Enriching Visually-Impaired Visitors’ Experiences at the Worcester Art Museum with a Software Navigation System

A Major Qualifying Project Proposal submitted to the Faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the degree of Bachelor of Science

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Abstract

Visually impaired visitors to the Worcester Art Museum often must arrange personal or group tours with staff to explore the museum while learning about the pieces. In the past, the museum has had headphone audio interpreters, however, these are no longer in commission. Thus, the museum asked the project team to develop a technