Likert Scale statements were followed by a series of eight questions. Participants were asked to be open, detailed, and honest in their responses. The eight questions are provided in Table 3.3.

Table 3.3: Impression questions

ID#	Question
H	What are your favorite smartphone apps?
I	Do you use any navigation apps currently? Which one(s)?
J	Do you currently use the MBTA for public transportation?
K	Was this your first time using PERCEPT? a. If not, how many instances have you previously used PERCEPT? b. If not, did you notice any changes in your experience with using PERCEPT? Please include both good and bad experiences.
L	What specific components of the PERCEPT system did you like or dislike?
M	Name the most difficult part of using the PERCEPT system.
N	Are there any improvements you can suggest for the PERCEPT system?
O	Are you planning to continue using PERCEPT throughout the beta time? a. Why?

All participants used the MBTA subway for public transportation. The participants shared various smartphone applications they used for navigation, which included Seeing Eye GPS, Blindways, AIRA, Nearby Explorer, Google Maps, and Apple Maps. Out of all of these, the participants had only used AIRA for indoor navigation.

Participants shared what they liked about the system:

- Setup of the app was straightforward.
- The app was easy to use.
- Quick to begin a journey within the app.
- Level of detail provided in instructions.
- The app informs the station and floors they are located in.
- Ability to explore station at home using pre-trip planning.
- Use the application to identify the commuter rail platform numbers.
- Announces regions within station while moving around.

Participants shared what they disliked about the system:

- Using cardinal directions cues indoors is difficult.
- Separate instruction step for stairs and escalator instructions are unnecessary.
- Too much detail in some instructions.
- Manually press next instruction button.
- Sometimes it took a while to load instructions.

Each participant had a unique way that they traveled and a preferred format for the navigation instructions. It was evident through the feedback that some participants liked the level of detail provided by the instructions, but a few participants felt these instructions were too detailed. PERCEPT attempts to walk a fine line to give the right amount of details so that the average blind or visually impaired traveler can follow the instructions to reach the destination, even though it may not be the optimal format based on the user's preference.

Participants were asked what improvements they would make to the system, and their responses were as follows:

- Prefer to disable shake device to open PERCEPT Help Menu (addressed in the application update; see Section 2.3.3.3).
- Open the PERCEPT Help Menu through a button on the page (addressed in the application update; see Section 2.3.3.6).
- Preference to hide tutorial hints (addressed in the application update; see Section 2.3.3.3).
- Prompt user that Bluetooth needs to be turned on in order for PERCEPT to provide navigation instructions (addressed in the application update; see Section 2.3.3.7).
- Prompt user that Localization Permission must be accepted for PERCEPT to provide navigation instructions (addressed in the application update; see Section 2.3.3.7).
- Access the station high-level description from the Instruction page (addressed in the application update; see Section 2.3.3.6).
- For entrances, include the street name they lead to (will be addressed in the future application update).

- Search bar for filtering destinations (Noted for future improvement. Only one participant requested this).
- Automatically read next instruction when completing an instruction step (feature request is outside the scope of this project and is noted as a future improvement).
- Automatically reroute if heading in the wrong direction (feature request is outside the scope of this project and is noted as a future improvement).
- Vibrate when close to the destination (exploring accessible options to relate the proximity of destination through the app).
- Add all food vendors present in the commuter rail (currently focused on transportation-related landmarks, but noted as a future improvement).
- Preference for grouping more instructions together (feature request is outside the scope of this project and is noted as a future improvement).
- Swipe gesture to prompt the next instruction (Noted as a possible future improvement. Only one participant requested this).

All participants said they would continue to use PERCEPT throughout the beta study and provide additional feedback. No enrolled participant has dropped out of the beta study. The remaining participants who have not provided feedback have all shared they did not have the opportunity to go to North Station yet but will try PERCEPT by the end of Sept. 2019.

3.2 Analytics (Task 3)

The following subsections summarize the results collected from the analytics module that includes usage and crash analytics; BLE tag analytics; and trip count per destination.

3.2.1. Usage and Crash Analytics (Task 3)

The PERCEPT application has been used 105 times by 14 of the enrolled study participants. There was a total of four application crashes. Three of these crashes occurred for a single user when utilizing the pre-trip planning feature within 10 minutes. The fourth logged crash occurred for the principal investigators while testing the release build of the application in North Station. Both issues stemming from the crash were resolved, and an updated version of the application was pushed to participants. Outside of the set of crashes that occurred for one participant, the functioning of the PERCEPT app has been smooth, and no other application crashes have occurred.

There was a single user-reported issue. The PERCEPT application was not able to detect that Participant P3 was in North Station, and, therefore, P3 was unable to start a journey. After discussing the issue with Participant P3 and looking at the logged data, it was determined that P3's iPhone Bluetooth was turned off. Bluetooth is required to be on in order for PERCEPT to localize the user through the BLE tags deployed in North Station. To address this issue, the application now checks to see if Bluetooth is turned on. If Bluetooth is off, it will prompt the user to turn it on.

3.2.2. BLE Tag Analytics (Task 3)

There have been no issues encountered with BLE tag deployment. This includes both the original deployed tags and the tags deployed for this project. The average remaining battery for the current tags is 93%, and the remaining battery for the prior deployed tags, which are 2.5 years operational, is 62% (tag configuration).

3.2.3. Trip Count per Destination (Task 3)

Participants used the app for both the pre-trip planning and navigating inside North Station. PERCEPT analytics captured 29 trips made by 10 of the participants, in which 18 were to destinations in the commuter rail and 11 in the subway. Six of these trips were to a commuter rail platform, followed by four trips each to the restrooms, Causeway Street stairs entrance, and Green platform to Copley and stations west. Figure 3.1 depicts the trip count for each destination.

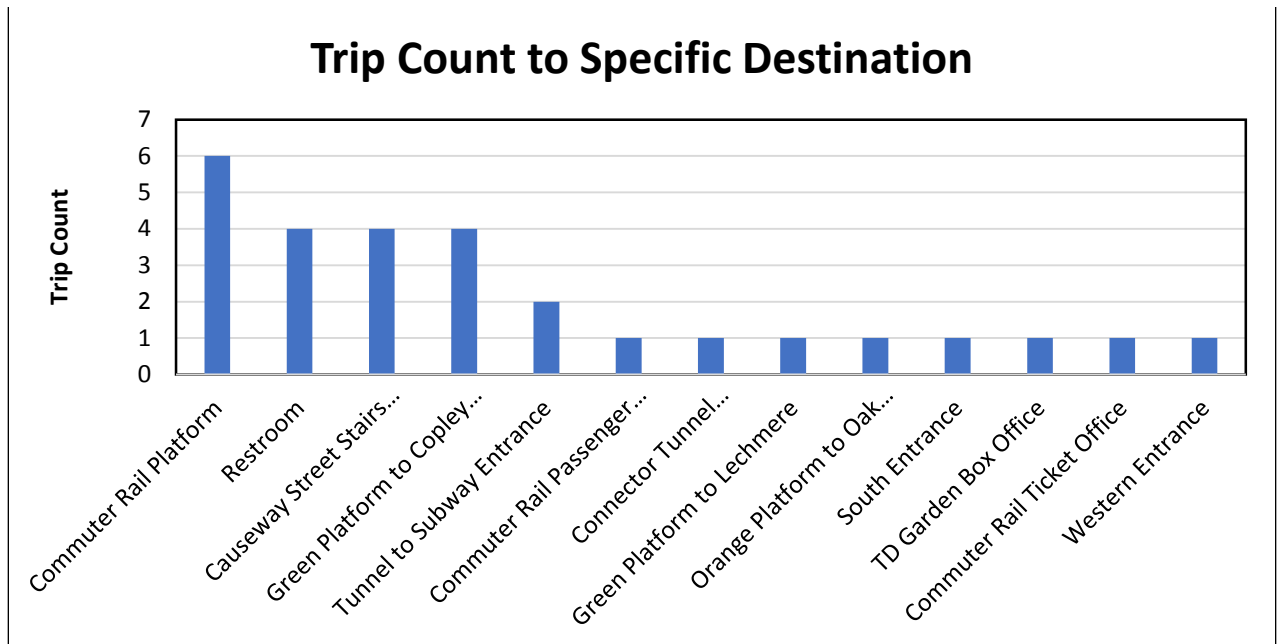


Figure 3.1: Trip count for each destination

4.0 Implementation and Technology Transfer

The principal investigators will provide the MBTA with detailed BLE deployment documentation so that they can leverage the BLEs for their purposes. This documentation includes:

- A blueprint containing each tag location
- Text description of the tag's location
- Each unique tag's identifiers

With this information, the MBTA will have everything to develop solutions that utilize the BLE infrastructure in North Station. This document can be found in Appendix A.

The PERCEPT system is the intellectual property of the University of Massachusetts Amherst and will not be transferred.

The principal investigators are working with the UMass Transportation Center to establish a Revenue Operations Entity, which will enable them to charge for their products and services.

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5.0 Conclusions

In this beta study, the research team leveraged its expertise in the following research and development areas: localization, BLE tag deployment, navigation instructions generation, user interface design, experimental design, human subjects trials, development and testing of working systems, and software development for the iOS platforms and cloud services.

The principal investigators conclude that the beta study was very successful, due to the following observations.

1. **The PERCEPT trial participants' feedback was very positive** (see Section 3.1.4. for quantitative and qualitative feedback statistics). All participants mentioned that they will use PERCEPT if deployed at the MBTA. Note that in this study, the participants independently downloaded and used the application, instead of the controlled trial used in previous studies. Participants were able to independently install PERCEPT, learn how to use the app, and navigate to the destinations in a complex station such as North Station (Section 3.1.4.). North Station is a challenging environment in which to navigate. It is large, open, complex, and can receive significant foot traffic during peak times. These facts shows the scalability of the PERCEPT application and its use by a large number of users in the MBTA.
2. **The BLE infrastructure is robust and easy to maintain** (see Section 3.2.2 for tag maintenance statistics). There were no malfunctions or vandalism of the BLE tags. The tag batteries drain about 18% per year, for a total of five years of battery life (there are tags with longer battery life). The team has also shown that the tag replacement or addition effort is minimal. These facts are evidence to the scalability of the PERCEPT system and its applicability to systemwide deployment.
3. **The PERCEPT application is robust and can be remotely monitored** (see Section 3.2.1. for usage statistics). There are two types of issues that are tracked: crashes in which a fatal error occurs and the application closes, and logical errors in which the application does not function as intended. Only a single type of each issue occurred early in the beta study. Both reports were identified through the analytics tools developed, and an updated version of the application was pushed to the participants.

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6.0 References

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7.0 Appendices

7.1: Appendix A: BLE Deployment Scheme

PERCEPT Tag Deployment for North Station

Last Updated July 28, 2019

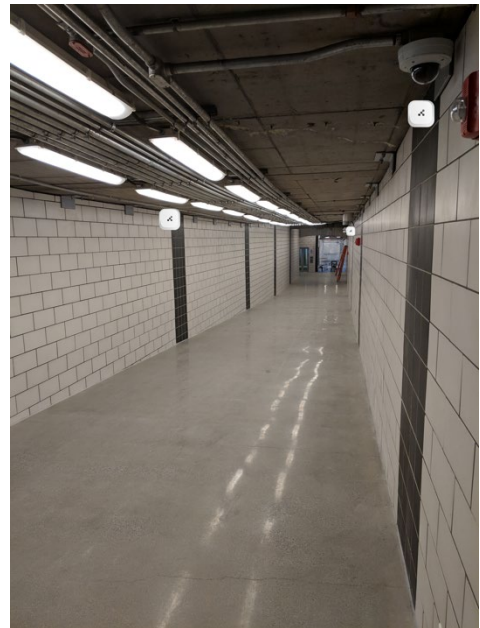
This document is broken into three sections:

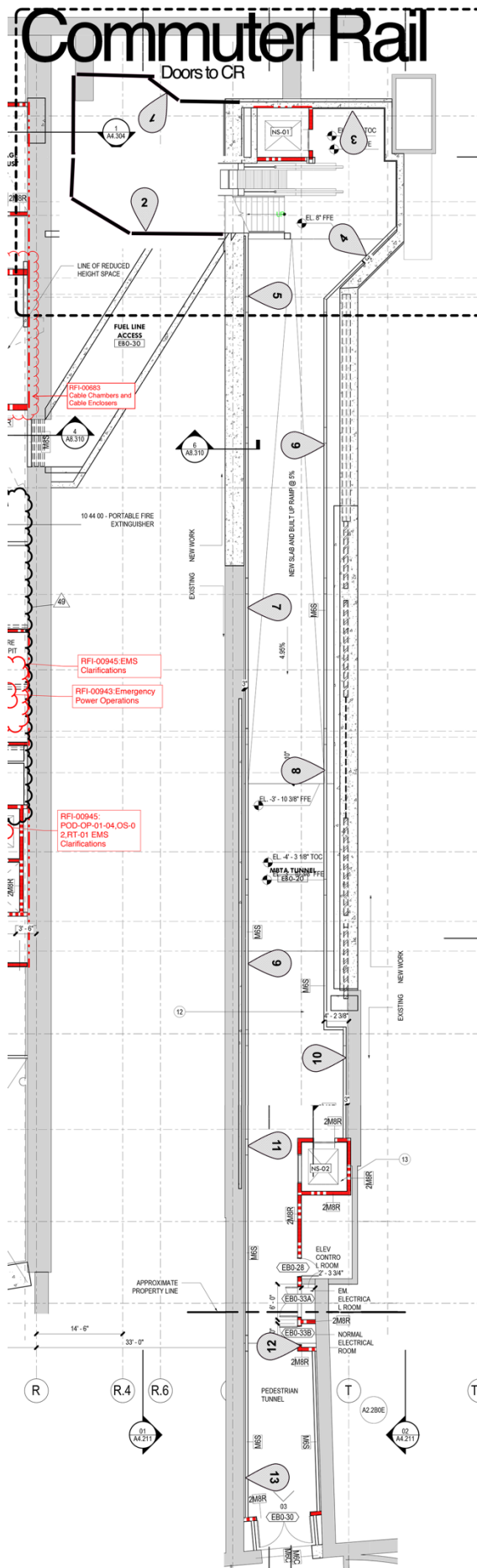
- North Station connector tunnel (Section 1)
- North Station subway (Section 2)
- North Station commuter rail (Section 3)

1. Deployment in North Station Connector Tunnel

Tunnel portion of connector

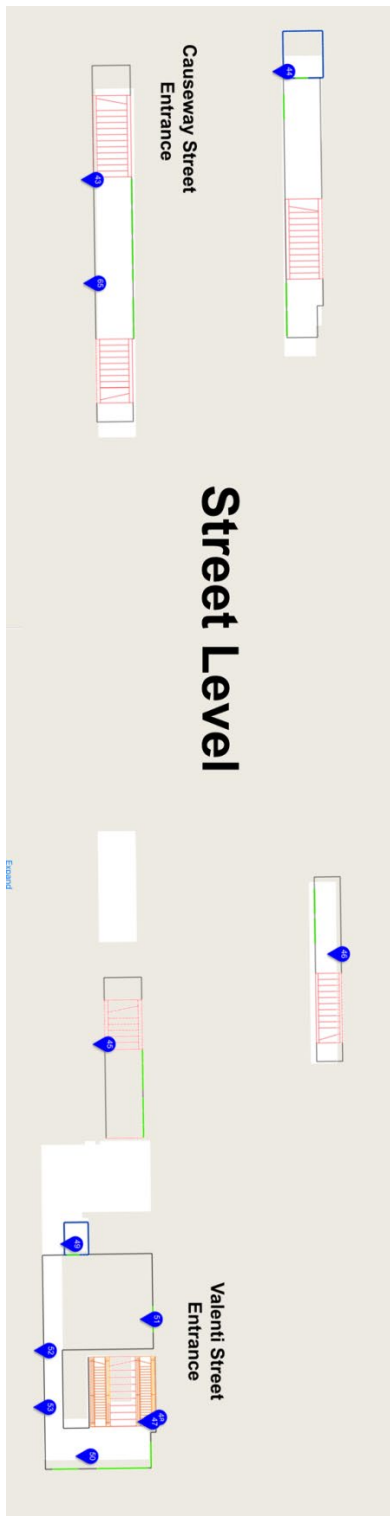
A tag is to be placed on the black tile stripe on the walls. The tags will alternate the side of the wall they are placed starting on the right side wall heading from commuter rail to the subway as depicted in the figure to the right. For the long hallway the only tags not placed on the black tiles are tags 10, 12, and 13. The tags placed on the black tiles will be black.

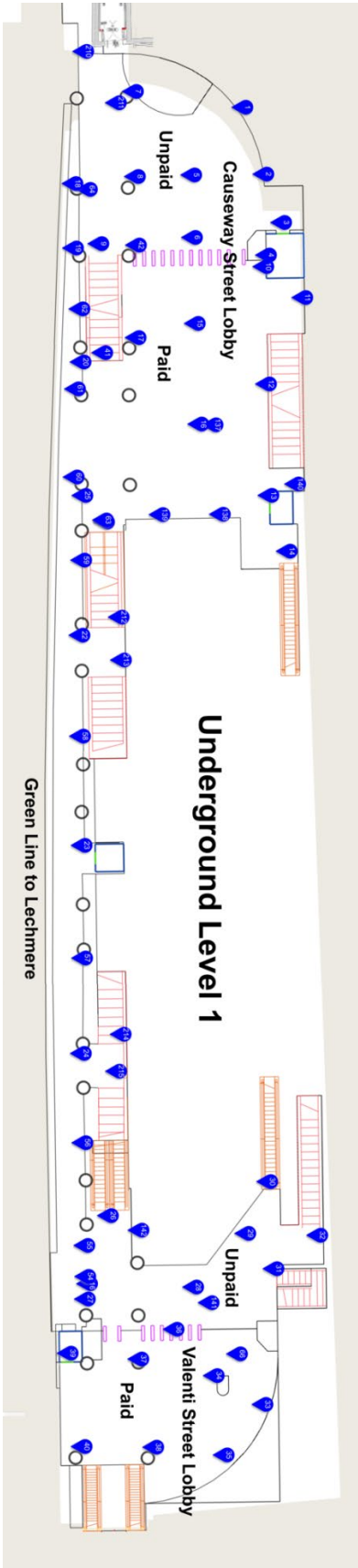




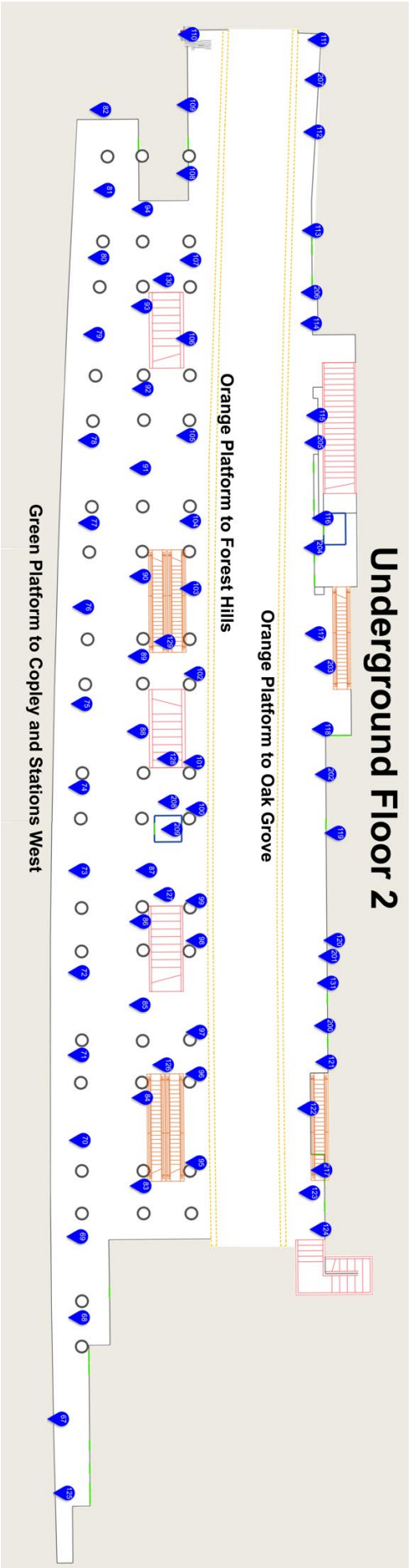
Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
15-1 black	0eOu	Tunnel Upper Floor	On the wall to the right of the entrances to Commuter Rail. Placed on the black tile horizontally centered across the wall.	Out towards tag 2
15-2 black	06nI	Tunnel Upper Floor	On the wall across from the entrances to the Commuter Rail. Placed on the black tile horizontally centered. 2ft to the left where wall intersects with diagonal wall with the subway map on it.	Out towards tag 1
15-3	o8fR	Tunnel Lower Floor	On the wall close to the right of the North Station Signage indicated direction of TD Garden. Placed as close to ceiling as possible	Out towards tag 4
15-4	w8sI	Tunnel Lower Floor	On the wall to the left of signage.	Facing stairs/escalator
15-5 black	0JJG	Tunnel Lower Floor	On black tile stripe as close to ceiling as possible	Out towards tag 4
15-6 black	zvMu	Tunnel Lower Floor	On black tile stripe 9ft in height from floor	Opposite hallway wall
15-7 black	DyFn	Tunnel Lower Floor	On black tile stripe 9ft in height from floor	Opposite hallway wall
15-8 black	nmRD	Tunnel Lower Floor	On black tile stripe 9ft in height from floor	Opposite hallway wall
15-9 black	RF6r	Tunnel Lower Floor	On black tile stripe 9ft in height from floor	Opposite hallway wall
15-10	G9W7	Tunnel Lower Floor	Centered horizontally on wall above map.	Opposite elevator to causeway street
15-11 black	N8W7	Tunnel Lower Floor	On black tile stripe 9ft in height from floor.	Opposite hallway wall
15-12	AVDh	Tunnel Lower Floor	Centered above doorway	Opposite hallway wall
15-13	7bij	Tunnel Lower Floor	On wall 9f in height from floor and 6 feet horizontally to the right from the intersecting doorways into the subway	Opposite hallway wall

2. Deployment in North Station Subway





Underground Floor 2



Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-1	RMFD	Northern Lobby	Wall-next to Fare machine	
4-2	pn7h	Northern Lobby	Wall-next to Fare machine, at corner	faces out in direction that fare machines along wall face out
4-3	UVsC	Northern Lobby	Above Elevator Door	
4-4	ZEOB	Northern Lobby	Concrete Beam	on the face of the beam that points towards tag 4-6
4-5	WpmF	Northern Lobby	Concrete Beam,	on the face of the beam that points towards the elevator and tag 4-2
4-6	09fZ	Northern Lobby	Concrete Beam above pillar,	on the face of the beam that points towards the elevator and tag 4-4
4-7	Mlm7	Northern Lobby	Concrete Beam above pillar,	on the face of the beam that points towards the elevator and tag 4-1
4-8	CmdB	Northern Lobby	Concrete Beam above pillar,	on the face of the beam that points towards the elevator and tag 4-1
4-9	o3lb	Northern Lobby	On center concrete arch	facing closed down exit/security room, and tag 4-7
4-10	7O0c	Northern Foyer	Wall, at corner,	facing tag 4-9
4-11	4BUg	Northern Foyer	Concrete Beam,	facing away from the main area, tags back would be tag 4-15
4-12	U631	Northern Foyer	Wall	
4-13	xmNJ	Northern Foyer	Above Elevator Door in just under signage for Orange Line	
4-14	RWFC	Northern Foyer	Arch	face to elevator
4-15	IZAI	Northern Foyer	Concrete Beam	face to platform and tag 4-20
4-16	TeZW	Northern Foyer	Concrete Beam	face to platform and tag 4-20
4-17	Yh7f	Northern Foyer	Concrete Beam	face main foyer area and tag 4-15
4-18	Av3t	Northern Green Inbound	Placed on concrete beam, above pillar, ensure out of reach of benches in area so individuals cannot stand on bench to touch the tags	platform

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-19	Kjhm	Northern Green Inbound	Placed on concrete beam, above pillar, between pipes on wall, ensure out of reach of benches in area so individuals cannot stand on bench to touch the tags	platform
4-20	noJU	Northern Green Inbound	concrete beam next to pillars	platform
4-21	nYqf	Northern Green Inbound	arch above escalator	fare gates and tag 4-20
4-22	76lb	Northern Green Inbound	on concrete beam that is in front of opening to stairways that go upstairs and downstairs.	platform
4-23	uUBs	Northern Green Inbound	on concrete beam that is in front of elevator.	platform
4-24	W8uu	Southern Green Inbound	on concrete beam that is in front of opening to stairways that go upstairs and downstairs.	platform
4-25	XGci	Southern Green Inbound	in a line with 4-22	platform
4-26	YS46	Southern Green Inbound	arch above escalator	fare gates and tag 4-27
4-27	DT5Y	Southern Green Inbound	concrete beam above pillar	Facing out from wall behind column, towards escalator to downstairs platforms
4-28	Y4zz	Southern Foyer	concrete beam centrally located between fare gate and opposing wall	face platform and towards tag 4-27
4-29	TEW2	Southern Foyer	concrete beam centrally located between opening with stairways leading up where tag 4-32 is located	face tag 4-32
4-30	R7Qe	Southern Foyer	arch	fare gates and tag 4-31
4-31	Bagf	Southern Foyer	concrete beam centrally located between stairway	lobby and tag 4-28
4-32	EK7S	Southern Foyer	Wall, with height thats placed above the metal frame that houses lighting	
4-33	WYDg	Southern Lobby	Wall	
4-34	b5g9	Southern Lobby	Placed on concrete beam, above pillar, located in front of the standalone booth	Face elevator towards tag 4-37
4-35	X3B0	Southern Lobby	Wall	
4-36	pJ1V	Southern Lobby	concrete beam above fare gates	Face elevator and tag 4-39
4-37	SuLu	Southern Lobby	Placed on concrete beam, above pillar	Face elevator and tag 4-39
4-38	NFTl	Southern Lobby	Placed on concrete beam, above pillar	Facing stairs and tag 4-40

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-39	Q48n	Southern Lobby	Above Elevator Door	
4-40	ntCu	Southern Lobby	Placed on concrete beam, above pillar	Facing stairs and tag 4-38
4-41	zWf9	Nothern Foyer	arch above stairway	faces 4-21
4-42	raXg	Northern Lobby	Concrete Beam	on the face of the beam that points towards the elevator and tag 4-6
4-43	Tx7f	Street Level	Wall above advertisement (currently placed above ducks head)	
4-44	Yika	Street Level	Wall next to entry door and nearby to elevator	
4-45	vZAb	Street Level	Wall	
4-46	8Lpc	Nothern Foyer	Wall next to stairway	faces platform
4-47	Folc	Street Level	Wall to Left of Entry Doors	
4-48	TeCQ	Street Level	Above Doorway to the right of signage	
4-49	zCiD	Street Level	Above Elevator	
4-50	89Bj	Street Level	Wall Between Doorways	
4-51	OIXI	Street Level	Above Doorway to the right of signage, this entrance doorway is across from elevator	Facing elevator
4-52	kvSb	Street Level	Longest wall in hallway for the Valenti Street entrances. In the hallway the tag will be placed 6 feet from start of hallway on the elevator side.	
4-53	QGto	Street Level	Longest wall in hallway for the Valenti Street entrances. In the hallway the tag will be placed 6 feet from start of hallway on the Valenti street entrance side.(The map is inaccurate with regards to the length of this hallway)	
4-54	7RCJ	Southern Lobby & Foyer	Concrete Beam, in middle of the pathway between escalator and wall with adjacent fare gates. .(The map is inaccurate with regards to the length of this hallway)	Faces towards Stairs that go down to Orange Outbound and tag 28.
4-55	S1uT	Southern Lobby & Foyer	Concrete Beam above pillar with the help call box.(The map does not visually show the pillar here. But this is the last fenced pillar along the platform.) The tag should be placed 4 inches to the left of the vertical piping	Faces towards platform
4-56	04gu	Southern Lobby & Foyer	Concrete Beam, Roughly halfway between tag 55 & 24.	Faces towards platform

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-57	Tfb4	Green Inbound Platform	Concrete Beam. In between the pillar and standup subway map.	Faces towards platform
4-58	404s	Green Inbound Platform	Concrete Beam , 4 feet to the left of column that has the help call box	Faces towards platform
4-59	esAS	Northern Foyer	Concrete Beam	Facing towards platform
4-60	ykOG	Northern Foyer	Concrete Beam, above Pillar, 4 inches to the left of the vertical metal piping	Facing towards platform
4-61	a3ev	Northern Foyer	Concrete Beam, above Pillar, 2 feet to the right of the thick vertical metal piping	Facing towards platform
4-62	WRCq	Northern Foyer	Concrete Beam, halfway between column with help call box and the stand subway map	Facing towards platform
4-63	ae0U	Northern Foyer	On the bottom side of the arch, Just below tag 21	Facing down towards escalator
4-64	OhQN	Northern Lobby	Concrete Beam above pillar	Facing towards elevator and tag 2
4-65	s8UY	Street Level	Wall across from entrance door that is closest to the exit only turnstiles. This should be 3 feet to the right from turnstiles.	Entrance door
4-66	I9AF	Southern Lobby & Foyer	Concrete Beam above metal pillar	Faces in the direction of tag 31 and 33. Also faces in the direction of closest wall .
4-67	scdz	Green Inbound Platform	Slanted concrete 'ceiling', that hangs over narrow portion of platform. The tag should be centrally placed on concrete, from wall to platform.	Down towards floor
4-68	ccfz	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-69	tprR	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-70	EpgM	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-71	avPA	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-72	RUFh	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-73	m4uY	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-74	lGZI	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-75	IGZA	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-76	oPJI	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-77	xLI2	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-78	tzIs	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-79	cfka	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-80	yhYc	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-81	v6pD	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-82	lkgc	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the track. Tag should be placed on the flat bottom of the pillar and centered along width of pillar	Down towards floor.
4-83	49MG	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-84	EAXL	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-85	DYGI	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-86	WNph	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-87	p0WF	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-88	ZUc0	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-89	cmxj	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-90	Vf6u	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-91	jkYy	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-92	cUps	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-93	jUse	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-94	Xsmy	Green Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on green inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-95	JBdB	Orange Inbound Platform	On vertical column, 2 inches below where light post sticks out	Faces Orange Inbound Platform
4-96	rDac	Orange Inbound Platform	On vertical column, 2 inches below where light post sticks out	Faces Orange Inbound Platform
4-97	fN6n	Orange Inbound Platform	On vertical column, 2 inches below where light post sticks out	Faces Orange Inbound Platform
4-98	0ZMb	Orange Inbound Platform	On vertical column, 2 inches below where light post sticks out	Faces Orange Inbound Platform
4-99	Gigs	Orange Inbound Platform	On vertical column, 2 inches below where light post sticks out	Faces Orange Inbound Platform
4-100	WG8M	Orange Inbound Platform	On vertical column, 2 inches below where light post sticks out	Faces Orange Inbound Platform
4-101	K8IV	Orange Inbound Platform	On vertical column, 2 inches below where light post sticks out	Faces Orange Inbound Platform
4-102	zGWA	Orange Inbound Platform	On vertical column, 2 inches below where light post sticks out	Faces Orange Inbound Platform
4-103	A7QR	Orange Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on Orange inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-104	uXu3	Orange Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on Orange inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-105	p4AD	Orange Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on Orange inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.

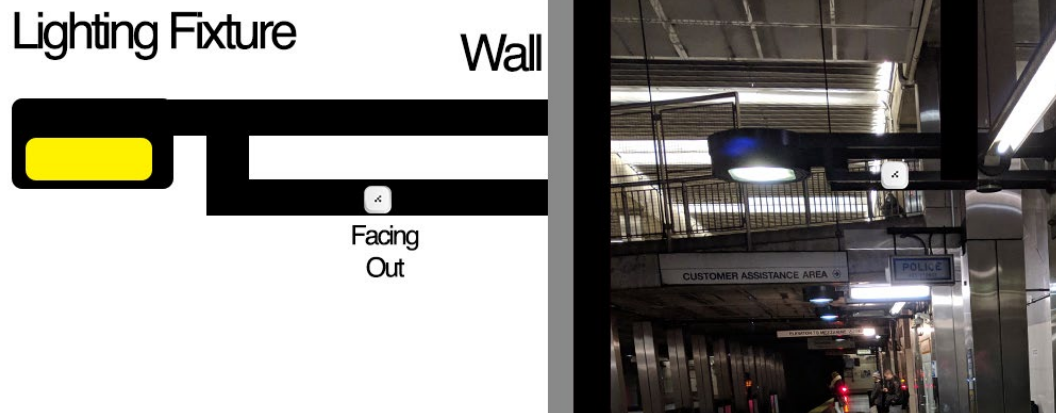
Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-106	uxgd	Orange Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on Orange inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-107	BQoe	Orange Inbound Platform	On horizontal concrete pillar that runs the length of the columns along the stairs/elevator/escalator on Orange inbound side. Tag should be placed on the flat bottom of the pillar and centered along width of pillar.	Down towards floor.
4-108	9IzB	Orange Inbound Platform	On Wall 9ft vertical height from floor	Face towards Orange Inbound platform
4-109	xNgM	Orange Inbound Platform	On Wall 9ft vertical height from floor	Face towards Orange Inbound platform
4-110	vmFm	Orange Inbound Platform	On Wall 9ft vertical height from floor	Face towards Orange Inbound platform
4-111	6cLs	Orange Outbound Platform	On Wall 9ft vertical Height from floor, positioned above the security monitor	Face towards Orange Outbound platform
4-112	yhsA	Orange Outbound Platform	On Wall 9ft vertical Height from floor, positioned above and to the right of the bench	Face towards Orange Outbound platform
4-113	QsFZ	Orange Outbound Platform	On Wall positioned above and between two doorways, 2 inches under the horizontal light post	Face towards Orange Outbound platform
4-114	N9wS	Orange Outbound Platform	On Wall 9ft vertical Height from floor	Face towards Orange Outbound platform
4-115	HUzm	Orange Outbound Platform	On Wall 9ft vertical Height from floor	Face towards Orange Outbound platform
4-116	qhYj	Orange Outbound Platform	Centered above elevator door	Face towards Orange Outbound platform
4-117	pppM	Orange Outbound Platform	On vertical support column 9f vertical height from floor. This is the column with a call box.	Face towards Orange Outbound platform
4-118	VF1a	Orange Outbound Platform	On Wall 9ft vertical Height from floor	Face towards Orange Outbound platform
4-119	Tn05	Orange Outbound Platform	On Wall 9ft vertical Height from floor to left of doorway and benches	Face towards Orange Outbound platform
4-120	VpNN	Orange Outbound Platform	On Wall 9ft vertical Height from floor to left of doorway	Face towards Orange Outbound platform

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-121	zOkm	Orange Outbound Platform	On Wall 9ft vertical Height from floor to left of escalator	Face towards Orange Outbound platform
4-122	hJMX	Orange Outbound Platform	On Wall 9ft vertical Height from floor	Face towards Orange Outbound platform
4-123	JneY	Orange Outbound Platform	On vertical column 9ft vertical height from floor	Face towards Orange Outbound platform
4-124	kURa	Orange Outbound Platform	On Wall 9ft vertical Height from floor to left of stairs	Face towards Orange Outbound platform
4-125	f5rN	Green Inbound Platform	Slanted concrete 'ceiling', that hangs over narrow portion of platform. The tag should be centrally placed on concrete, from wall to platform.	Down towards floor
4-126	1DC4	Lower Floor, Southern Escalator	On bottom side of the signage indicating green and orange lines above the beginning of the escalator	Down towards floor
4-127	aPz0	Lower Floor, Southern Stairs	On bottom side of the signage indicating green and orange lines above the beginning of the stairs	Down towards floor
4-128	fZOO	Lower Floor, Central Stairs	On bottom side of the signage indicating green and orange lines above the beginning of the stairs	Down towards floor
4-129	OQE2	Lower Floor, Northern Escalator	On bottom side of the signage indicating green and orange lines above the beginning of the escalator	Down towards floor
4-130	BS94	Lower Floor, Northern Stairs	On bottom side of the signage indicating green and orange lines above the beginning of the stairs	Down towards floor
4-131	WiC1	Orange Outbound Platform	On Wall 9ft vertical Height from floor	Face towards Orange Outbound platform
4-132	sCt1	Orange Outbound Platform	Wall centered across from stairs going up.	Stairway.
4-133	CrWZ	Orange Outbound Platform	Wall 3 feet to the left of stairway	Orange Outbound Platform
4-134	C13H	Orange Outbound Platform	Wall 3 feet to the right of escalator	Orange Outbound Platform
4-135	5JuH	Orange Outbound Platform	Wall centered across from escalator going up.	escalator.
4-136	qKyE	backup		

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-137	ovRK	Northern Foyer/paid lobby	Same location on Concrete Beam as 16 except on the opposite face	face towards elevator and tag 13
4-138	9LV2	Northern Foyer/paid lobby	Concrete beam 5 feet from metal fence that looks to platforms below	face towards elevator and tag 13
4-139	V1nh	Northern Foyer/paid lobby	Concrete beam 5 feet from metal fence that looks to platforms below. Opposite face of beam from tag 138	face towards elevator and tag 13
4-140	hI2P	Northern Foyer/paid lobby	On Wall centrally located to the opposing stairs	Face towards stairway going down
4-141	r50P	Valenti Paid Lobby/ Southern Foyer	concrete beam centrally located between fare gate and opposing wall. Opposite face of beam to tag 28	face stairway to orange outbound and tag 31
4-142	LpFc	Valenti Paid Lobby/ Southern	Centrally located on the face of the concrete upper beam	Face green outbound platform
4-143	6Ib6	Street Level	On Wall on opposite end of tag 44	Facing street
4-144	tODJ	Street Level	On Wall	Facing street
4-145	orQP	Street Level	On Wall	Facing Street
4-146	q15J	Street Level	On Wall on opposite end of tag 45	Facing street
4-147	RAvL	Green Inbound Platform	Slanted concrete 'ceiling', that hangs over narrow portion of platform. This tag and tag 148 should be evenly spaced between tags 68 and 125.	Down towards floor
4-148	6MFm	Green Inbound Platform	Slanted concrete 'ceiling', that hangs over narrow portion of platform. This tag and tag 147 should be evenly spaced between tags 68 and 125.	Down towards floor

Orange Line Outbound to Oak Grove Lighting Fixture Details

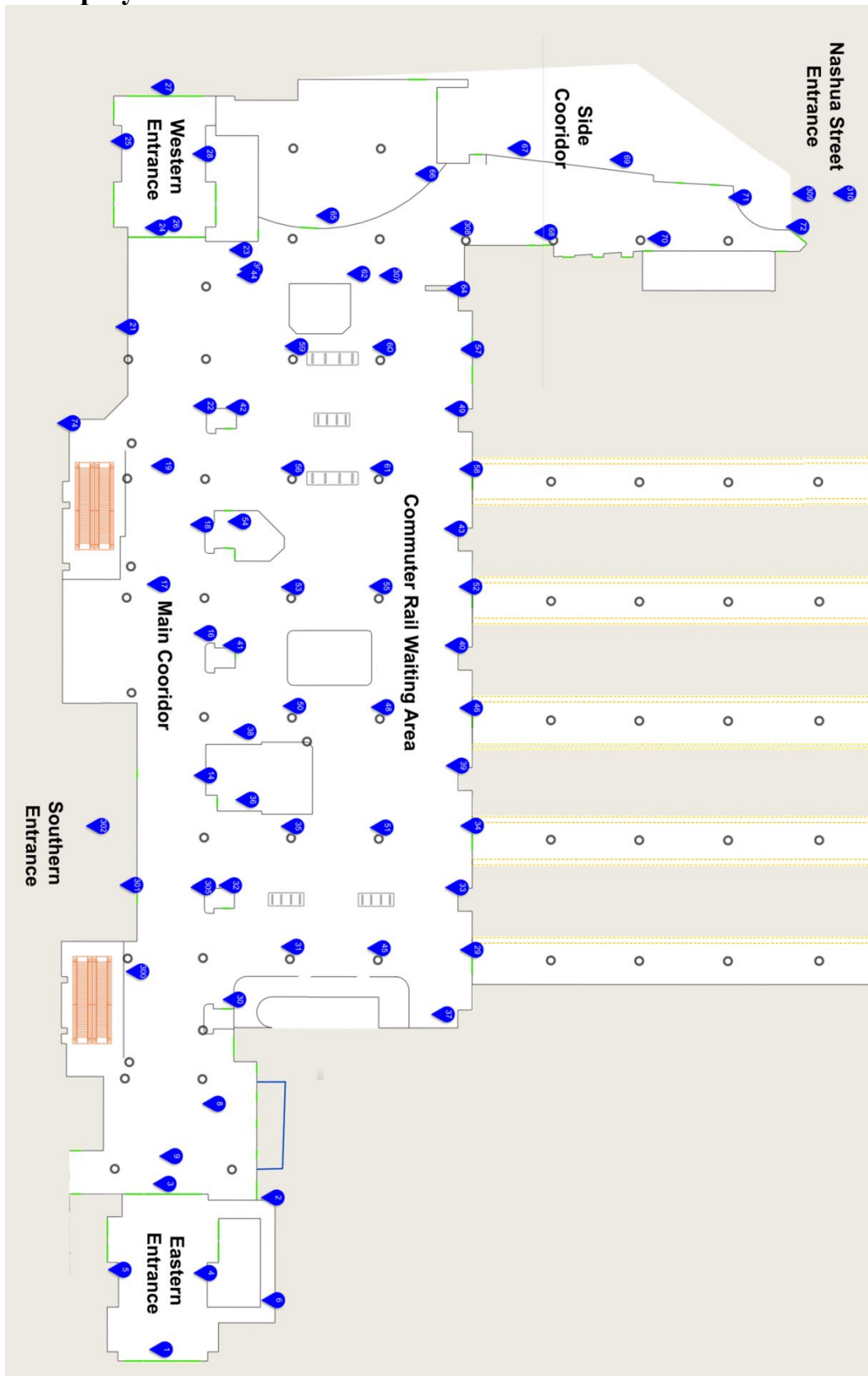
A tag to be placed on every other lower metal beam that supports the lighting that is along the Oak Grove beam for the lighting along. Each tag should be centered horizontally on the beam and face out in the direction towards the Valenti Street lobby of North Station subway (See figure below). These tags will be a lightly glossy black with a close match to the beam color.



Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
4-200 black	7qIo	Orange Outbound Platform	2 nd lighting fixture beam from the escalator that leads into the Valenti Street Lobby. This beam also has a fan attached to it.	There are two horizontal beams that support the lighting fixture. This tag is to be placed on the lower beam and centered horizontally.(See Figure 1 above) The tag should face out towards the Escalator that leads into Valenti Street lobby.
4-201 black	CKcP	Orange Outbound Platform	Heading from Valenti Street escalator, this is the lighting beam right before the bench.	Same as tag 4-200 above
4-202 black	BZrw	Orange Outbound Platform	Heading from Valenti Street escalator, this is the last fixture before the platform widens to the escalator to causeway street	Same as tag 4-200 above
4-203 black	1zvD	Orange Outbound Platform	Fixture directly next to escalator heads into Causeway street lobby	Same as tag 4-200 above
4-204 black	5WSg	Orange Outbound Platform	Heading from Valenti Street escalator, this is the fixture just prior to the elevator	Same as tag 4-200 above
4-205 black	iR1N	Orange Outbound Platform	This is the fixture right next to stairway heading up to Causeway street lobby.	Same as tag 4-200 above
4-206 black	GhQT	Orange Outbound	Heading from Valenti Street escalator, this is the 3 rd to last fixture	Same as tag 4-200 above

Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
		Platform	and it is the one placed near doorway.	
4-207 black	ciBp	Orange Outbound Platform	Heading from Valenti Street escalator, this is the last fixture.	Same as tag 4-200
4-208	OnsC	Green Inbound Platform	On wall that encloses Elevator above payphones. 9ft in height from floor.	Face towards stairway with tag Id 126
4-209	Pb2N	Green Inbound Platform	On wall that encloses Elevator. 9ft in height from floor.	Face towards stairway with tag Id 127
4-210	J33W	Causeway Unpaid Lobby	On concrete wall above metal fencing, 2ft to the left of intersecting upper wall for the connecting tunnel.	Face towards security booth
4-211	DEK8	Causeway Unpaid Lobby	On concrete wall above metal fencing, 2ft to the left of intersecting upper wall for the connecting tunnel.	Face towards Green Outbound Platform towards Lechmere
4-212	CoIJ	Green Inbound Platform	On upper concrete wall positioned horizontally just right of the stairways leading up.	Face towards Green Outbound Platform towards Lechmere
4-213	fmT3	Green Inbound Platform	On upper concrete wall above railing. Positioned horizontally left of the stairways leading down, 1ft left from the metal pipe.	Face towards Green Outbound Platform towards Lechmere
4-214	zSNT	Green Inbound Platform	On upper concrete wall above railing. Positioned horizontally right of stairway leading down, 1ft right from metal pipe.	Face towards Green Outbound Platform towards Lechmere
4-215	eYQO	Green Inbound Platform	On upper concrete wall above railing. Positioned horizontally left of stairway leading up.	Face towards Green Outbound Platform towards Lechmere
4-216	muGL	Green Inbound Platform	On upper concrete wall, 4ft to the right of the metal support column coming from floor.	Face towards Green Outbound Platform towards Lechmere
4-217	CEBM	Orange Outbound Platform	Centered above doorway	Opposite Stairway that leads up to Valenti Street lobby

3. Deployment in Commuter Rail



Tag ID	Tag Code	Region	Surface	Positioned	Tag Faces
3-1	3auM	East Entrance	Doorway	Center of the doorways, placed under advertisement	To the stairs
3-2	MB1r	East Entrance	Wall	Centered to the Hallway leading to it	Out to the main entrance area
3-3	KBjg	East Entrance	Doorway	Center of the doorways, placed under advertisement	
3-4	2qB0	East Entrance	Wall	Halfway up the stairs, placed at similar height to opposing tag 5	towards stairs, opposite of 5
3-5	YGly	East Entrance	Wall	Halfway up the stairs, Above 'East Entrance' decal	towards stairs, opposite of 4
3-6	9M10	East Entrance	Wall	Centered to the hallway leading to it	Out to the main entrance area
3-7	qu8y	East Entrance	Wall	placed above #2 decal	towards elevator
3-8	xY5c	Main Corridor	Center of Ceiling Tile	prior to the 3rd row of lights from entrance doors, 4 tiles to the left of elevators	Floor
3-9	vymk	Main Corridor	Doorway	Center of the doorways, placed under advertisement	
3-10	LD6c	Main Corridor	White Facia with lighting soffit	At the start of the Facia	facing ATM
3-11	MeX0	Main Corridor	White Facia with lighting soffit	At the end of the Facia	facing ATM
3-12	Sy3r	Main Corridor	Metal Wall	Centered, above large black panel	MBTA Info Booth
3-13	p5F4	Main Corridor	Center of Ceiling Tile	positioned centrally along this corridor and in row with the pillar just after the commuter rail information office	Floor
3-14	sMnB	Main Corridor	Wall	Aligned above the right of doorway	DownEaster Ticket Booth
3-15	MNQ2	Main Corridor	Center of Ceiling Tile	positioned centrally along this corridor, in row with pillars located to Amtrak ticket booths	Floor
3-16	DVSC	Main Corridor	Metal Wall	Just left on the portion of metal where it starts to curve.	Amtrak Ticket Area
3-17	qECs	Main Corridor	White Facia with lighting soffit	At the start of the Facia	Commuter Terminal Seating Area
3-18	Je0o	Main Corridor	Metal Wall	Centered, above large black panel	Escalator
3-19	1ELC	Main Corridor	White Facia with lighting soffit	At the end of the Facia	Commuter Terminal Seating Area
3-20	Xpdf	Main Corridor	Center of Ceiling Tile	Centered across of the Amtrak Ticket Booths, 3 feet from the booths	Floor
3-21	7pxi	Main Corridor	Wall	3 feet to the right of McDonalds ceiling hanging sign	Crazy Dough Pizza

Tag ID	Tag Code	Region	Surface	Positioned	Tag Faces
3-22	nmxY	Main Corridor	Metal Wall	Centered, above large black panel	McDonalds
3-23	Wg2k	Box Office Corridor	Center of Ceiling Tile	Between Proshop Wall advertisement, and Doorways that indicate for Lease, centered in hallway	Floor
3-24	IEr4	West Entrance	Doorway	Center of the doorways, placed under advertisement	McDonalds and DD side on doorway
3-25	mQ1x	West Entrance	Facia Board	positioned to just left of 'W' in West Entrance decal on wall	
3-26	RoXM	West Entrance	Doorway	Center of the doorways, placed under advertisement	Facing Outer Entrance door
3-27	yIRC	West Entrance	Doorway	Center of the doorways, placed under advertisement	Facing Inner Entrance Door
3-28	HS5S	West Entrance	Facia Board	positioned above where wall goes from grey to black	
3-29	7A6d	Commuter Rail Waiting Area	Grey pillar	Centered between platform 2 and 1	Facing seating area
3-30	D9fG	Commuter Rail Waiting Area	Wall	Centered along wall	Facing Bar
3-31	uvLt	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-32	YZF0	Commuter Rail Waiting Area	Wall	Centered above plaque	Facing platform
3-33	WXos	Commuter Rail Waiting Area	Grey wall	Center between platform 3 and 2	Facing seating area
3-34	B0OP	Commuter Rail Waiting Area	Grey pillar	Centered between platform 4 and 3	Facing seating area
3-35	OFCq	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-36	JY9c	Commuter Rail Waiting Area	Upper wall	This wall intersects Dunkin Donuts on left side, tag is positioned to right of exit sign	Facing platform
3-37	lb9T	Commuter Rail Waiting Area	Grey Wall	Aligned under the P, in the proshop sign	
3-38	5E2V	Commuter Rail Waiting Area	Upper wall	This wall intersects Dunkin Donuts, tag is positioned to left of exit sign	Facing platform
3-39	UB7b	Commuter Rail Waiting Area	Grey wall	Centered between platform 5 and 4	Facing seating area
3-40	D5sH	Commuter Rail Waiting Area	Grey wall	Centered between platform 7 and 6	Facing seating area

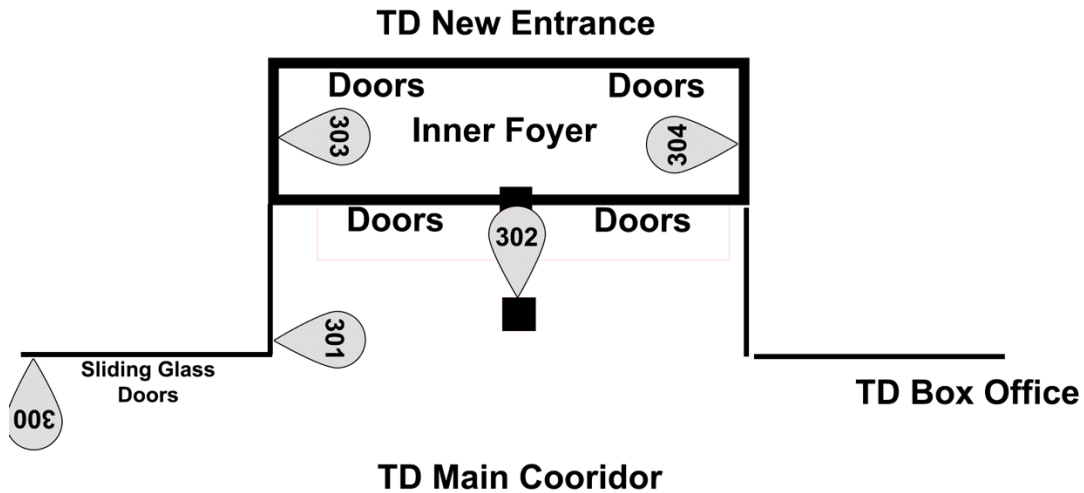
Tag ID	Tag Code	Region	Surface	Positioned	Tag Faces
3-41	nRte	Commuter Rail Waiting Area	Wall	Positioned below security camera	Facing platforms
3-42	BDKn	Commuter Rail Waiting Area	Wall	Placed centrally along wall under advertisement	
3-43	d9tK	Commuter Rail Waiting Area	Grey Wall	Centered between platform 9 and 8	Facing seating area
3-44	BYIT	Commuter Rail Waiting Area	Upper Wall	2 feet left from intersection of perpendicular upper wall	Facing Crazy Dough Pizza
3-45	EJR4	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-46	YRMq	Commuter Rail Waiting Area	Grey pillar	Centered between platform 6 and 5	Facing seating area
3-47	Ez4G	Commuter Rail Waiting Area	Grey facia with lighting fossit	Centrally located	Facing platform
3-48	HGbx	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-49	IWzd	Commuter Rail Waiting Area	Grey Wall	Centrally located on wall to Left of platform 10	Facing seating area
3-50	kiSG	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-51	2jSh	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-52	OKtM	Commuter Rail Waiting Area	Grey pillar	Centrally located between platform 8 and 7	Facing seating area
3-53	46GB	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-54	B5Tx	Commuter Rail Waiting Area	Grey wall	Centrally located above frozen yogurt stand	Facing platform, behind tag 18
3-55	nKO2	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-56	E3HC	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-57	BsrY	Commuter Rail Waiting Area	Column	Placed centrally on column between 2 doors	facing seating area
3-58	UXXx	Commuter Rail Waiting	Grey Pillar	Centrally located between platform 10 and 9	Facing seating area

Tag ID	Tag Code	Region	Surface	Positioned	Tag Faces
		Area			
3-59	NLLd	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-60	VemQ	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-61	HORv	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing platform
3-62	zJ3g	Commuter Rail Waiting Area	Upper Wall	Positioned centrally above the left opening that transitions from Platform Seating area to Box office corridor	Facing platform seating area
3-63	v5rZ	Box Office Corridor	Grey Wall	Centered above middle picture frame	
3-64	qiNB	Commuter Rail Waiting Area	Wall	Centered on surface	Facing Crazy Dough
3-65	bTN8	Box Office Corridor	Yellow Facia	centered on 2nd large panel to the right of Doors and pillar	Tag 62
3-66	wEz9	Box Office Corridor	Yellow Facia	centered on 5th large panel from the left of the garden box offices	Tag 63
3-67	la19	Box Office Corridor	Yellow Facia	centered above box office 3	Facing elevators
3-68	5Ltb	Box Office Corridor	Wall	just left of Men's Room Door	Facing Box office
3-69	JN52	Box Office Corridor	Yellow Facia	centered above box office 9	Facing elevators
3-70	aOQD	Box Office Corridor	Wall	just left of Women's Room Door	Facing Box office
3-71	XL4R	Box Office Corridor	Blue wall	Centered along curved surface	Facing Women's Room
3-72	A3Az	Box Office Corridor	Doorway	Centered Above Exit Door	
3-73	p955	Main Corridor	Wall	positioned just before the ceiling turns a purple color over the phone booths	Facing platform seating area
3-74	cl5S	Main Corridor	Wall	positioned above the 'R' in the TD garden signage	Facing platform seating area
3-75	fuBP	Main Corridor	Wall	positioned above the 'R' in the TD garden signage	Facing Elevator
3-76	ylKt	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-77	Kj0Q	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-78	cjLZ	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor

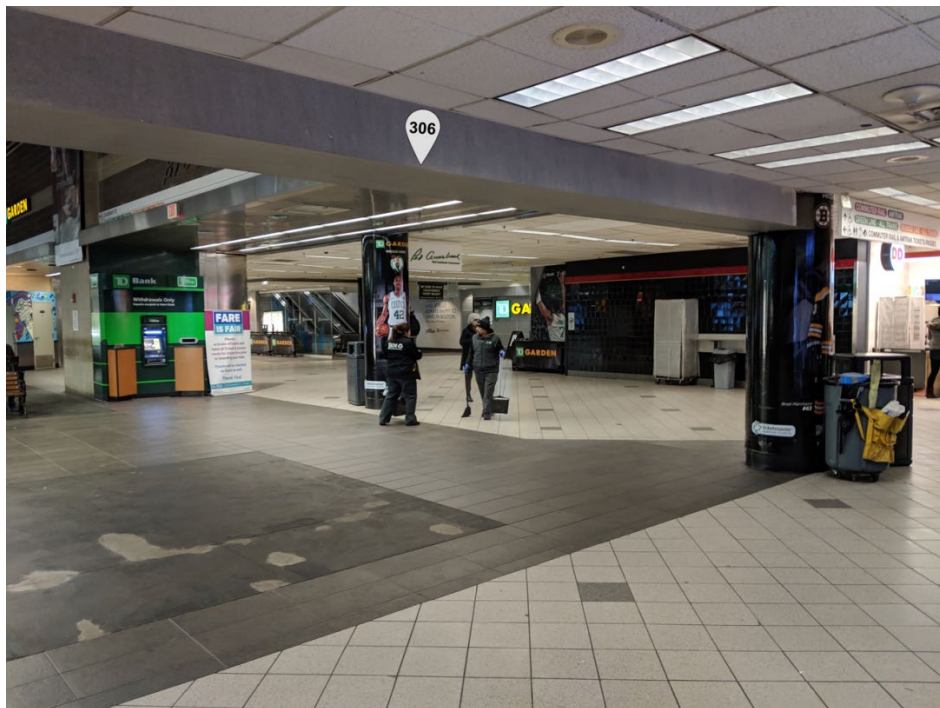
Tag ID	Tag Code	Region	Surface	Positioned	Tag Faces
3-79	a8fa	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-80	2bWb	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-81	hOTS	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-82	RHf1	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-83	iRXC	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-84	qSvx	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-85	649E	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-86	wRas	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor
3-87	llsf	Commuter Rail Waiting Area	Pillar	Placed above trim that is between speaker and lighting fixture	Facing Main Corridor

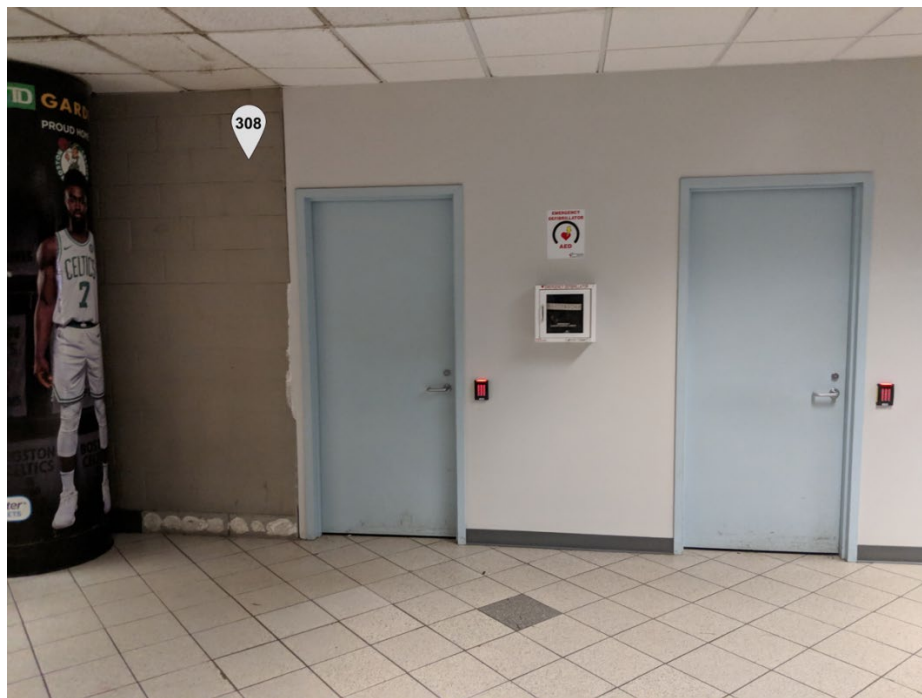
New TD Garden Entrance Tags

Included is a basic sketch of TD Garden entrance and pictures taken from the environment overlaid where tags are being requested to be placed.



Remainder of TD Garden





Tag ID	Tag Code	Region	Placed On	Tag Faces(Columns)
3-300 black	qWMn	Main Corridor Near New entrance	On wall left of sliding glass doors and above the Boston Garden Society decal. 9 ft vertical height from floor.	Facing towards the commuter rail platform entrances
3-301 black	HoXt	New Entrance	On wall left of sliding glass doors and above the Boston Garden Society decal. 9 ft vertical height from floor.	Facing column that has tag 3-302
3-302 black	cbfW	New Entrance	Centered on column 9 ft vertical height from floor	Facing the new entrance doors
3-303 black	tWBI	New Entrance	Centered horizontally on wall 9ft in vertical height from floor.	Facing tag 3-304
3-304 black	pcTt	New Entrance	Heading from Valenti Street escalator, this is the fixture just prior to the elevator	Facing tag 3-303
3-305	NLN1	Main Corridor Near New entrance	On the right side of this support structure, on the curved metal portion. This should mirror the placement of the tag that is already on the left side	Facing towards the new entrance
3-306	AwyU	Restroom Corridor(Old Box Office)	Centered across the vertical cement pillar.	Facing direction of the opposite wall. (see photo of 306 placement above)
3-307	UwRF	Restroom Corridor(Old Box Office)	Centered on the concrete block pillar 9ft height from ground.	Facing away from commuter rail area. (see photo for 307 above)
3-308	GJNg	Restroom Corridor(Old Box Office)	To the right of column on the concrete block wall.	Facing towards the the commuter rail ticket area.
3-309	p8Gj	Northwest Entrance	On wall. 9ft in height from floor.	Face towards tag 3-310
3-310	8Ud2	Northwest Entrance	On wall. 9ft in height from floor.	Face towards tag 3-309

7.2 Appendix B: Letter of advertisement

Subject: Test PERCEPT system that facilitates navigation of blind or visually impaired people in North Station within the MBTA in Boston

Project objective: Assist MBTA evaluate PERCEPT suitability for MBTA system-wide deployment. To accomplish this objective we will conduct a beta study with at least 20 blind and visually impaired participants that will download and use PERCEPT on their Smartphone to independently access North Station.

From: Prof. Aura Ganz, Department of Electrical and Computer Engineering, University of Massachusetts Amherst

Dear Participant,

You are asked to participate in a research study entitled, PERCEPT Beta Study of Indoor Navigation System for Visually Impaired, conducted by Prof. Aura Ganz, from the Electrical and Computer Engineering department at University of Massachusetts Amherst (UMass Amherst).

We are seeking volunteers that are 18 years or older. Volunteers should not have any further complication restricting physical or mental ability. Additionally, they should have received some degree of orientation and mobility training. Volunteers should have an iPhone 4s or newer in order to use the PERCEPT application. This beta is not available to participants with Android smartphones.

PERCEPT assists blind and visually impaired people to independently navigate through unfamiliar indoor environments and reach their destination as accurately and as quickly as possible. The overall goal of this project is assist MBTA evaluate PERCEPT's suitability for MBTA system-wide deployment. To accomplish this goal, we are currently enrolling at least 20 blind and visually impaired participants to download and use PERCEPT on their personal iPhone. Participants will then use the app to navigate North Station within the MBTA. Enrolled participants will help us evaluate and improve the current PERCEPT system.

If you volunteer to participate in this study, you will be asked to provide your email address in order to receive a link to download PERCEPT application on your personal iPhone. Then, you will follow the tutorials within the application to familiarize yourself with how to use PERCEPT. Afterwards you will be asked to travel to North Station in Boston Massachusetts to evaluate PERCEPT at your own convenience. Once at North Station you will independently use PERCEPT application on your iPhone to navigate throughout the station. There is no limit placed on how long you can use PERCEPT, or where you should navigate to in North station. However, keep in mind that PERCEPT is only available within North Station and should you choose to leave North Station PERCEPT will be unable to assist you. Following your visit, you will be administered a qualitative evaluation regarding your experience either in person or

over the phone depending on your preference. You may utilize PERCEPT app as many times as you wish throughout the duration of this beta that will end on September 30th 2019. Should you use PERCEPT multiple times over the beta you will receive multiple qualitative evaluation on a monthly basis. You can withdraw from the study at any time without prejudice.

There will be PERCEPT workshops open to all beta participants that will take place throughout the duration of the study. For these events PERCEPT researchers will be at North Station to discuss PERCEPT with you, provide training on the application, and administer in person a qualitative evaluation of your experience with PERCEPT. These special events are optional, and should you choose to enroll in the study you will be informed by email and phone when these events occur.

Frequently Asked Questions

How can I get the PERCEPT application onto my Smartphone?

The PERCEPT application will be available exclusively to enrolled participants in the PERCEPT North Station beta study. Once you have become enrolled in the study you will receive an email from Apple's Test Flight program with a link to download the application. Apple's Test Flight is similar to the App Store but is for beta applications. Once downloaded you can access the PERCEPT application like any other app on your smartphone.

I commute in North Station often. Can I use PERCEPT application during my commute?

There are no limitations to when you can use PERCEPT app, or how many times you can use it. You can use PERCEPT during your commute, you can use PERCEPT if you go to subway stations with your friends and/or family, or you can use PERCEPT independently to evaluate the technology in North Station. With PERCEPT application installed on your personal device you can use it whenever North Station is open to the public and for the duration of the beta which ends on September 30th 2019. PERCEPT application is currently only available in North Station and should you leave North Station PERCEPT will be unable to provide navigation instructions.

How will my privacy be protected?

Only people who have been approved by the Human Research Protection Office (HRPO) at UMass Amherst will be allowed to see the information you give us. The system use and tracking information will be kept for up to 6 months after the end of the grant. Only summarized data will be used to discuss the results of the study (in publications or presentations of research results). When information is summarized, it is impossible to tell who it came from, and you cannot be identified.

All the information we collect will be kept private according to federal government privacy policies. It will be stored in locked files in our offices. Electronic data will be password protected and accessible only to research staff. We will link the information we receive from your responses to your personal identity through an ID code number. Your name and personal information will not be contained in the same dataset as the collected study data.

What are my rights?

Your participation is **voluntary**. You can leave the study at any time. You may also tell us we cannot use and disclose your study data (i.e., revoke your authorization). However, any study data collected and not related to personal health information will be used as necessary to maintain the integrity of the research.

Do you provide compensation for participation in the study?

No compensation is provided for this study. However, you are exposed to a state-of-the-art technology and your invaluable feedback in this study will help inform the MBTA whether or not they should adopt PERCEPT system wide. This would make the MBTA one of the first transit authorities in the world to adopt a real-time navigation system for the blind and visually impaired. The availability of such an affordable and accurate indoor navigation system can help MBTA blind and visually impaired patrons overcome barriers in navigating a complex transit venues and promote an equitable culture that serves all patrons fairly.

Are there any risks from being in the study?

Minimal risk or discomfort is expected. The main risk in this study is the potential loss of privacy. We will do our utmost to ensure confidentiality. We will assign each participant a number. The list matching names and numbers will be kept in a locked file at UMass Amherst. The file cabinet will have limited accessibility to members of the evaluation team only. All system use, tracking and survey data will be secured with a password and will be restricted to only authorized staff.

What are the benefits of the study?

In terms of benefits, you will be exposed to state-of-the-art technology developed at UMass Amherst that will facilitate navigation of blind and visually impaired people in an unfamiliar indoor environment. Your participation will help us advance the technology being tested to provide mobility assistance to the visually impaired. Moreover, your invaluable feedback in this study will help inform the MBTA whether or not they should adopt PERCEPT system wide. A prior participant in PERCEPT North Station study shared with the PERCEPT team this quote, "I truly believe that PERCEPT is the gateway to independence. Spontaneity is often an unreachable ideal for people like myself. I personally feel like I could go to places without much prior planning now, knowing that I would have complete independence within stations I have never been to."

Whom do I call if I have questions or problems?

If you have any questions about your rights as a participant or if you decide to leave the study or revoke your authorization, please contact the Principal Investigator:

Prof. Aura Ganz
Department of Electrical and Computer Engineering
University of Massachusetts
151 Holdsworth Way
Amherst, MA 01003
Phone: 413-545-0574
E-Mail: ganz@ecs.umass.edu

Any data collected that is not related to personal health information and acted upon before your withdrawal will be used as necessary to maintain the integrity of the research. All protocols and documents related to this study have been approved by the Human Research Protection Office (HRPO) at UMass Amherst.

7.3 Appendix B: Screening Questions

Thank you for your time today. Before you officially enroll in this research study, I will be asking you some questions. It should take you no more than 2 minutes to complete. This questionnaire is a screening tool that will ask you questions to determine your eligibility for participation in the study. If you are determined ineligible to participate, your completed questionnaire will be destroyed. If you are determined eligible to participate, the completed questionnaire will become part of the study materials, and we will protect your information as confidential and safeguard it from unauthorized disclosure.

Please respond yes or no to the following questions?

1. Are you 18 years of age or older?
2. Are you legally blind or visually impaired?
3. Do you have any complicating physical or mental disability beyond visual impairment?
4. Have you received orientation and mobility training from a certified orientation and mobility specialist?
5. Do you own an iPhone 4S or newer?

Potential participants that answer **No** to any of the above questions are unable to participate in the study.

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7.4 Appendix D: Consent form

Consent Form for Participation in a Research Study at at North Station in Boston Massachusetts

Principal Investigator: Aura Ganz

Sponsor: Massachusetts Department of Transportation (MassDOT)

Project Title: PERCEPT Beta Study of Indoor Navigation System for Visually Impaired

1. WHAT IS THIS FORM?

This is an Informed Consent Form. It will give you information about this study so you can make an informed decision about participating.

2. WHO IS ELIGIBLE TO PARTICIPATE?

Individuals who are 18 years or older. Visually impaired volunteers should not have any further complication restricting physical or mental ability. Also, they should have received some degree of orientation and mobility training from a certified Orientation and Mobility Instructor.

3. WHO IS SPONSORING THIS STUDY?

Massachusetts Department of Transportation (MassDOT)

4. WHAT IS THE PURPOSE OF THE STUDY?

You have been asked to participate in this study because we would like to test how the PERCEPT system developed at UMASS will help visually impaired to navigate in large transportation hubs.

The purpose of this study is to assist MBTA evaluate PERCEPT's suitability for MBTA system-wide deployment.

5. WHERE WILL THE STUDY TAKE PLACE AND HOW LONG WILL IT LAST?

This beta study will take place at North Station in Boston Massachusetts. You will be asked to visit North Station when it is open at least once at a time that is convenient for you. We recommend giving yourself an hour to evaluate PERCEPT but you are free to use PERCEPT for as little or as much as you would like. This study will end on September 30th 2019.

6. WHAT IS PERCEPT SYSTEM?

The PERCEPT system includes the following main components:

1. Environment: we will deploy PERCEPT tags throughout the building at landmarks such as entrances, elevators, restrooms, escalators. The user will interact with these tags using their phones.
2. Client device: an iPhone that runs PERCEPT application. The client uses the device to enter the desired destination and receives navigation instructions to the selected destination.

Scenario of use:

- (a) Client turns on the PERCEPT application and enters the destination room using PERCEPT application.
- (b) In case the user is in the vicinity of a landmark spoken navigation directions to the chosen destination are provided to the client
- (c) In case there is no landmark in the vicinity of the user, spoken orientation instructions will be provided, i.e., description of the general area where the user is located and what are the landmarks in his/her vicinity.
- (d) As the client travels through the environment the client device provides additional directions

7. WHAT WILL I BE ASKED TO DO?

If you volunteer to participate in this study, you will be asked to provide your email address in order to receive a link to download the PERCEPT application on your personal iPhone. Then you will follow the tutorials within the application to familiarize yourself with how to use PERCEPT. Afterwards you will be asked to travel to the the North Station, at time that it is open and convenient for you, to evaluate PERCEPT application. Once at North Station you will use the PERCEPT application to navigate to destinations of your choice from within the station. There is no limit placed on how long you can use PERCEPT, or where you should navigate to in North station. However, keep in mind that PERCEPT is only available within North Station and should you choose to leave North Station PERCEPT will be unable to assist you. Following your visit, we will schedule qualitative evaluation regarding your experience over the phone or in person. You may utilize the PERCEPT app as many times as you wish throughout the duration of this beta. Should you use PERCEPT multiple times over the beta you will receive a follow-up qualitative evaluation on a monthly basis. You can withdraw from the study at any time without prejudice.

8. ARE THERE ANY RISKS OR BENEFITS ASSOCIATED WITH PARTICIPATION?

Minimal risk or discomfort is expected. You may become fatigued or frustrated. At any point during the trial session you can choose to stop your participation in the trial without penalty.

The main risk in this study is the potential loss of privacy. We will do our utmost to ensure confidentiality. We will assign each participant a number. The list matching names and numbers will be kept in a locked file at UMass. The file cabinet will have limited accessibility to members of the evaluation team only. All tracking and survey data will be secured with a password and will be restricted to only authorized staff.

In terms of benefits, you will be exposed to state-of-the-art technology developed at UMASS that will facilitate navigation of visually impaired people in an unfamiliar indoor environment. Your participation will help us advance the technology being tested to provide mobility assistance to the visually impaired. Your invaluable feedback in this study will help inform the MBTA whether or not they should adopt PERCEPT system wide. This would make the MBTA one of the first transit authorities in the world to adopt a real-time navigation system for the blind and visually impaired. The availability of such an affordable and accurate indoor navigation system can help MBTA blind and visually impaired patrons overcome barriers in navigating a complex transit venues and promote an equitable culture that serves all patrons fairly.

You may realize through usage of PERCEPT system that it may not benefit you in navigating unfamiliar environments.

9. WHO WILL SEE THE RESULTS OF MY PERFORMANCE IN THE STUDY?

The results of this research may be published and submitted for presentation at professional society meetings and/or used by UMASS 5G Mobile Evolution Laboratory for internal purposes. No participant will be identifiable from the reports nor will any participant's name or initials be used in the reports. To maintain confidentiality of your records, the researchers will use subject codes, rather than names, to identify all data collected through the questionnaires and during your participation in the trials. The data will be secured in the 5G Mobile Evolution Laboratory and will be only accessible by the principal investigator, Dr. Aura Ganz and the other lab researchers for the study.

It is possible that your research record, including sensitive information and/or identifying information, may be inspected and/or copied by the study sponsor (and/or its agent), the Commonwealth of Massachusetts in the course of carrying out their duties, authorized persons from the University of Massachusetts Amherst and members of the Institutional Review Board. If your record is inspected by the study sponsor (and/or its agents), or by any of these agencies, your confidentiality will be maintained to the extent permissible by law.

10. WHAT IF I HAVE A QUESTION?

Should you have any questions about the experiment or any other matter relative to your participation in this project, or if you experience a research related injury as a result of this study, you may contact the primary researcher, Dr. Aura Ganz, at 413-545-0574 or ganz@ecs.umass.edu. If, during the study or later, you wish to discuss your participation or concerns regarding it with a person not directly involved in the research, you can contact the University of Massachusetts-Amherst's Human Subjects Research Administrator at (413) 545-3428 or humansubjects@ora.umass.edu. A copy of this consent form will be given to you to keep for your records.

11. WILL I RECEIVE ANY PAYMENT FOR TAKING PART IN THIS STUDY?

No compensation is provided for this study. However, you are exposed to a state-of-the-art technology and your invaluable feedback in this study will help inform the MBTA whether or not they should adopt PERCEPT system wide. This would make the MBTA one of the first transit authorities in the world to adopt a real-time navigation system for the blind and visually impaired. A real time navigation system such as PERCEPT has the potential to positively impact MBTA patrons of any ability, giving them the independence and spontaneity to travel the city of Boston.

12. WHAT IF I REFUSE TO GIVE OR WITHDRAW MY PERMISSION?

You do not have to be in this study if you do not want to. If you agree to be in the study, but later change your mind, you may drop out at any time. There are no penalties or consequences of any kind if you decide that you do not want to participate.

13. WHAT IF I AM INJURED?

The University of Massachusetts at Amherst does not have a program for compensating subjects for injury or complications related to human subjects' research

14. SUBJECT STATEMENT OF VOLUNTARY CONSENT / ASSENT

When signing this form I am agreeing to voluntarily enter this study. The consent form was read and explained to me in a language which I use and understand. I have had the opportunity to ask questions and have received satisfactory answers. I understand that I can withdraw at any time. A copy of this signed Informed Consent Form has been given to me.

_____ I agree to disclose my email address below so that I may receive an invitation to download the PERCEPT application.

Personal Email Address

By signing this consent form, I, the participant, confirm that the experimenter has explained to me the purpose of the research, the study procedures that I will undergo and the benefits as well as the possible risks that I may experience. This consent form was in an accessible format and I understand it.

Typed name and signature of participant

Date

15. EXPERIMENTER STATEMENT

By signing below, I the experimenter, indicate that I read and explained this study to the participant, and to the best of my knowledge, the participant understands the details contained in this document and has been given a copy.

Typed name and signature of person obtaining informed consent

Date

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7.5 Appendix D: Beta Questionnaire

PERCEPT North Station Beta Questionnaire

Subject ID Code : _____

Date: _____

We thank you for participating in the PERCEPT beta study in North Station. Your help in testing the system and your feedback will significantly help us improve the system design to better serve the blind and visually impaired achieve independent navigation in an indoor environment. Moreover, your participation and invaluable feedback for this study will help inform the MBTA whether or not they should adopt PERCEPT system-wide. The availability of such an affordable and accurate indoor navigation system can help MBTA blind and visually impaired patrons overcome barriers in navigating a complex transit venues and promote an equitable culture that serves all patrons fairly.

I will now read you six statements with which you may agree or disagree.

Using the 1-7 scale, indicate your agreement with each item.

Please be open and honest in your responding.

The 7-point scale is: 1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = neither agree nor disagree, 5 =slightly agree, 6 =agree, 7 =strongly agree.

It is easy to learn how to use the PERCEPT system	
It is easy to use the PERCEPT system	
It is easy to follow the tutorial	
The PERCEPT app user interface is clear	
The PERCEPT system provided sufficient re-orientation information when lost	
I am confident when navigating North Station	
PERCEPT gives me the confidence to use public transportation independently	

Please give your impression on the following:

1. What are your favorite Smartphone Apps?
2. Do you use any navigation apps currently? Which one(s)?
3. Do you currently use MBTA for public transportation?
4. Was this your first time using PERCEPT?
 - c. If not, how many instances have you used PERCEPT prior?
 - d. If not, did you notice any changes in your experience with using PERCEPT?
Please include both good and bad experiences.
5. What specific components of the PERCEPT system did you like or dislike?
6. Name the most difficult part of using the PERCEPT system.
7. Are there any improvements you can suggest for the PERCEPT system?
Are you planning to continue using PERCEPT throughout the beta time period?
Why?

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7.6 Appendix E: IRB Protocol

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**PROTOCOL
APPLICATION FORM**
BIOMEDICAL EXPEDITED REVIEW
HUMAN SUBJECTS IN BIOMEDICAL RESEARCH
University of Massachusetts Amherst

Protocol ID: 2018-5229
Title: PERCEPT Beta Study of Indoor Navigation System for Visually Impaired

Protocol Director Aura Ganz		Degree: (MS/PhD)	Title Professor	
Department Name Electrical & Computer Eng	Mailing Address	Phone	Fax	E-mail ganz@ecs.umass.edu
http://www.umass.edu/research/compliance/human-subjects-irb/training-education-and-outreach/citi-trai > Human Subjects Training Completed?				

Co-Protocol Director		Degree: (MS/PhD)	Title	
Department Name	Mailing Address	Phone	Fax	E-mail
http://www.umass.edu/research/compliance/human-subjects-irb/training-education-and-outreach/citi-trai > Human Subjects Training Completed?				

Other Contact		Degree:	Title	
Department Name	Mailing Address	Phone	Fax	E-mail
http://www.umass.edu/research/compliance/human-subjects-irb/training-education-and-outreach/citi-trai > Human Subjects Training Completed?				

Faculty Sponsor		Degree:	Title	
Department Name	Mailing Address	Phone	Fax	E-mail
http://www.umass.edu/research/compliance/human-subjects-irb/training-education-and-outreach/citi-trai > Human Subjects Training Completed?				

Administrative Contact		Degree:	Title	
Department Name	Mailing Address	Phone	Fax	E-mail
http://www.umass.edu/research/compliance/human-subjects-irb/training-education-and-outreach/citi-trai > Human Subjects Training Completed?				

Other Personnel				
Name of Other Personnel	Degree	Title	Department Name	E-mail
http://www.umass.edu/research/compliance/human-subjects-irb/training-education-and-outreach/citi-trai > Human Subjects Training Completed?				

				Training Completed?
James Schafer		Systems Engineer	Electrical & Computer Eng	Y

Subject Population(s) Checklist

Yes/No

- Minors (under 18)
- Pregnant Women
- Older Individuals (75 and over)
- Veterans
- Cognitively Impaired
- Decisionally Challenged
- International Populations
- Healthy Volunteers
- Students
- Employees
- Prisoners
- Other (i.e., any population that is not specified above)

N
N
N
N
N
N
N
N
N
N
N
N
Y

Vision-impaired subjects

Study Location(s) Checklist

Yes/No

- University of Massachusetts Amherst
- Baystate Medical
- University Health Services
- Hartford Hospital
- Other (Specify other Study Locations)

Y

North Station in MBTA (Boston)

General Checklist

Yes/No

- Training Grant
- Funded Study (or proposal submitted to sponsor)?
- Cooperating Institution(s)?
- Federally Sponsored Project?
- Industry Sponsored Clinical Trial?
- Radioisotopes/radiation-producing machines, even if standard of care?
- Human blood, cells, tissues, or body fluids (tissues)?
- Tissues to be stored for future research projects?
- Tissues to be sent out of this institution as part of a research agreement.
- Human Embryos?
- Human Embryonic Cells? Provide NIH Code Number(s) or state that no federal

N
Y
N
Y
N
N
N
N
N
N
N

funding will be used to support this research.

- | | |
|--|---|
| • Use of Patient related equipment? If Yes, specify what equipment is being used. | N |
| • Medical equipment used for human patients/subjects also used on animals? | N |
| • Subjects will be paid for participation? | N |
| • Protocol involves studying potentially addicting drugs? | N |
| • Investigational drugs, reagents, or chemicals? | N |
| • Commercially available drugs, dietary supplements, reagents, or other chemicals administered to subjects (even if they are not being studied)? | N |
| • Investigational Device? | Y |
| • Cancer Subjects (e.g., clinical trials, behavior/prevention) or Cancer Tissues (e.g., blood, cells, body fluids). | N |

Funding Checklist

Funding - Grants/Contracts

Funding Administered By UNIVERSITY	OGCA #:	119-0692:
GAID #:	Funded By:	MassDOT
Principal Investigator: Aura Ganz		
Grant/Contract Title		
Y	Are contents of this protocol the same as described in grant/contract proposal?	
N	Is this a training grant?	
N	Are any subcontracts issued under this grant?	

Funding - Fellowships

NONE

Gift Funding

Dept. Funding

Other Funding (e.g., FRG, Healey)

Expedited Review

A protocol must be no more than minimal risk (i.e., "not greater than those ordinarily encountered in daily life") AND must only involve human subjects in one or more of the following paragraphs.

Select one or more of the following paragraphs:

1. N **Clinical studies of drugs and medical devices only when condition (a) or (b) is met.**
 - a) Research on drugs for which an investigational new drug application (21 CFR Part 31,32) is not required. (Note: Research on marketed drugs that significantly increases the risks or decreases the acceptability of the risks associated with the use of the product is not eligible for expedited review.)
 - b) Research on medical devices for which
 - i) an investigational device exemption application (21 CFR Part 812) is not required; or
 - ii) the medical device is cleared/approved for marketing and the medical device is

being used in accordance with its cleared/approved labeling.

2. N **Collection of blood samples by finger stick, heel stick, ear stick, or venipuncture as follows:**
 - a) from healthy, nonpregnant adults who weigh at least 110 pounds. For these subjects, the amounts drawn may not exceed 550 ml in an 8 week period and collection may not occur more frequently than 2 times per week; or
 - b) from other adults and children, considering the age, weight, and health of the subjects, the collection procedure, the amount of blood to be collected, and the frequency with which it will be collected. For these subjects, the amount drawn may not exceed the lesser of 50 ml or 3 ml per kg in an 8 week period and collection may not occur more frequently than 2 times per week.
3. N **Prospective collection of biological specimens for research purposes by non invasive means.**
4. N **Collection of data through non invasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.)**

Examples:

 - a) physical sensors that are applied either to the surface of the body or at a distance and do not involve input of significant amounts of energy into the subject or an invasion of the subject's privacy;
 - b) weighing or testing sensory acuity;
 - c) magnetic resonance imaging;
 - d) electrocardiography, electroencephalography, thermography, detection of naturally occurring radioactivity, electroretinography, ultrasound, diagnostic infrared imaging, doppler blood flow, and echocardiography;
 - e) moderate exercise, muscular strength testing, body composition assessment, and flexibility testing where appropriate given the age, weight, and health of the individual.
5. N **Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis). (NOTE: Some research in this paragraph may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(4). This listing refers only to research that is not exempt.)**
6. Y **Collection of data from voice, video, digital, or image recordings made for research purposes.**
7. Y **Research on individual or group characteristics or behavior(including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies. (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.)**

1. Purpose of the study

- a) Provide a brief lay summary of the purpose of the study.

The study objective is to assist the Massachusetts Bay Transportation Authority (MBTA) evaluate PERCEPT's suitability for MBTA system-wide deployment. To accomplish this objective

we will conduct a beta usability study with at least 20 blind or visually impaired participants who will download and use PERCEPT on their Smartphones to independently access and navigate the MBTA's subway and Commuter Rail system at North Station.

b) What does the Investigator(s) hope to learn from the study?

This project objective is to assist MBTA evaluate PERCEPT suitability for MBTA system-wide deployment. To accomplish this objective we will conduct a beta study with at least 20 blind and visually impaired participants that will download and use PERCEPT on their Smartphone to independently access North Station. We will provide the following information at the end of the study:

- User feedback statistics: user satisfaction obtained from collecting the participants' feedback

- Usage statistics: number of participants, number of times the application was used, percentage of users that successfully navigated to the chosen destinations

- Tags maintenance statistics: issues encountered with the tags (battery, vandalism, internal malfunction) and time taken to address them. Work involved in tag deployment when the environment undertakes changes due to renovations

This information will be used to determine MBTA systemwide deployment of PERCEPT.

2. Study Procedures

a) Describe all the procedures (in sequence) that human subjects will undergo in the research project. This section can be written in bullet form.

The PERCEPT system includes the following main components:

1. Environment: we will deploy digital landmarks implemented by Bluetooth Low Energy (BLE) (BLE tags) in the environment. The BLE tags will be deployed at landmarks such as entrances, elevators, escalators, stairways, restrooms, subway platforms, as well as on walls, ceilings, and pillars to ensure complete BLE coverage of the entire environment.

2. PERCEPT server: the server will maintain an updated database of the environment, Blueprint, ID, location, and description of each BLE-tag deployed in the environment. The server will include the navigation algorithm that will compute the navigation instructions for the client.

3. Client devices (carried by the study participant): participants personal iPhone that runs PERCEPT application. The application will interact with the client and will be the conduit between the client, the environment and the server.

User experience:

- a) Download PERCEPT App: After signing the consent form, the participant will receive an email with a one-time link that authorizes them to download PERCEPT application. The app will then be downloaded onto the participant device. Only authorized users are able to install PERCEPT application on their smartphone and this application is set to expire when the study is finished on September 30th 2019. Once expired, the participant can no longer open the application on their device. . This application can be removed from the participant's iPhone at any time and in a similar manner to any other app on the device.

- b) Tutorial: Built into the application are tutorials that are used to familiarize the participant with usage of PERCEPT application. The participants can follow these tutorials from the

comfort of their own home. The participant can access these tutorials as many times as needed in order to become comfortable with using PERCEPT.

c) PERCEPT usage in North Station: The study participant will evaluate PERCEPT application at a date and time that is convenient for them. When the participant arrives at North Station they will open up PERCEPT application and select a destination from a list of available destinations in North Station. The participant will then follow these detailed navigation instructions from their current location in order to reach the destination. A navigation task is determined successful when the subject reaches the destination. In case the participant chooses, he/she can select another destination in order to perform another navigation task. The trial is finished when the participant chooses to stop the trial. This can be done after or during a navigation task. For more details regarding PERCEPT app functionality, see details of expected usage of PERCEPT app and a scenario below. During the trial we track and record the following information that captures the participant's interaction with PERCEPT: selected destinations, navigation instructions provided by PERCEPT, location data (only from within North Station), and should the app have a failure a crash report is generated. This information is captured only from within PERCEPT app - we do not track or monitor other applications on the iPhone. This recorded data is de-identified and electronically sent to study personnel.

d) Post trial questionnaire : After completion of the trial we collect participant's feedback and experience using a qualitative questionnaire. This will be conducted either in person or over the phone at a scheduled time that is convenient for the participant. This part will take at most 30 minutes. Should the participant choose to continue usage of PERCEPT application past the initial trial, follow-up post trial questionnaires will be scheduled on a monthly basis.

e) Workshops (Participants attendance in the workshop is optional): James Schafer will host workshops for enrolled participants at North Station. This workshop will include:

- 1) background and overview of PERCEPT,
- 2) orientation on how to use PERCEPT works,
- 3) questions and answers.

After the session participants are encouraged to use PERCEPT in North Station and James will be available for the next two hours to answer any further questions participants may have regarding their use of the system and also to collect feedback by conducting an onsite Post Trial Questionnaire.

Details of expected usage of PERCEPT application:

(a) The participant turns on PERCEPT application and enters the destination using PERCEPT user interface. The user interface is designed for blind and visually impaired usage and is built on top of accessibility services provided by the iPhone. Once the participant enters the destination, PERCEPT application will provide two different types of navigation instructions:

(a.1) In case the participant is in the vicinity of a landmark (e.g. entrance, elevator, stairs, ATM Machines), PERCEPT application provides detailed spoken navigation directions to the chosen destination,

(a.2) In case there is no landmark in the vicinity of the participant, PERCEPT application will provide spoken orientation instructions, i.e., description of the general area where the participant is located and what are the landmarks in his/her vicinity (the participant knows that detailed navigation instructions will be provided once he/she reaches a landmark).

(b) As the participant travels through the environment enroute to the chosen destination the participant can prompt PERCEPT application to provide updated navigation instructions. Depending on the location of the participant the application will provide either detailed navigation instructions (see a1 above) or orientation instructions (see a2 above).

Mock Usage Scenario:

To better understand how the user interacts with PERCEPT system we will describe the navigation experience of our hypothetical user, Kara, in the North Station subway. Kara would like to board a subway train on Inbound Green Platform heading towards Copley and stations West. The following are five steps Kara must take to reach her destination platform:

Step 1. (Valenti Street Entrance) Kara arrives at North Station and enters through the Valenti Street Entrance. Once inside, Kara takes out her iPhone and opens PERCEPT App. PERCEPT App informs Kara, "You are in North Station Subway that services green and orange subway lines. You are located on street level at the Valenti Street Entrance." Kara selects "Start Journey" in PERCEPT main menu, and then selects "Green Platform to Copley and West" from a list of destinations. PERCEPT app responds: "Your current location is: Valenti Way Entrance, With the Valenti Way Entrance to your back, Walk straight ahead, heading north, reach the Escalator to your right side, 20 feet away, You will hear the escalator noise. Take the escalator down. Select next instruction button."

Step 2. (Valenti Street Unpaid Lobby) After Kara reaches the bottom of the escalator she selects the next instruction button and the app responds: "With the Escalator to your back, Walk across the opening, heading north, until you reach the Fare Gates, 40 feet away, You will reach: Fare Gates. Select next instruction button."

Step 3. (Lost in Unpaid Lobby) Kara follows the instructions but becomes disoriented along the route and is now unsure where to go. She shakes the phone to bring up the help menu and selects "Where Am I?" option. The app then responds with the rerouting instructions: "You are currently in the Southern Unpaid Lobby region. You have been traveling northeast. The fare gates unpaid side is located 25 feet to your 11 o'clock in the northwest direction. Head towards fare gates unpaid side and go through the fare gates. Select next instruction button." Kara follows the rerouting instructions and is back on track and heading towards her destination.

Step 4. (Paid Lobby to Lower Platforms) Once through the fare gates Kara selects next instruction button and the app responds: "With the Fare Gates to your back, there is Escalator to your 12 o'clock direction, Walk across to the Escalator to your 12 o'clock direction, heading northwest, 50 feet away. Take the escalator down. Select next instruction button."

Step 5. (To Green Platform to Copley and West) At the bottom of the escalator Kara selects next instruction button and the app responds: "Your current location is: Escalator, With the Escalator to your back, Turn left, Walk straight ahead, heading southwest, until you reach the Green Platform to Copley and stations West, 40 feet away, You will face the track. You have reached your destination: Green Platform to Copley and stations West. Select End Journey to end the journey."

- b) **If applicable, list any investigator(s) who will be performing procedures such as blood draws. Describe the credentials and/or training of any individuals performing such procedures.**
N/A
- c) **Alternative Procedures. Describe alternative procedures, if any, that might be advantageous to the subject. Describe all risks and benefits associated with the alternative procedure(s) or course(s) of treatment. Any standard treatment that is being withheld must be disclosed. This information must be included in the consent form.**
N/A
- d) **Will it be possible to continue the more (most) appropriate therapy for the subject(s) after the conclusion of the study?**
N/A
- e) **Study Endpoint. What are the guidelines or end points by which you can evaluate the**

alternative treatments during the study? If one treatment proves to be clearly more effective than another (or others) will the study be terminated before the projected total subject population has been enrolled? When will the study end if no important differences are detected?

Data analysis may take place until the anticipated end date of the project, on September 30th 2019.

- e) **State if deception will be used. If so, provide a rationale and describe debriefing procedures. Submit a debriefing script in Section #16 (Attachments).**

3. Background

- a) **Describe past experimental and/or clinical findings leading to the formulation of the study.**

PERCEPT was developed at UMASS 5G Lab with the cooperation of the Massachusetts Orientation and Mobility division from Massachusetts Commission for the Blind (MCB). Since 2010 PERCEPT project was continuously funded by the National Institute of Health/National Eye Institute, University of Massachusetts, and MassDOT (New Freedom 5310). Approved by the Institutional Review Board (IRB), we conducted five separate studies of PERCEPT with over 70 blind and visually impaired participants who were able to successfully navigate through buildings at University of Massachusetts Amherst, Carroll Center for the Blind, and a number of transportation venues at MBTA subway stations as detailed below.

New Freedom 5310 funding was used to test PERCEPT in Arlington subway station (2014-2016) and in North Station (2016-2018). There was a significant change in the localization technology between the Arlington and North Station projects due to the fact that North Station is a large open space (details are available in reference [1]). The North Station trials included 14 BVI participants.

A video of PERCEPT in North Station: <https://www.youtube.com/watch?v=DPdW0h6FZTw>

The North Station participants received hands-on training by the research team on how to use PERCEPT application. Using the Smartphone (running PERCEPT application) provided by the research team, the participants were asked to independently navigate the complex multi-modal transportation venue. The research team was always in vicinity in case they needed assistance or encountered any issues with the application. The results demonstrated the BVI participants were able to navigate independently throughout these venues using PERCEPT. Some participants shared that it was their first time independently navigating a transportation venue, which to them was even more impressive because it is a complex transportation venue. All participants indicated that PERCEPT gave them confidence when traveling without sighted aid within the station. All participants said they would use this system if it were available in the subway. User satisfaction scores can be found in [1].

PERCEPT has demonstrated significant promise through the North Station pilot by providing BVI the independence to navigate a complex and busy transit venue and lessening their stress and concerns. The proposed PERCEPT beta study is incremental with the aim to inform MBTA about PERCEPT feasibility and usability.

In this PERCEPT beta study we will leverage the following areas of expertise that we acquired during the multiple studies over many years that we worked on research, development and testing of PERCEPT system:

1. Localization algorithm design
2. BLE tag deployment algorithm design
3. Navigation instructions generation algorithm design
4. User interface design
5. Vast experience working with BVI participants

6. Vast experience in experimental design
7. Vast experience to develop and test working systems
8. Vast experience in software development for the iOS platforms and cloud services
9. Deep understanding of BVI user needs

[1] A. Ganz, J. Schafer, Y. Tao, Z. Yang, C. Sanderson, L. Haile, "PERCEPT Navigation for Visually Impaired in Large Transportation Hubs?", Journal on Technology and Persons with Disabilities, 2018.

- b) Describe any animal experimentation and findings leading to the formulation of the study.
N/A

4. Radioisotopes or Radiation Machines

- a) State whether the radiation procedures are performed as a normal part of clinical management for the medical condition that is under study or whether they are being performed because the research subject is participating in this project (extra CT scans, more fluoroscopy time, additional Nuclear Medicine Studies, etc.,). If some are Standard of Care and some are Not Standard of Care, check both boxes.

NOT STANDARD OF CARE

If it is not standard of care, complete the rest of this section.

STANDARD OF CARE

If it is only standard of care, skip the rest of this section.

For more information see: <http://www.umass.edu/research/comply/radioisotope.html>

- b) For radioisotope projects, provide the following radiation-related information:

Identify the radionuclide and chemical form.

For each dosage, provide the route of administration and the amount administered (mCi).

Provide dosimetry information and reference the source documents (package insert, MIRD calculation, peer reviewed literature, attach the source documents if electronically available).

- c) For radiation machine projects, provide the following diagnostic procedures:

For well-established radiographic procedures, identify the procedures and the number of times each will be performed on a single research subject.

For each radiographic procedure, provide the setup and technique sufficient to permit dose modeling. The chief technologist can usually provide this information.

For radiographic procedures that are not well-established, provide FDA status of the machine, and information sufficient to permit dose modeling.

- d) For radiation machine projects, provide the following therapeutic procedures:

For a well-established therapeutic procedure, identify the area treated, dose per fraction and number of fractions. State whether the therapeutic procedure is being performed as a normal part of clinical management for the research subject's medical condition or whether it is being performed because the research subject is participating in this project.

For a therapeutic procedure that is not well-established, provide FDA status of the machine, basis for dosimetry, area treated, dose per fraction and number of fractions.

5. Medical Equipment for Human Subjects

If medical equipment is being used for human subjects/patients, describe such equipment and if the use is normal practice for the population under study.

N/A

6. Investigational Devices

6.1 Smartphone

Smartphone running iOS operating system

**Non
Significant**

Smartphone

Apple Inc.

Y

This is an off-the-shelf smartphone which causes no significant risk to the subject.

7. Drugs, Reagents, or Chemicals

- b) Please list in the table below all commercial drugs, reagents or chemicals to be administered to subjects during this study.

8.(a-g) Subject Population

- a) State how many subjects you propose to use and state the rationale for the proposed number.

We plan to enroll at least 20 blind and visually impaired (BVI) participants. PI Ganz has significant experience running trials with visually impaired subjects using way-finding instructions. Participants will be recruited through the MBTA resources, which provided this number as a recruitment expectation.

- b) Describe your subject population, including the age range, gender, ethnic background, and type of subjects (e.g., students, subjects with cardiac problems, particular kind of cancer, etc.).

All participants will be male and female age 18 years or older who speak English. The subjects may have no complicating physical or mental disability beyond visual impairment. All participants must own an iPhone 4S or newer to run PERCEPT application.

- c) State the number and rationale for involvement of potentially vulnerable subjects to be entered into the study, including minors, pregnant women, prisoners, economically and educationally disadvantaged, decisionally challenged, and homeless people.

We will not recruit vulnerable subjects.

- d) If women, minorities, or minors are not included, a clear compelling rationale must be provided. Examples for not including minors: disease does not occur in children; drug or device would interfere with normal growth and development; etc.

We will not recruit minors, as we do not believe that additional usability information can be obtained from minor subjects in contrast to adult subjects.

- e) State the number, if any, of subjects who are laboratory personnel, employees, and/or

students. They should be presented with the same written informed consent. If compensation is allowed, they should also receive it.

We will provide access to PERCEPT application to sighted individuals who provide services to the BVI. This includes MBTA staff whom the MBTA Chief Technology Officer (CTO) David Block-Schachter identifies, certified orientation and mobility specialists from Massachusetts Commission for the Blind, travel trainers and specialists from different organizations such as Perkins School for Blind, Carroll Center for the Blind, and other similar organizations.

- f) State the number, if any, of subjects involved in research conducted abroad and describe any unique cultural, economic or political conditions.**

N/A

- g) Describe your procedures for recruiting subjects, including how potential subjects will be identified for recruitment. Attach all recruitment materials in section 16 (Attachments). Note: Potential subjects may not be contacted before IRB approval.**

MBTA CTO David Block-Schachter will appoint MBTA staff members to identify potential participants from their internal database of MBTA patrons. This staff will inform the candidate participants about the study using the included Letter of Advertisement. James Schafer contact information will also be provided in case potential participants have additional questions and/or would like to enroll in the study.

8.(h-m) Subject Population

- h) Inclusion and Exclusion Criteria.**

Identify inclusion criteria.

All human subjects will be 18 or older and own an iPhone 4S or newer. The participants must be visually impaired, and participants should have received some degree of orientation and mobility training from a Certified Orientation and Mobility Instructor (as indicated in the consent document).

Identify exclusion criteria.

We will not recruit subjects having physical complications or mental disabilities beyond visual impairment.

- i) Describe your screening procedures.**

James Schafer will screen the subjects to ensure that they meet the inclusion criteria.

- j) Describe how you will be cognizant of other protocols in which subjects might be participating. Please explain if subjects will be participating in more than one study.**

N/A

- k) Compensation. Explain the amount and type of compensation (payment, experimental credit, gift card, etc.), if any, that will be given for participation in the study. Include a schedule for compensation and provisions for prorating.**

Subjects will not be compensated.

- l) Costs. Please explain any costs that will be charged to the subject.**

None.

- m) Please state: A: The total expected duration of the study, including the time expected for data analysis (e.g., This study is expected to last 1 year) AND B: How much time each subject is expected to be involved in the study (e.g., The involvement of each subject will be 1-session for a total of 90 minutes).**

This study will last for 9 months. We expect each participant will be a part of the study for 5 months. During this period they can use PERCEPT application as many times as they wish. There is no penalty if the subjects decide to drop out from the study.

9. Risks

HHS Regulations define a subject at risk as "...any individual who may be exposed to the possibility of injury, including physical, psychological, or social injury, as a consequence of participation as a subject in any research..." Also included are risks to participant confidentiality and any discomforts, hazards, or inconveniences.

a) For the following categories include a description of risks:

Physical well-being.

Minimal risk. Subjects may become fatigued or frustrated. At any point during the trial session the subject may choose to stop his/her participation in the trial without penalty.

Psychological well-being.

Minimal risk. Subjects may become fatigued or frustrated. At any point during the trial session the subject may choose to stop his/her participation in the trial without penalty.

Economic well-being.

No known risks.

Social well-being.

No known risks.

Breach of confidentiality (including audio/video taping).

We will do our utmost to ensure confidentiality. We will assign each participant a number code. The list matching names and numbers will be kept in a locked file at UMass. The file cabinet will have limited accessibility to members of the evaluation team only. All survey data will be secured with a password and will be restricted to only authorized staff.

All the information we collect will be kept private according to federal government privacy policies. It will be stored in locked files in our offices. Electronic data will be password protected and accessible only to research staff. The subject name and personal information will not be contained in the same dataset as the collected study data.

For the following categories include a scientific estimate of the frequency, severity, and reversibility of risks. Wherever possible, include statistical incidence of complications of proposed procedures (from investigator's brochure or package, insert where applicable). Address any risks related to:

Use of investigational drugs or devices.

Minimal risk. Subjects may become fatigued or frustrated. At any point during the trial session the subject may choose to stop his/her participation in the trial without penalty.

Use of commercially available drugs, supplements, reagents or chemicals.

N/A

Performing procedures including all investigational, non-investigational and non-invasive procedures (e.g. surgery, blood draws, treadmill tests).

N/A

Radioisotopes/radiation (e.g. X-rays, CT scans, DEXA).

N/A

b) **For research conducted internationally, describe any political or sociocultural considerations that may affect your research design (for example, in some communities it may not be customary to sign documents, etc.)**

N/A

c) **For grant funded studies, where the funder plans to pay for any necessary medical**

expenses, describe plans for ensuring medical or professional interventions.

N/A

d) Data Safety Monitoring (See HELP (?) above for more information)

N Is there a Data and Safety Monitoring Board (DSMB)?

If yes, describe its role and indicate who set up the Data and Safety Monitoring Board (e.g. Protocol Director).

If you have a Data and Safety Monitoring Plan (DSMP), briefly describe how you plan to ensure the safety of participants and the validity and integrity of research data. Attach the plan in Section 16.

e) Evaluation of level of Risk. Please select one - see "HELP" for classification.

Minimal

10. Benefits

a) Describe the potential benefit(s) to be gained by the subjects or by the acquisition of important knowledge which may benefit future subjects, etc. (This DOES NOT include compensation or extra credit).

The subject will become familiar with the state-of-the-art technologies developed at UMass Amherst. The subject may not directly benefit from participation. The subject may realize through usage of PERCEPT system that the system may not benefit him/her in navigating unfamiliar environments. Their feedback will be used to assist the MBTA in deciding whether PERCEPT should be deployed system-wide. The availability of such an affordable and accurate indoor navigation system will:

-Help BVI customers overcome barriers in navigating a complex MBTA transportation venue to access MBTA's subway and commuter rail systems.

-Strengthen MassDOT's and MBTA's ongoing commitment to serve customers with disabilities.

-Promote an equitable culture that serves all customers fairly.

11. Procedures to Maintain Confidentiality

a) Describe the procedures in place which protect the privacy of the subjects and maintain the confidentiality of the data, as required by the federal regulations, if applicable.

We will do our utmost to ensure confidentiality. We will assign each participant a number code. The list matching names and numbers will be kept in a locked file at UMass. The file cabinet will have limited accessibility to members of the evaluation team only.

All the information we collect will be kept private according to federal government privacy policies. It will be stored in locked files in our offices. Electronic data will be password protected and accessible only to research staff. The subject name and personal information will not be contained in the same dataset as the collected study data.

b) If information derived from the study will be provided to the subject's personal physician, a government agency, or any other person or group, describe to whom the information will be given and the nature of the information.

Information on the study may be provided to the funding agency (MassDOT) and MBTA. We may also provide aggregate information on the usability of the system (degree of accuracy, navigation success rate, average satisfaction) to the research community via project website, research papers, and conference presentations.

- c) **Specify where and under what conditions study data (including videos) will be kept, how specimens will be labeled and stored (if applicable), who has access to data and/or specimens, and what will be available to whom.**

We will do our utmost to ensure confidentiality. We will assign each participant a number code. The list matching names and numbers will be kept in a locked file at UMass. The file cabinet will have limited accessibility to members of the evaluation team only. All survey data will be secured with a password and will be restricted to only authorized staff.

12. Potential Conflict of Interest

- | | | |
|----|---|---|
| a) | N | Do any of the involved investigators or their immediate family (as described below) have consulting arrangements, management responsibilities or equity holdings in the Sponsoring company, vendor(s), provider(s) of goods, or subcontractor(s)? |
| b) | N | Do any investigators or their immediate family have any financial relationship with the Sponsoring company, including the receipt of honoraria, income, or stock/stock options as payment? |
| c) | N | Is any Investigator(s) a member of an advisory board with the Sponsoring company? |
| d) | N | Do any investigators receive gift funds from the Sponsoring company? |
| e) | N | Do any investigators or their immediate family have an ownership or royalty interest in any intellectual property utilized in this protocol? |

"Immediate family" means a spouse, dependent children as defined by the IRS, or a domestic partner.

If one or more of the above relationships exist, please include a statement in the consent form to disclose this relationship. i.e., a paid consultant, a paid member of the Scientific Advisory Board, has stock or stock options, or receives payment for lectures given on behalf of the sponsor. The consent form should disclose what institution(s) or companies are involved in the study through funding, cooperative research, or by providing study drugs or equipment.

If you answer yes to any of the questions above, please go to the policies for more information.

13. Informed Consent

You can add different Consent Forms, Alteration Forms, and Waivers. Provide consent process background information, in the table below, for each Consent Form(s), Alteration Form(s), and Waiver(s).

13.1 Consent Form informed consent v3

Who is obtaining consent? The person obtaining consent must be knowledgeable about the study and authorized by the PI to consent human subjects.

Systems engineer James Schafer will obtain consent from the subjects.

How is consent being obtained?

Consent will be obtained one of two ways before receiving invitation to download the application:
 1) Subjects will be presented with and read an informed consent form to sign
 2) Subjects will be emailed an accessible consent form to digitally sign and return by email

Subjects will be presented with an accessible digital informed consent form through email in which they must digitally sign before enrollment into the study.

What steps are you taking to determine that potential subjects are competent to participate in the decision-making process?

BVI participants will be screened using MBTA patrons database which includes details about different disabilities. In addition James Schafer will ask participants screening questions as

detailed in the screening questions document provided in the attachment.

13.2 Consent Form stamped 01/17/19

Who is obtaining consent? The person obtaining consent must be knowledgeable about the study and authorized by the PI to consent human subjects.

How is consent being obtained?

What steps are you taking to determine that potential subjects are competent to participate in the decision-making process?

14. Assent Background

All minors must provide an affirmative consent to participate by signing a simplified assent form, unless the Investigator(s) provides evidence to the IRB that the minor subjects are not capable of assenting because of age, maturity, psychological state, or other factors.

15. HIPAA

Are you using Protected Health Information (PHI)? **N**

Protected Health Information (PHI) is health information that has been collected by a covered entity (e.g. a hospital or other organization providing health care) and has one or more of the following identifiers:

1. Names
2. Social Security numbers
3. Telephone numbers
4. All geographic subdivisions smaller than a State, including street address, city, county, precinct, zip code, and their equivalent geocodes, except for the initial three digits of a zip code, if, according to the current publicly available data from the Bureau of the Census: (1) The geographic unit formed by combining all zip codes with the same three initial digits contains more than 20,000 people; and (2) The initial three digits of a zip code for all such geographic units containing 20,000 or fewer people is changed to 000
5. All elements of dates (except year) for dates directly related to an individual, including birth date, admission date, discharge date, date of death; and all ages over 89 and all elements of dates (including year) indicative of such age, except that such ages and elements may be aggregated into a single category of age 90 or older
6. Fax numbers
7. Electronic mail addresses
8. Medical record numbers
9. Health plan beneficiary numbers
10. Account numbers
11. Certificate/license numbers
12. Vehicle identifiers and serial numbers, including license plate numbers
13. Device identifiers and serial numbers
14. Web Universal Resource Locations (URLs).
15. Internet Protocol (IP) address numbers
16. Biometric identifiers, including finger and voice prints
17. Full face photographic images and any comparable images; and
18. Any other unique identifying number, characteristic, or code (note this does not mean the unique

code assigned by the Investigator(s) to code the research data)

Provide HIPAA background information, in the table below, for each waiver of authorization or alteration of authorization requested, e.g., waiver of authorization for access to medical records. Include HIPAA authorization language in the consent form(s) as appropriate, e.g., when enrolling subjects.

Use table below ONLY when requesting waiver/alteration of HIPAA authorization.

16. Attachments

Document Type	Document Name	Attached Date
Questionnaires	PERCEPTNorthStationBeta-Questi	11/29/2018
Federal Grant/Sub-contract	PERCEPT CTO Beta SOW	11/29/2018
Advertisements	PERCEPTBeta Letter of Advertisement v2	12/12/2018
Other	PERCEPTWorkshopOutline	12/12/2018
Other	PERCEPT Screenshots	12/12/2018
Other	Participant Screening Questions	12/12/2018
Advertisements	PERCEPTBeta Letter of Advertisement v4	01/08/2019
Other	Participant Screening Questions v3	01/08/2019

Obligations

Obligations of the Principal Investigator are: Modifications - Changes in any aspect of the study (for example, project design, procedures, consent forms, advertising materials, additional key personnel or subject population) will be submitted to the IRB for approval before instituting the changes; Consent Forms - All subjects will be given a copy of the signed consent form. Investigators will be required to retain signed consent documents for six (6) years after close of the grant or three (3) years if unfunded; Training - Human subject training certificates, including those for any newly added personnel, will be provided for all key personnel;

Adverse Events - All adverse events occurring in the course of the protocol will be reported to the IRB as soon as possible, but not later than ten (10) working days; Continuing Review - IRB Protocol Report Forms will be submitted annually at least two weeks prior to expiration, six weeks for protocols that require full review; Completion Report - The IRB will be notified when the study is complete. To do this, complete the IRB Protocol Report Form and select "Final Report."

Training - Human subject training certificates, including those for any newly added personnel, will be provided for all key personnel;

Adverse Events/Unanticipated Problems - All events occurring in the course of the protocol will be reported to the IRB as soon as possible, but not later than five (5) working days;

Continuing Review - IRB Protocol Report Forms will be submitted annually at least two weeks prior to expiration, six weeks for protocols that require full review;

Completion Report - The IRB will be notified when the study is complete. To do this,

complete the IRB Protocol Report Form and select "Final Report."

Y The Principal Investigator has read and agrees to abide by the above obligations.

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7.7 Appendix G: Terms of Use

TERMS OF USE:

PERCEPTS NAVIGATION SYSTEM ("SERVICE") IS PROVIDED ON AN "AS IS" AND "AS AVAILABLE" BASIS. UMASS DISCLAIMS ANY AND ALL WARRANTIES, WHETHER EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO ANY WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OR NON-INFRINGEMENT. UMASS DOES NOT REPRESENT OR WARRANT THAT THE SERVICE OR CONTENT, OR ANY PORTION THEREOF, IS OR WILL BE FREE OF DEFECTS OR ERRORS (OR THAT ANY SUCH DEFECTS OR ERRORS WILL BE CORRECTED), VIRUS FREE, ABLE TO OPERATE ON AN UNINTERRUPTED BASIS, MEET YOUR REQUIREMENTS, OR CAPABLE OF BEING INTEGRATED INTO OR WITH YOUR COMPUTER SYSTEM, APPLICATIONS OR NETWORK. FURTHER, UMASS DOES NOT WARRANT OR MAKE ANY REPRESENTATIONS REGARDING THE USE OR THE RESULTS OF THE USE OF THE SERVICE, OR ANY PORTION THEREOF, IN TERMS OF ITS CORRECTNESS, ACCURACY, QUALITY, RELIABILITY, OR OTHERWISE. THIS DISCLAIMER CONSTITUTES AN ESSENTIAL PART OF THESE TERMS OF USE. IF THIS EXCLUSION IS HELD UNENFORCEABLE, THEN THIS SERVICE MAY BE DISCONTINUED WITHOUT NOTICE.

Governing Law and Jurisdiction:

These Terms of Use are made under and shall be governed by and construed in accordance with the laws of the Commonwealth of Massachusetts (except for its conflicts of laws principles). UMASS and You expressly agree that exclusive jurisdiction for any claim or dispute relating to or arising out of these Terms of Use resides in the state courts in Suffolk County, Massachusetts and the federal courts of the District of Massachusetts and further agree and expressly consent to the exercise of personal jurisdiction in such state and federal courts of Massachusetts in connection with any such dispute.

7.8 Appendix H: Localization Publication

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A Sensing Framework for Indoor Spatial Awareness for Blind and Visually Impaired Users

ZHUORUI YANG, (Student Member, IEEE), AND AURA GANZ[✉], (Fellow, IEEE)

Department of Electrical and Computer Engineering, University of Massachusetts at Amherst, Amherst, MA 01002, USA

Corresponding author: Aura Ganz (ganz@umass.edu)

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ABSTRACT In this paper, we present Bluetooth low energy (BLE)-based sensing framework that provides real time spatial awareness for blind and visually impaired (BVI) users while navigating independently through large public venues. The proposed framework includes the following functionalities using only the received signal strength indicator obtained from the BLE sensors: 1) determining the location of the user, 2) estimating the user's moving direction, and 3) detecting the proximity of landmarks next to the user. We evaluate these functionalities individually. Moreover, we incorporate the proposed framework in PERCEPT indoor navigation system and test it with BVI users in a large public venue. Testing results show that the location, moving direction, and landmark proximity computed by the framework, although not very accurate, provide sufficient information to enable BVI users to independently navigate in large indoor venues. This conclusion aligns with Nobel Prize winning findings that confirm the spatial nature of the entorhinal-hippocampal system and the existence of a positioning system in the brain.

INDEX TERMS Indoor localization, bluetooth low energy, sensing framework, spatial cognition, cognitive neuroscience, visually impaired.

I. INTRODUCTION

Traveling independently in unfamiliar large public venues is a very challenging task for blind and visually impaired (BVI) people [1]. In [2]–[4] we introduced PERCEPT indoor navigation system for BVI users which enables them to independently navigate in large indoor spaces. In this paper we introduce a sensing framework which was integrated and successfully tested in PERCEPT system. The framework provides user location, moving direction and proximity to landmarks.

In cognitive neuroscience, there is a consensus [5] that one's ability of navigation depends on one's capability to build the cognitive map of the space. Using this map, humans can position and navigate themselves inside the space. To identify the needs of humans in spatial positioning and navigation and develop corresponding navigation aids, it is necessary to know how the brain encodes the space from a neuroscientific viewpoint [6]. There are four types of cells found in the spatial representation in the brain (see Fig. 1).

1. **Place cells (Fig. 1a)** are pyramidal neurons inside the hippocampus which fire when an individual (animal or human) visits a particular place (small region) in the

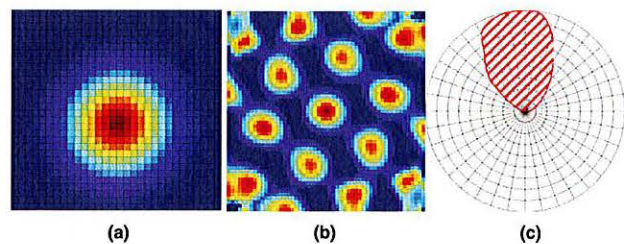


FIGURE 1. Illustration of firing patterns. In (a) and (b) the color code demonstrates the rate of firing: red shows high activity and blue shows low activity. (a) Place cells (b) Grid cells (c) Head-direction cells.

environment, thereby exhibiting a representation of the place with respect to the environment [7]. This area of high firing rate is known as the cell's 'place field'. Such place fields are considered to be allocentric, implying that they are defined by the external recognizable cues in the environment, for instance, landmarks. While visual input comprises a key element in the formation of place fields, it was shown in [8] that in the absence of visual input, both humans and other vertebrates studied in this context, are capable of generating very

effective spatial representations using other sensory input. To strengthen the sensing ability of the BVI user, the proposed framework determines user's location. Moreover, the sensory cues associated with the specific location can be extracted and provided to the BVI user through PERCEPT system.

2. **Grid cells (Fig. 1b)** are neurons within the medial entorhinal cortex (MEC) which exhibit firing at multiple locations in the environment. The spatial firing fields are positioned regularly in a grid across the environment comprised of equilateral triangles. Unlike place cells, grid cells seem to be the internal cognitive representation of the external Euclidean space. Moreover, it is found that grid cells play a critical role in path integration (i.e. navigation or wayfinding) since their firing depends on the ego-motion of the individuals, such as moving direction.

3. **Border/boundary vector cells** are neurons found in the hippocampal formation which fire when the individual is at a specific distance and direction relative to the environment boundaries such as walls, low ridges or vertical drops. The landmark proximity function in the proposed sensing framework enables PERCEPT to alert the user about these environment boundaries.

4. **Head-direction cells (Fig. 1c)** are neurons which fire maximally when an animal's head faces a particular direction in the azimuthal (horizontal) plane. The firing relies on the angular position of environmental cues [9]–[12]. Like place cells, the firing of head direction cells has been shown to rely on the angular position of environmental cues and generate a lobe of a certain width. The sensing framework estimates the user moving direction which enables PERCEPT to provide directional instructions to the BVI user.

These extraordinary findings that confirm the spatial nature of the entorhinal-hippocampal system led to the award of the 2014 Nobel Prize in Physiology or Medicine to O'Keefe and the Mosers for their discovery of "a positioning system in the brain." [13].

It is important to mention that researchers [14]–[17] have shown that the hippocampus can use non-visuospatial input such as spatial olfactory and tactile information, to generate spatial representations. In spite of the fact that olfactory input is less precise than visual input, it can substitute for visual inputs to enable the acquisition of metric information about space. However, for BVI users traveling through large public venues it is difficult or sometime impossible to use only olfactory and/or tactile information to form the cognitive map of the space. PERCEPT system complements these senses and helps the BVI user to build the cognitive map which helps them independently navigate through large public venues. PERCEPT provides users with audio/text information about their location in space relative to landmarks, proximity to landmarks as well as detailed instructions to their chosen destination. In order to provide such information, PERCEPT system incorporates the sensing framework introduced in this paper. As reported later in this paper, the framework was tested within the entire PERCEPT system and shown that it provides the necessary information that helps BVI users build

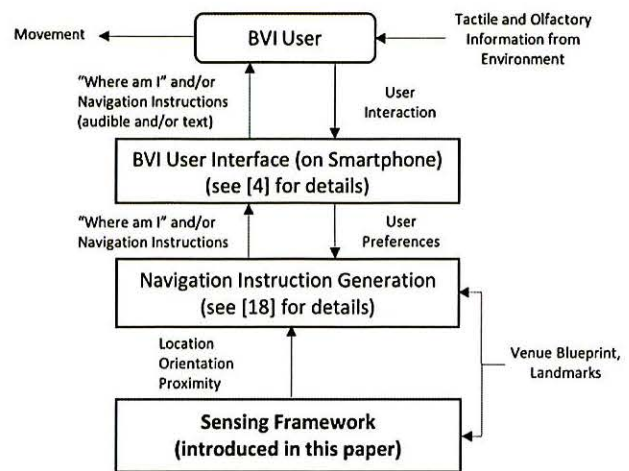


FIGURE 2. PERCEPT system architecture.

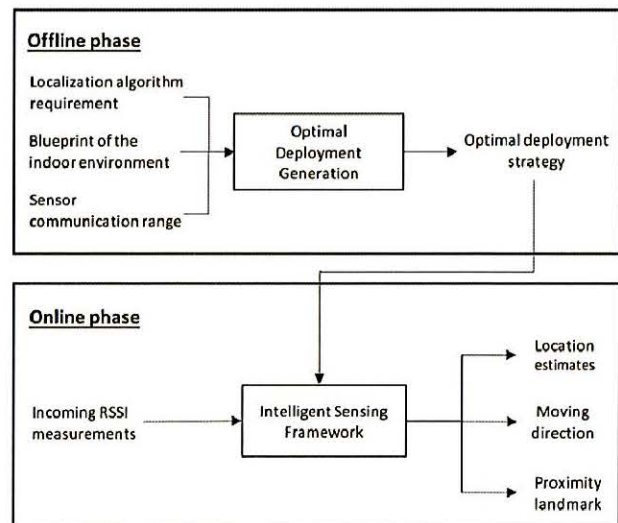


FIGURE 3. Sensing framework overview.

a cognitive map of the space and reach the chosen destination independently [4]. Fig. 2 illustrates the architecture of PERCEPT system which includes the sensing framework presented in this paper, the navigation and instruction generation module and the user interface.

The sensing framework introduced in this paper includes the following modules that correspond to the abovementioned place, border and head-direction cells: a localization module, a moving direction estimation module and a landmark proximity detection module. Grid cells correspond to the graph representation of space included in the Navigation Instruction Generation Module (see Fig. 2) [18]. As shown in Fig. 3, the proposed framework includes two phases, the offline phase and the online phase. In the offline phase, we generate the optimal sensor deployment strategy for the indoor space, minimizing the cost of the deployment while considering the requirements of the localization algorithm. During the online

phase, we develop intelligent sensing algorithms that provide location estimates, moving direction estimates and detect landmarks next to the user. To the best of our knowledge, this is the first comprehensive BLE-based sensing solution that can determine location, moving direction and landmark proximity using only RSSI values. In addition, to make our sensing solution scalable and practical to different spaces, we have introduced an algorithm to determine the sensors' locations in the indoor environment.

Table 1 summarizes the spatial information represented in each type of neuron and the corresponding modules provided in our framework.

TABLE 1. Analogy between neural representation of space and proposed framework.

Neuron Type	Neuron Firing Condition given Environment Input	Technical Equivalence (modules) in Sensing Framework (synthesizing input)
Place cells	Fired in small specific regions of the environment	Localization module
Border cells	Fired in small regions around the environment boundary	Landmark proximity detection module (provides border detection as well as proximity to other landmarks)
Head-direction cells	Fired in a range around the head direction	Moving direction module

In contrast to the established literature, our framework will not seek to achieve the exact coordinates (e.g. singular point) of the user location or exact value of user orientation in degrees. Neuroscience reveals that the human cognitive system for positioning and navigation uses a *region* to understand the location instead of a singular point. Therefore, we propose to evaluate the performance of the localization algorithm using the success rate of region detection for different region sizes. In addition, as shown in Fig. 1c and reported in [19], head-direction cells fire in a *range* around the preferred firing direction (e.g. the direction at which neurons fire maximally). Thus, instead of evaluating the moving direction algorithm using deviation of the estimated moving direction from the ground truth, we evaluate its performance using success rate of estimating a 4-way or 8-way cardinal directions.

The remainder of the paper is organized as follows. Section II discusses the related work. The offline phase which includes the optimal deployment strategy generation is introduced in Section III. The online phase which includes localization, moving direction estimation and landmark proximity detection is detailed in Section IV. Experimental results are shown in Section V and Section VI concludes the paper.

II. RELATED WORK

With the advent of smartphones and sensors, indoor localization techniques using Bluetooth Low Energy (BLE) technology have attracted significant interest. In this section, we will

present an overview of recent advances in the development of BLE-based indoor localization techniques followed by a discussion of the advantages of the proposed framework over other BLE-based indoor navigation systems for BVI users.

A. INDOOR LOCALIZATION

Using multilateration [20], we can determine the location of the target from the distances between the target and the beacons using the least square algorithm. Given the RSSI, we can derive the distance between the target and the beacon using a prebuilt propagation model. To compensate for the inaccuracy of deriving distance from the propagation model, Kuxdorf-Alkirata *et al.* [21] perform additional signal processing of the RSSI values and propose to auto-calibrate the propagation model with respect to environmental textures. Thaljaoui *et al.* [22] present an approach similar to trilateration, named inter Ring Localization Algorithm (iRingLA). Instead of treating the communication range of the transmitter as a circle, iRingLA regards it as a ring and determines the target's location from the intersection of three rings. Jianyong *et al.* [23] try to improve the localization accuracy by applying several techniques. First, instead of using one propagation model for all beacons, they build a propagation model for each beacon. Second, the authors take advantages of Gaussian filtering and other smoothing approaches to reduce the fluctuations of noisy RSSI measurements.

As the least computational expensive approach among all methodologies, proximity algorithms can locate a target using the approximate communication range of a beacon to detect whether the target is in range or not. One of the most popular methods in proximity algorithms is Min-Max approach [20], which aims to find the intersection region from beacons' communication ranges. Wang *et al.* [24] present a two-level localization approach, including low-precision and high-precision indoor localization components. The main idea is to find the intersection region of the beacons using the beacons' different transmission power levels. Palumbo *et al.* [25] combine the stigmergic marking approach with the Min-Max algorithm and draw the location estimation from the stigmergic map. Two other BLE-based approaches [26], [27] adopt the same idea of deriving the location using the beacon with the strongest RSSI value.

Fingerprinting-based algorithms typically contain two phases, the offline training phase and the online localization phase [20]. During the offline phase, the fingerprint data is collected at each reference point in space and then stored in the database. In the online phase, given an RSSI vector collected by a target at a certain point, the algorithm derives the target's location from the location of the reference point at which the fingerprint is most similar to the given RSSI vector using K-nearest neighbors (KNN) algorithm. Xiao *et al.* [28] utilize the autoencoder, an unsupervised learning algorithm as the denoising function for raw RSSI values. Ma *et al.* [29] exploit the Kendall Tau Correlation Coefficient to generate the weights and integrate it into the fingerprinting algorithm. Peng *et al.* [30] present an iterative approach for localizing the

target by selecting different beacons to obtain RSSI in each iteration and then averaging the location estimations.

Even though fingerprinting-based algorithm can effectively alleviate the negative effect of localizing targets from noisy RSSI measurements to a certain degree, the time-consuming preparation procedure makes it an impractical solution. Thus, some researchers started to work on a more flexible and computation-efficient approach, called Weighted Centroid Localization (WCL). Subedi *et al.* [31] utilize a Kalman filter to derive the weights for each nearby beacon and then calculate the target's location from the generated weights. Lohan *et al.* [32] leverage a self-defined propagation model to compute the weights and perform a comprehensive performance comparison between BLE and Wireless Local Area Networks (WLAN) at 2.4GHz and 5GHz. They show that BLE outperforms WLAN in terms of the localization performance using WCL. In our work, we utilize RSSI directly without applying any sophisticated smoothing methods [33]. We compute the weights using the Weighted Path Loss Localization (WPLL) algorithm [35].

B. INDOOR NAVIGATION SYSTEMS FOR BVI

Different types of indoor navigation systems have been designed and implemented to make indoor spaces more accessible to BVI users. Such systems use different localizations schemes such as vision-based systems [36]–[41] wireless-based systems [42]–[47] and hybrid systems [48]–[54]. Here, we elaborate on BLE-based systems and compare them with the proposed framework.

A system called NavCog [42] uses a BLE-based localization scheme and was tested by 6 BVI subjects. A fingerprint-based algorithm is used to compute the user's location and the Smartphone compass is used to determine the user's orientation. They reported several interesting conclusions obtained from users' feedback. One of them is that the precision of the localization algorithm is not a concern as long as the system can help them recover from mistakes quickly.

A hybrid indoor navigation system for BVI users using BLE and Google Tango is proposed in [48]. Authors implemented a two-level localization strategy. At the first level, the RSSI fingerprints are used to find the coarse location of the user and builds an Area Description File (ADF), i.e. a feature map of the space, built by Google Tango. Given the ADF, the software and hardware on Google Tango can localize users with high accuracy. Unfortunately, Google Tango phone was discontinued.

A wayfinding system for large indoor spaces, which is named GuideBeacon, was introduced in [43]. The system can localize the user using a proximity algorithm, which identifies the closest beacon using thresholds. Similar to [42], the directional information is determined by the compass. Bilgi *et al.* [44] propose a localization method that uses the user proximity to a beacon. It is well known that the localization accuracy of the beacon proximity approach depends on the density of the beacons. High beacon density will increase the deployment and maintenance cost.

Unlike prior works in which the BLE sensors' RSSI is used to determine only the user location, our framework provides the user location, orientation and landmark proximity. Our approach does not require any specialized hardware and/or software (e.g. Tango platform) since the user can run the algorithm in any Smartphone. It is important to mention that compass based approaches to determine the user orientation in indoor spaces is very unreliable in areas with strong and changing magnetic fields such as areas near elevators and subway platforms with frequent arrivals of trains. Moreover, to make our solution scalable, we have introduced a systematic way of planning sensor deployment in indoor environments, which is not covered by prior works [42]–[47]. In addition, we introduce a novel way to evaluate the localization performance which is zone localization, inspired by space encoding in the human brain.

III. OFFLINE PHASE

In this phase we generate an optimal sensor deployment strategy for an indoor environment. The input includes: the blueprint and its associated scale, the sensor communication range and the number of sensors, k , that should cover each point in the blueprint (k is determined by the localization algorithm). To ensure coverage, we use the optimal deployment pattern that guarantees k -covering [55]. If k equals to 3, the optimal deployed pattern is shown in Fig. 4.

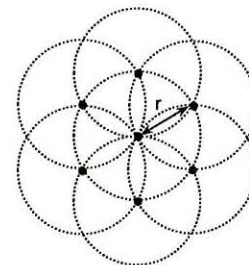


FIGURE 4. Optimal pattern when $k = 3$ (r is BLE communication range in ft.).

The sensor deployment algorithm is implemented in Matlab. The graphical user interface (GUI) which is shown in Fig. 5 includes:

- *Blueprint (Top)*: displays the blueprint as background and the superimposed locations of the sensors obtained from the deployment algorithm using red dots.
- *Parameter settings (Input-Bottom Left)*: includes the number of sensors, k , that should cover each point in the blueprint, the BLE communication range and the scale of the blueprint.
- *Interaction (Center)*: marks the deployment area with a blue box, triggers the action of computing the optimal deployment or resets the current parameters.
- *Results (Output-Bottom Right)*: the size of the entire area, the total number of beacons required and the density which is defined as the size of area covered by one beacon.

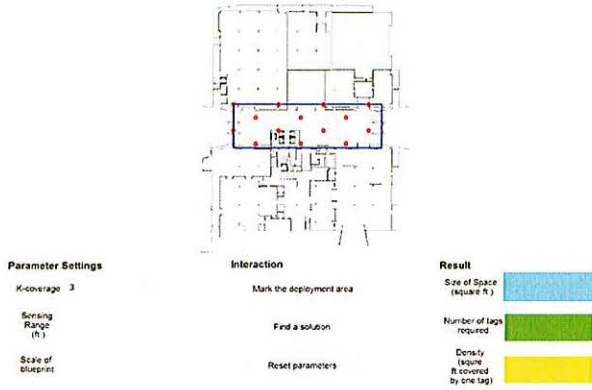


FIGURE 5. GUI of the optimal deployment strategy generation.

Note that the generated optimal sensor deployment may not be followed exactly while deploying the sensors in the environment due to the physical limitations of each suggested location. Nevertheless, the optimal deployment strategy provides valuable guidelines for guaranteeing the performance of the localization algorithm across the entire environment.

IV. ONLINE PHASE

The online phase includes the following modules: localization (Section IV.A), moving direction estimation (Section IV.B), and landmark proximity detection (Section IV.C).

A. LOCALIZATION

We assume that the user's smartphone can collect RSSI measurements from k nearby BLE sensors simultaneously. Distance d_i from BLE sensor i to user's smartphone is given by:

$$d_i = 10^{\frac{s_i - PL_0}{10\gamma}} \quad (1)$$

where s_i is the RSSI collected from BLE sensor i , γ is the path loss component and PL_0 is the path loss at the reference distance d_0 .

Equation (2) describes the Log-distance path loss propagation model. Given a certain distance, d_i , s_i can be computed by:

$$s_i = PL_0 + 10 * \gamma * \log_{10}(d_i/d_0) \quad (2)$$

The weighting factor w_i is given by:

$$w_i = \frac{1/d_i}{\sum_{i=1}^k 1/d_i} \quad (3)$$

The location estimate (u, v) of the user can be obtained by:

$$u = \sum_{i=1}^k w_i * x_i \quad (4)$$

$$v = \sum_{i=1}^k w_i * y_i \quad (5)$$

where (x_i, y_i) is the 2D location of BLE sensor i .

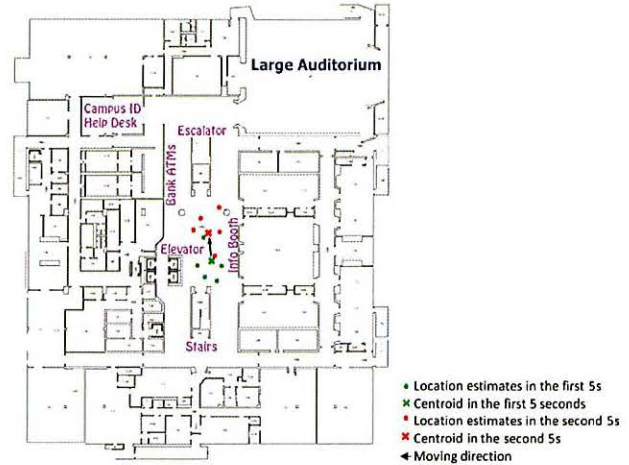


FIGURE 6. Illustration of moving direction estimation.

B. MOVING DIRECTION ESTIMATION

To determine user's moving direction from the sequence of location estimations, we use the K-means clustering algorithm in conjunction with a sliding time window.

Given a set of location estimates computed in the past N seconds, $e^{(1)}, \dots, e^{(N)}$, we group the data into two cohesive clusters, extracting the moving trajectory from two centroids. The pseudocode implementation of the algorithm is provided in Table 2.

As shown in Fig. 6, we cluster the location estimates in a time window into two groups using K-means algorithm. Using the centroids of the two clusters, we determine the moving direction by finding the trajectory from the past centroid to the present one.

C. LANDMARK PROXIMITY DETECTION

In addition to location and moving direction estimation, the proposed framework also offers the functionality of landmark proximity detection which can help the user build the cognitive map of the space.

We define a proximity radius for each landmark. Since our detection problem can be treated as a binary classification problem, we leverage the naïve Bayes classifier to detect a landmark next to the user. For each landmark, the two possible outcomes are either the user location is in close proximity to the landmark (i.e. within the proximity radius of the landmark) or not (i.e., the user location is out of the proximity radius of the landmark). We train the probabilistic model that will be used in naïve Bayes classifier using the RSSI measurements collected at different distances. For the labelling process, all the RSSI measurements collected within the radius are labelled with 1, and other measurements are labelled with 0.

Mathematically, the conditional probability model for each landmark can be calculated using (6).

$$p(C_i^k | x_i^1, \dots, x_i^n) \propto p(C_i^k, x_i^1, \dots, x_i^n) \quad (6)$$

TABLE 2. Pseudocode of moving direction estimation.

Input: $N = 10$ seconds (size of the sliding window)
 $E = \{\}$ (set of entities to be clustered)
 $k = 2$ (number of clusters)
 $MaxIters = 300$

Output: $C = \{c_{past}, c_{present}\}$ (set of start and the end of the moving trajectory)

Do the following forever:
if a new location estimate e_i is received, **then**
 add e_i into E
end
if E contains more than N elements, **then**
 foreach $c_i \in C$ **do**
 $c_i \leftarrow e_j \in E$ (e.g. random selection)
 end
 foreach $e_i \in E$ **do**
 $l(e_i) \leftarrow \text{argminDistance}(e_i, c_j) j \in \{1 \dots k\}$ (e.g. Euclidean distance)
 end

 $changed \leftarrow false;$
 $iter \leftarrow 0;$
 repeat
 foreach $c_i \in C$ **do**
 $updateCluster(c_i);$
 end
 foreach $e_i \in E$ **do**
 $minDist \leftarrow \text{argminDistance}(e_i, c_j) j \in \{1 \dots k\};$
 if $minDist \neq l(e_i)$ **then**
 $l(e_i) \leftarrow minDist;$
 $changed \leftarrow true;$
 end
 end
 $iter++;$
 until $changed = true$ and $iter \leq MaxIters;$

 $c_{previous} \leftarrow \text{findMostCommonLabel}(\{l(e)|e = 1, 2, \dots, 5\});$
 $c_{present} \leftarrow \text{findMostCommonLabel}(\{l(e)|e = 6, 7, \dots, 10\});$
 $C = \{c_{previous}, c_{present}\};$
end

where x_i^j denotes the j th RSSI measurement from sensor i , and C_i^k refers to class k for landmark i (each landmark is paired with a certain sensor) with $k = 1$ (we are in the proximity of landmark k), $k = 0$ otherwise.

The joint model can be expressed as follows:

$$p(C_i^k, x_i^1, \dots, x_i^n) = p(C_i^k) p(x_i^1 | C_i^k) p(x_i^2 | C_i^k) \dots = p(C_i^k) \prod_{j=1}^n p(x_i^j | C_i^k) \quad (7)$$

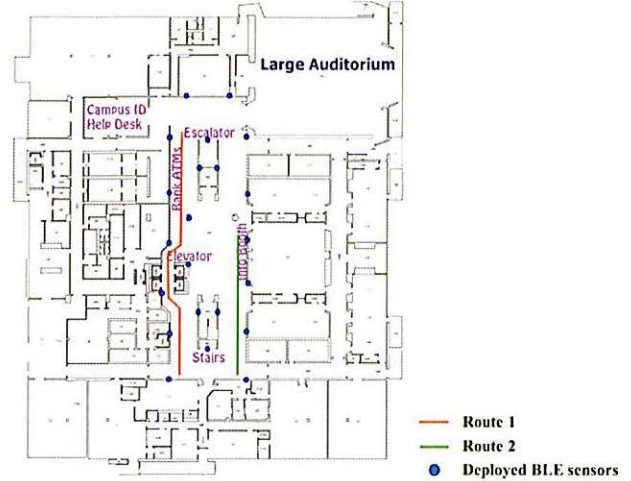
Finally, the decision can be made using:

$$\hat{y}_i = \arg \max_{k \in \{0, 1\}} p(C_i^k) \prod_{j=1}^n p(x_i^j | C_i^k) \quad (8)$$

where n refers to the number of RSSI measurements collected from the sensor that is paired with landmark i , \hat{y}_i denotes the estimated class for landmark i .

V. EXPERIMENTAL RESULTS

To evaluate the performance of the algorithms included in the proposed framework, we deployed our testbed at the basement level of UMass Campus Center, which is a 9,000 ft² area

**FIGURE 7.** Testbed at UMass campus center (180 ft. x 50 ft.).**TABLE 3.** Hardware specifications of tough beacon.

Model	Tough Beacon
Operating Frequency	2.4 GHz
Transmission Power	-30 dBm to 4 dBm
Transmission Range	Up to 100 ft.
Time Interval	350 ms
Battery Life	Up to 2 years with default setting

(see Fig. 7). We use BLE sensors manufactured by Kontakt.io and different models of iPhones (iPhone 6, iPhone 6 plus and iPhone 6s plus). The hardware specifications [56] of the BLE sensor are provided in Table 3. The sensors' transmission power is set to medium level, -12 dBm. Due to the default Bluetooth communication setting in iOS, the frequency of collecting the RSSI signal is 1 Hz. The BLE sensors are deployed following the guidelines provided by the optimal deployment strategy with minor adjustment to the environment.

Our dataset contains 35 and 34 groups of RSSI measurements along Route 1 and Route 2, respectively. On each route that takes about 1-2 minutes from start to end, we collect about 100 location estimates. With nearly 7,000 location estimations calculated in total, over a thousand orientation and landmark proximity estimates are computed. As shown in Fig. 7, we collected RSSI measurements following the testing routes so that the ground truth walking trajectory is known to us. Along each route, we pressed a button on our data collection application when we passed by the marked checkpoints (6 for Route 1 and 4 for Route 2). The recorded information is used as the ground truth for evaluating the proximity landmark detection module. Since we also know that the moving direction for each walking trajectory, the ground truth moving direction can be collected as well.

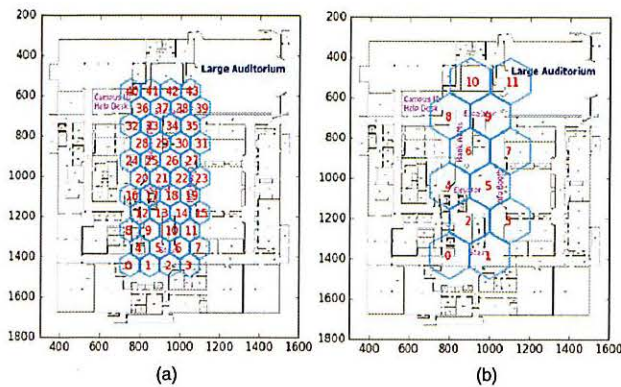


FIGURE 8. Hexagon tessellation of the space (a) Radius is 10 ft. (b) Radius is 20 ft.

A. LOCALIZATION

In equations introduced in Section IV.A we use $PL_0 = -63.5379$ dB, $\gamma = -2.086$ and $d_0 = 3$ ft. These parameters in (2) are calculated by solving the nonlinear regression problem of the pre-collected data at different sampling points between 3 ft and 45 ft at 3 ft intervals. We collected 200 readings at each sampling point.

We evaluate the success rate of region detection which is defined as the ratio between the number of correct region estimations over the total number of region estimations (correct and incorrect). The choice of region localization is inspired by the spatial representation in cognitive neuroscience [6]. As detailed above, the human cognitive system for positioning and navigation uses a region to understand the location instead of a singular point. As shown in Fig. 8, we generate the hexagon tessellation of the space following the format of spatial representation used in neural cells [6]. As we learned from cognitive neuroscience, grid cells fire in a certain pattern (see the Fig. 9a). If we connect the centers of the firing regions, it can cover the entire space with equilateral triangles. As shown in Fig. 9b, we connected the centroids of the neighboring equilateral triangles of a certain region, which form a hexagon pattern. It turns out this is the best tessellation pattern that determines regions used to evaluate the accuracy of the proposed localization algorithm. As shown in Fig. 10, while the radius of the hexagon-shaped region increases from 10 ft. to 20 ft., the success rate of region detection increases from 62.5% to 83%.

B. MOVING DIRECTION ESTIMATION

According to a neuroscientific study reported in [19], the head-direction cells used in human cognitive system for orientation will fire in a *range* around the preferred firing direction which is defined as the direction at which the neuron fires maximally. Thus, to evaluate the moving direction module, we propose to evaluate the success rate of estimating a specific cardinal direction (see Fig. 11) determined by the orientation vector calculated in Section IV.B. Using a

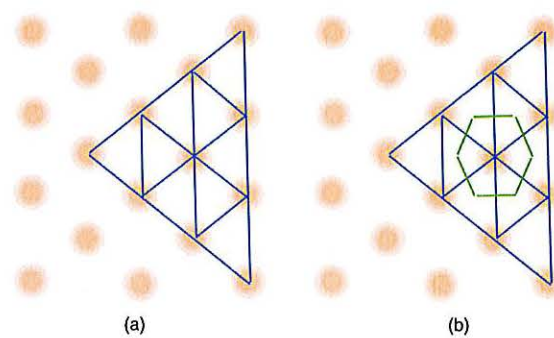


FIGURE 9. Grid cell firing pattern in (a) and Hexagon formation in (b).

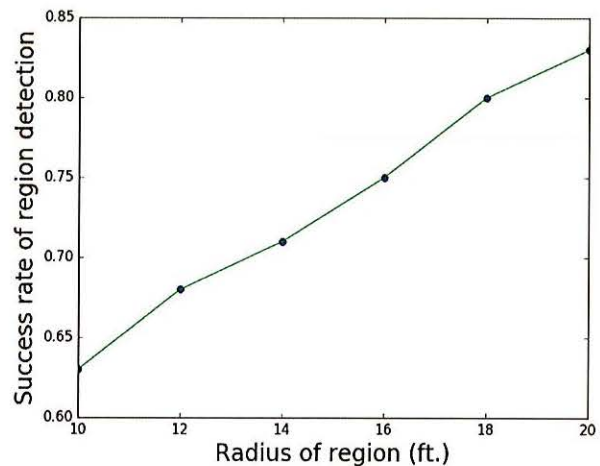


FIGURE 10. Experimental results of region detection.

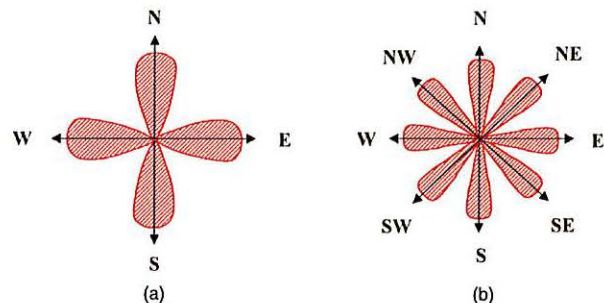


FIGURE 11. Illustration of Head-direction cells firing pattern around cardinal directions (a) 4-way cardinal directions (b) 8-way cardinal directions.

10-second sliding window, 1395 estimates are generated by our dataset.

Among these estimates, the orientation estimation success rates for 4-way and 8-way cardinal directions are about 94% and 60%, respectively.

C. LANDMARK PROXIMITY DETECTION

The success rate of landmark proximity detection is defined as the ratio between the number of correct proximity landmark detections over the total number of proximity landmark

TABLE 4. Post-Trial questionnaire using likert scale score.

Statements	Average Score
Easy to learn how to use system	6.7
Easy to use the system	6.7
Trial design was easy to complete	6.3
Easy to use User Interface	6.5
System provided sufficient re-orientation information when lost	5.5
I am confident I will reach the destination using this system	6.7

detections (correct and incorrect). Using a 6-ft. proximity radius around each landmark, and 1153 estimates, we obtain a landmark proximity detection success rate of 81%.

D. INTEGRATION WITH PERCEPT INDOOR NAVIGATION SYSTEM FOR BVI USERS

The proposed sensing framework was integrated in PERCEPT system (see Fig. 2) and tested in a large public transportation hub in Boston [4]. Using PERCEPT application installed on users' iPhones, BVI users can: 1) understand where they are in space audibly using regions and moving direction calculated by our sensing framework, 2) receive audible navigation instructions from one landmark to another using surrounding landmarks, and 3) receive alerts if they approach some landmarks via proximity landmark detection.

The system has been tested by 6 BVI subjects in a subway station [4]. The experiments show that the users can successfully and independently reach their chosen destinations. All participants were very satisfied with the navigational aid provided by PERCEPT. Details of this deployment as well as testing results can be found in [4].

It is important to note that we expect that the user will make mistakes (i.e., reach wrong landmarks or just get disoriented in the environment) and therefore require rerouting. Rerouting assistance in the application includes the ability to press "Where am I" as well as provide instructions from any landmark to the chosen destination. It was interesting to observe that the participants reported that they have built a cognitive map of the environment using the application routing and rerouting features as well as the "Where am I" feature.

For completeness of the paper we include some of the feedback provided by the BVI users which participated in these trials. We collected the participants' feedback using a qualitative questionnaire. Each participant was asked to score their agreement with specific statements related to their experience during the trial. The score followed Likert scale from 1 strongly disagree to 7 strongly agree with, with 4 being neither agreeing or disagreeing with the statement. The average scores are provided in Table 4. The nine additional trials

we performed in a large indoor transportation venue showed similar trends.

As shown above, we conclude that the information we compute in the proposed sensing framework, i.e., zone localization, region orientation and proximity, can be successfully used by the navigation instructions module to convey the necessary information to allow the BVI user to independently navigate through large indoor venues.

VI. CONCLUSIONS

In this paper, we introduced a sensing framework that includes optimal deployment strategy, location estimation, moving direction estimation and landmark proximity detection. We note that in spite of the fact that the location, orientation and proximity results computed by our sensing framework are not accurate, they provide the necessary information to the rest of PERCEPT modules and ultimately enable the BVI user to successfully navigate independently in large indoor venues. It is interesting to note that unlike a sensing framework for robots that needs to provide very accurate location and orientation, in the proposed framework used by BVI users high accuracy is not necessary. The reason is that the movement/navigation decisions made by the user include diverse aspects such as how the navigation instructions are composed, how the user interface is designed and how accurate the user can interpret the instructions and/or manipulate the user interface. Our observation is also aligned with the space encoding methods presented in this paper which show that the brain encodes zones (place fields) using place cells (i.e., zones, not singular points) as well as orientation regions using head cells with wide lobes (see Fig. 1c) (i.e., do not record highly accurate directions using very narrow width lobe).

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ZHUORUI YANG (S'18) received the B.Eng. degree in electronic and information engineering from the Kunming University of Science and Technology, China, and the M.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Massachusetts at Amherst, Amherst, USA.

From 2012 to 2018, he was a Research Assistant with the 5G Mobile Evolution Laboratory, Department of Electrical and Computer Engineering, University of Massachusetts at Amherst. His research interests include indoor localization and navigation, computer vision, sensor fusion, machine learning, mobile computing, and assistive technologies.



AURA GANZ (M'88–SM'90–F'08) received the B.Sc., M.Sc., and Ph.D. degrees in computer science from Technion, Haifa, Israel.

She is currently a Professor with the Electrical and Computer Engineering Department, University of Massachusetts at Amherst, Amherst, and also the Director of the 5G Mobile Evolution Laboratory, University of Massachusetts at Amherst. She has more than 25 years of experience in research, development, implementation,

and testing of wireless systems and systems related to healthcare settings such as assistive technologies for the blind, disaster informatics mobile telemedicine, and tele-surgery. This work has resulted in more than 250 journal and conference publications in highly respected refereed journals (IEEE, IEE, ACM, Kluwer, and Elsevier) with multiple best paper awards. The external recognition of her work is also evidenced by having been selected to serve on leading roles in many professional conferences and workshops and being elected as IEEE Fellow. Her research was continuously funded by federal agencies, such as NSF, NIH, ARO, AFOSR, and DARPA, and state agencies, such as MassDOT, and industry, such as Microsoft, Intel, and EMC.

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7.9 Appendix I: System Publication

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PERCEPT Navigation for Visually Impaired in Large Transportation Hubs

Aura Ganz, James Schafer, Yang Tao, Zhuorui Yang
Electrical and Computer Engineering Department, University of Massachusetts

Charlene Sanderson
Orientation and Mobility Consultant

Larry Haile
Assistive Technology Consultant

ganz@ecs.umass.edu, schafer@umass.edu, ytao@umass.edu, zhuorui@umass.edu,
charlene.sanderson@gmail.com, hailelarry1@gmail.com

Abstract

In this paper we introduce PERCEPT indoor navigation system deployed in North Station subway in Boston and the successful experimental results with Blind and Visually Impaired (BVI) users. This is the first time PERCEPT system is deployed in a large venue such as North station which is a crowded open space multimodal transportation hub. Using Bluetooth low energy tags we can localize the BVI users in real time. Given the user location, PERCEPT provides the BVI user with detailed landmark based navigation instructions to the chosen destination. Our experiments show that using PERCEPT system, the users can successfully and independently reach their chosen destination. All participants were very satisfied with PERCEPT and thought it was easy to learn and had a friendly user interface.

Keywords

Indoor navigation, blind and visually impaired, user interface, navigation instructions, transportation hub

Introduction

The World Health Organization reported that 285 million people are estimated to be visually impaired worldwide: 39 million are blind and 246 million have low vision (World Health Organization, 2016). There is a recognized positive correlation between independent travel employment, and issues of social equity. Independent navigation through unfamiliar indoor spaces is beset with barriers for BVI individuals. A task that is trivial and spontaneous for people without disabilities has to be planned and coordinated with other individuals for the BVI population. Although many improvements and aides are available to assist BVI individuals in outdoor settings, there has yet to be developed a reliable system that combines independence with accuracy and affordability for indoor navigation.

Currently there are no commercial systems that enable BVI users to independently navigate in indoor environments using real time localization and detailed navigation instructions that are automatically generated. There have been a number of research projects that aim to help BVI users navigate in unfamiliar indoor environments (Ahmetovic, 2017; Basso, 2015; Cheraghi, 2017; Doush, 2016; Garcia, 2015; Idrees, 2015; Jaffer, 2016; Jonas, 2015; Kim, 2016; Riehle, 2013; Rituerto, 2016; Serrão, 2014; Tandon, 2015; Waris, 2015; H. Zhang, 2016; X. Zhang, 2015). However, none of these papers has introduced an automatic generation of detailed navigation instructions which is necessary for a scalable and affordable indoor navigation system for BVI users.

PERCEPT system, first generation affordable and accurate indoor navigation system for the blind and visually impaired in buildings, which was introduced by the authors in (Ganz, 2014) was developed with the cooperation of the Massachusetts Orientation and Mobility division from Massachusetts Commission for the Blind. In PERCEPT system (Ganz, 2014) the

user carries a Smartphone that runs PERCEPT application that provides landmark based navigation instructions helping the user navigate through indoor spaces to a chosen destination. PERCEPT includes three main modules: the vision free user interface using Android and iPhone accessibility features, the localization algorithm and the navigation instructions algorithm. The user downloads the application from PERCEPT server prior to his/her arrival to the indoor environment. The application flow includes the following steps: 1) start the application, 2) localize the user and determine current location, 3) select the destination using the accessible “vision free” interface, and 4) receive audible detailed navigation instructions.

In the first generation PERCEPT system we used Near Field Technology (NFC) for user localization which requires the BVI users to detect the landmarks (e.g. doors, stairs, escalators). NFC is a passive technology that does not require any maintenance (i.e., no need to replace batteries) and works well in buildings and indoor spaces where the users can follow the walls. We conducted IRB approved trials with 24 blind and visually impaired subjects that successfully navigated through a three-story building on the UMASS Amherst campus.

However, the users that participated in the trials requested changes so they can obtain navigation instructions anywhere in the physical environment. Motivated by the user feedback as well as the need to deploy the technology in large indoor environments (e.g. large transportation hubs) we developed the second generation of PERCEPT system. In this paper we introduce the second generation of PERCEPT system that involves Bluetooth Low Energy (BLE) tags deployed in the environment which enable PERCEPT to locate the users anywhere in the space and provide them with proper navigation instructions towards the chosen destination.

We have conducted a total of 6 trials in North Station subway. North Station is one of the main transportation hubs in Boston for the commuter rail and at peak time there are crowds

filling the platform. Each study participant was asked to navigate from each of the main entrances to a unique subway platform in the station. When reaching the platform, they were asked to exit the station through a specific exit. Despite these environmental challenges all the study participants were able to successfully utilize PERCEPT to reach the subway platforms as well as find the specific exit. All participants were very satisfied with PERCEPT and thought it was easy to learn and had a friendly user interface. When asked if they would use PERCEPT in the subway if available, all subjects said yes. The feedback provided from the subjects was that overall the app is great for providing wayfinding in the subway and in its current state it would be beneficial in their daily lives.

In this paper we briefly introduce PERCEPT system without providing technical details on the localization and navigation algorithms. We focus on the system usability through a scenario as well as the trial results.

The paper is organized as follows. In the next section we outline the second generation PERCEPT system and in Section C (PERCEPT in North Station) we provide a case study. The trials are described in Section D (Trials) and Section E (Conclusions) concludes the paper.

PERCEPT System

In PERCEPT system (Ganz, 2014) the user carries a Smartphone (Android or iPhone) that runs PERCEPT application which provides detailed landmark based navigation instructions helping the user navigate through indoor spaces to a chosen destination. PERCEPT includes three main modules: 1) the navigation instructions generation algorithm (Section B.1. Navigation Instructions), 2) the localization algorithm (Section B.2. Localization) and the vision free user interface using Android and iPhone accessibility features (Section B.3. Vision Free User Interface). Due to the complexity of the localization and navigation instruction generation

algorithms we omit them from this document.

The user downloads the application from PERCEPT server prior to his/her arrival to the indoor environment. The application flow includes the following steps: 1) start the application, 2) localize the user and determine current location, 3) select the destination using the accessible “vision free” interface, and 4) receive audible detailed navigation instructions.

Navigation Instructions

In this system the user receives instructions through two modes: 1) detailed landmark based navigation instructions generated by the PERCEPT navigation instructions generation algorithm introduced in (Tao, 2015), 2) in case the user is lost he/she presses “Where am I” the user will receive a detailed description of the landmarks around him/her, the distance to the landmark and the orientation relative to the user orientation. In Section C (PERCEPT in North Station) we illustrate the navigation instructions and “Where am I” modes through a detailed scenario.

Localization

The user is localized in specific zones (e.g., entrances, platforms, etc) in the venue using the receive signal strength indicator from multiple BLE tags which are deployed in the venue. BLE tags are used in many indoor venues such as malls. Retailers push to the users’ Smartphones advertising information when they are in the proximity of the product.

We have developed an optimal BLE tags deployment scheme which minimizes the number of tags while ensuring that every zone in the venue is covered by at least three tags. In case we deploy PERCEPT in a venue that has deployed infrastructure for localization we can use it in our system replacing the localization algorithm we developed.

Vision Free User Interface

The visually impaired user interacts with the Smartphone using vision free accessibility features provided by the Smartphone operating system. On Android this accessibility features is called “Talkback” and on iOS “Voiceover”. PERCEPT app is tightly integrated with these services to provide an accessible user experience. On both platforms the user can navigate the device through gestures on the screen. Using this accessibility service the users can immediately interact this application as they would with other common applications (Mail, Web Browser, Messaging, etc...). An example of the user interface is provided in Figure 1. In addition to vision free interface PERCEPT also is integrated with large font accessibility features for low vision users. This provides the user with consistent accessible font size across all applications that support this feature.

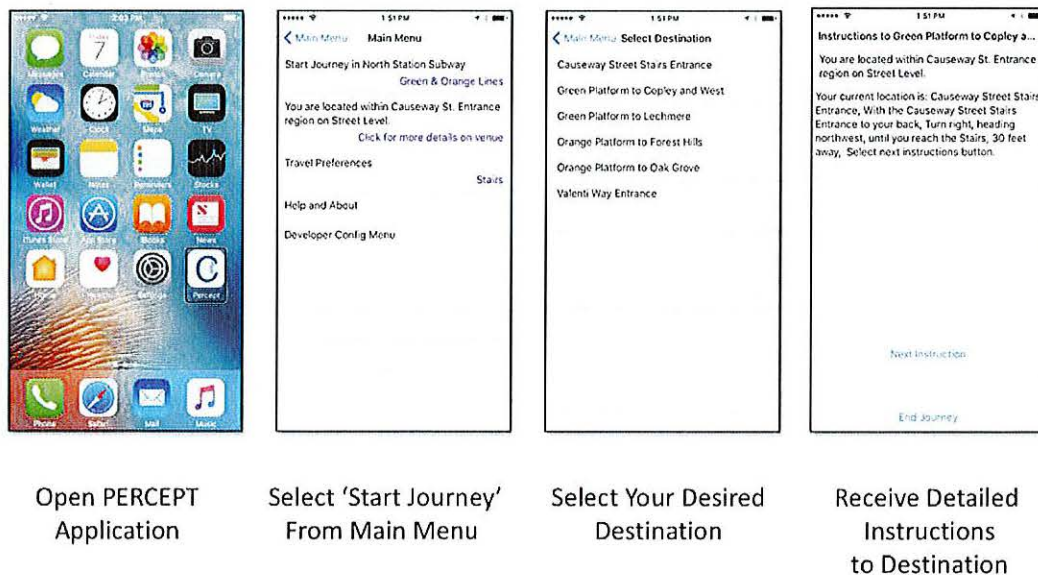


Fig. 1. PERCEPT application user interface

PERCEPT in North Station

We selected North Station Subway in Boston as an evaluation site for PERCEPT due to the following reasons:

- It is multi-modal hub for subway, commuter rail, bus, and Amtrak lines
- It gathers considerable foot traffic with often crowds of people waiting along the subway platform
- It has a large, complex layout, with vast open areas

Therefore, North Station is an excellent testbed for PERCEPT since it is a large, complex, open space, and crowded venue.

Figure 2 depicts the layout of all three floors of the North Station Subway starting from the street level entrance and going underground for two levels. We have deployed in all three levels 148 BLE tags in the environment (approximately 25 feet apart).

These tags are manufactured by Kontakt.IO which have a battery life of 5 years, have a small footprint (15mm x 55mm x 56 mm) as well as a replaceable battery. The cost of each BLE tag in quantities is approximately \$15 (for larger quantities the cost is lower).

Scenario

The following scenario illustrates how PERCEPT system works in North Station. We follow the navigation experience of our hypothetical user, Kara, in North Station Subway. Kara would like to board the Inbound Green Platform to Copley and stations West. To get an idea of how Kara will use PERCEPT to navigate the station, we will cover the first five steps in her journey (follow the steps in Figure 3 using the markers):

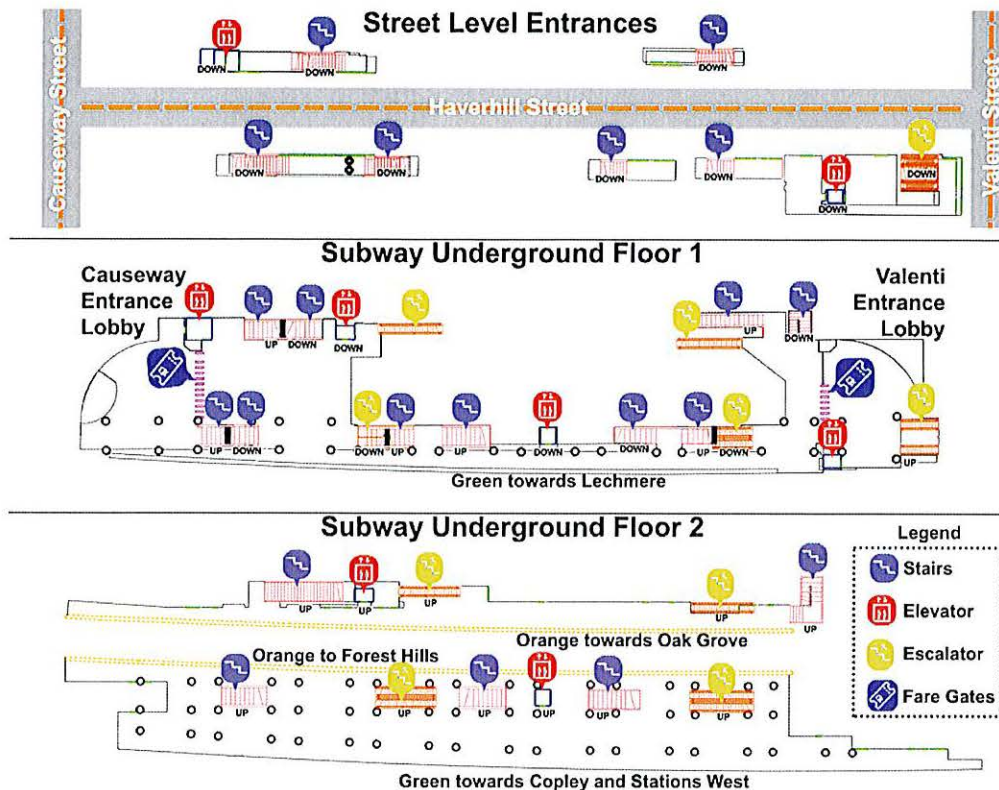


Fig. 2. North Station layout.

1. Valenti Street Entrance (Marker 1): Kara arrives at North Station and enters through the Valenti Street Entrance. Once inside, Kara takes out her iPhone and opens PERCEPT App. PERCEPT App informs Kara, “You are in North Station Subway that services green and orange subway lines. You are located on street level at the Valenti Street Entrance.” Kara selects ‘Start Journey’ in PERCEPT main menu, and then selects ‘Green Platform to Copley and West’ from a list of destinations. PERCEPT app responds: “Your current location is: Valenti Way Entrance, With the Valenti Way Entrance to your back, Walk straight ahead, heading north, reach the Escalator to your right side, 20 feet away, You will hear the escalator noise. Take the escalator down. Select next instruction button.”

2. Valenti Street Unpaid Lobby (Marker 2): After Kara reaches the bottom of the escalator she selects the next instruction button and the app responds: “With the Escalator to your back, Walk across the opening, heading north, until you reach the Fare Gates, 40 feet away, You will reach: Fare Gates. Select next instruction button.”

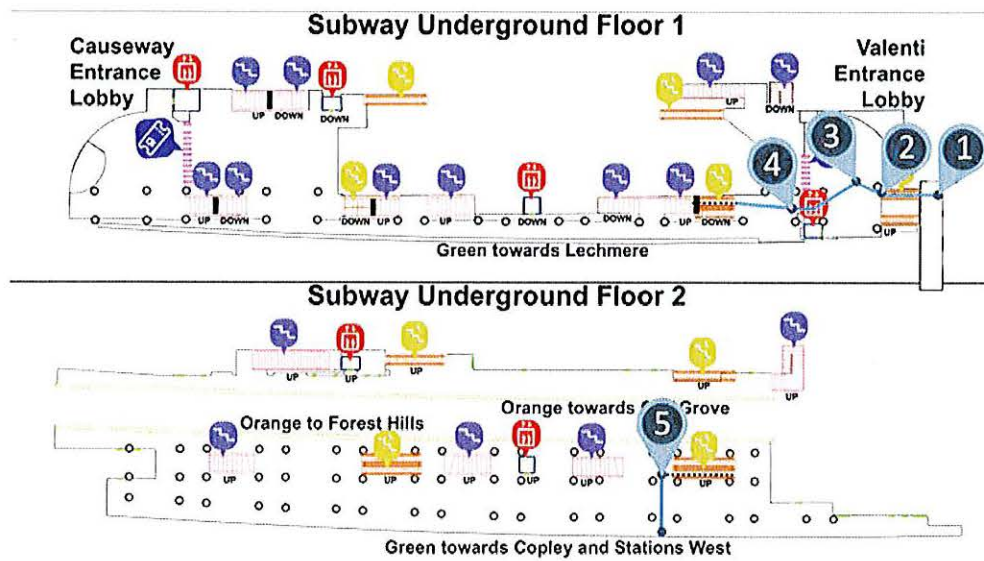


Fig. 3. User navigation journey in North Station (markers represent the navigation steps).

1. Lost in Unpaid Lobby (Marker 3): Kara follows the instructions but becomes disoriented along the route and is now unsure where to go. She shakes the phone to bring up the help menu and selects “Where Am I” option. The app then responds with the rerouting instructions: “You are currently in the Southern Unpaid Lobby region. You have been traveling northeast. The fare gates unpaid side is located 25 feet to your 11 o’clock in the northwest direction. Head towards fare gates unpaid side and go through the fare gates. Select next instruction button.” Kara follows the rerouting instructions and is back on track and heading towards her destination.

2. Paid Lobby to Lower Platforms (Marker 4): Once through the fare gates Kara selects next instruction button and the app responds: “With the Fare Gates to your

back, there is Escalator to your 12 o'clock direction, Walk across to the Escalator to your 12 o'clock direction, heading northwest, 50 feet away. Take the escalator down. Select next instruction button."

3. To Green Platform to Copley and West (Marker 5): At the bottom of the escalator Kara selects next instruction button and the app responds: "Your current location is: Escalator, With the Escalator to your back, Turn left, Walk straight ahead, heading southwest, until you reach the Green Platform to Copley and stations West, 40 feet away, You will face the track. You have reached your destination: Green Platform to Copley and stations West. Select End Journey to end the journey."

Trials

The user perspective is very important for our project. Given that our system is an assistive technology for the blind and visually impaired, it needs to be designed and constantly improved with user feedback. Users' feedback helped us 1) identify the important landmarks to include in the navigation instructions, 2) determine level of details of the navigation instructions, 3) identify methods to reorient when the BVI user becomes disoriented in the venue, and 4) improve the user interface.

In this paper we report PERCEPT testing with 6 blind and visually impaired participants. None of the participants were familiar with the North Station venue and its layout although a few participants had shared that they have been in the station in the past. We do not collect information such as age, vision acuity, and other personal health metrics, however the participants did share the level of vision they had which ranged from no visual acuity, to some light perception, to some vision and shapes, to partial blurred vision with a limited field of view. Each trial includes hands-on orientation, PERCEPT trial, and post-trial questionnaire.

Part I: Hands-on Orientation

The hands-on orientation includes sit down orientation and on site experimentation:

- **Sit down orientation:** The instructor goes over PERCEPT app functionality and answers any questions the participant has. When the participant is comfortable they proceed to on site experimentation.
- **On site experimentation:** the participant uses PERCEPT App in North Station subway along routes that will not be included in the actual trial. This allows the participant to become familiar with use of PERCEPT in the environment without compromising the trials. The Instructor answers any questions the participant has and when the participant is comfortable they move to Part II described below.

Part II: PERCEPT Trial

We asked the participant to accomplish the following four navigation tasks (see Figure 4) that include two entrances (to/from) and two subway platforms inbound/outbound (to/from):

- **Task 1:** Causeway Street Entrance (A) to Green Line Platform towards Lechmere (B)
– RED
- **Task 2:** Green Line Platform towards Lechmere (C) to Causeway Street Entrance (D)
– BLUE
- **Task 3:** Causeway Street Entrance (A) towards Green Line towards Copley and stations West (E) – GREEN
- **Task 4:** Green Line towards Copley and stations West (F) to Valenti Street Entrance (G) - PINK

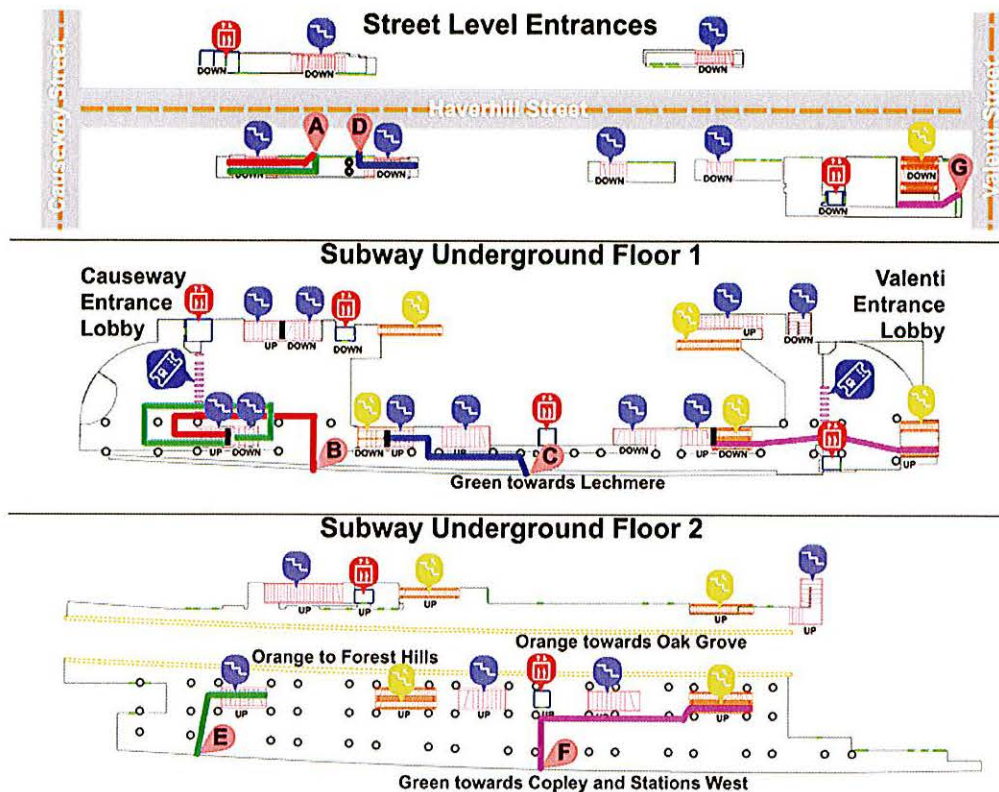


Fig. 4. Landmarks (markers A-F) used in trials navigation tasks

During the trial the participant is asked to complete these tasks relying only on their mobility skills and PERCEPT App. The Instructor accompanies the participant at all times but will no longer answer any questions. For each navigation task each participant was brought to a specific starting location in the venue and was told to navigate to a specific destination. Once the study participant had confidence that they reached the destination, they were required to indicate to the instructor that they had reached the destination. In the circumstance that they had indeed reached the destination the instructor would bring the participant to the next starting point to begin the next navigation task. If the participant was not at the location they would be informed by the instructor and asked to continue to the destination. In case the participant cannot proceed without assistance we determine the navigation task as unsuccessful. The trial ends either when

all tasks are completed or the participant decides to stop.

Part III: Post Trial Questionnaire

After the trials we collected the participants' feedback and experience using a qualitative questionnaire. All six participants were able to use PERCEPT to complete each of the four navigation tasks with no outside assistance.

It is important to note that we expect for that the user will make mistakes (i.e., reach wrong landmarks or just get disoriented in the environment) and therefore require rerouting as provided by the application. Rerouting assistance in the application includes the ability to press "Where am I" as well as getting instructions from any landmark to the chosen destination. It was interesting to observe that the participants reported that they have built a mental map of the environment using the application rerouting feature as well as the "Where am I" feature.

Feedback per Task

The study personnel observed each one of the trial participants (P1-P6) while performing each one of the four navigation tasks. Table 1 includes these observations quantified as follows:

1. Reached destination with no issues
2. Reached destination with few issues
3. Reached destination with issues and required rerouting
4. Unable to reach destination.

Table 1. Users (P1-P6) feedback for the four navigation tasks

Navigation Tasks	P1	P2	P3	P4	P5	P6
Task 1	2	1	1	1	1	1
Task 2	1	1	1	1	1	1
Task 3	2	1	2	2	1	2
Task 4	3	3	3	1	1	3

We observe that the study participants had the most trouble with Task 4 which is indeed the most complex. In Task 4 the participant begins in a large open area and is asked to cross this large open area to reach an elevator in the middle of the open area. However after some time, the participants reached the destination.

Trial Feedback

Each participant was asked to score their agreement with specific statements related to their experience during the trial. The score followed Likert scale from 1 strongly disagree to 7 strongly agree with, with 4 being neither agreeing or disagreeing with the statement. The six statements, individual participant scores, and averaged score are provided in Table 2.

Table 2. Post-Trial questionnaire using Likert Scale scores

Statements	Average Score	P1	P2	P3	P4	P5	P6
Easy to learn how to use system	6.7	7	7	7	7	6	6
Easy to use the system	6.7	7	7	7	7	6	6
Trial design was easy to complete	6.3	6	6	7	7	7	5
Easy to use User Interface	6.5	7	6	7	7	5	7
System provided sufficient re-orientation information when lost	5.5	5	7	7	6	3	5
I am confident I will reach the destination using the system	6.7	6	7	7	7	7	6

Conclusions

In this paper we introduced the second generation PERCEPT system which enables independent indoor navigation in large and open indoor environments such as subway stations. The system was deployed at the North Station subway in Boston. We describe in details the experiments conducted with BVI users. All six BVI users successfully navigated through this subway station using PERCEPT application. Moreover, all participants were very satisfied with

the system as evidenced by their very high scores in the post-trial questionnaire.

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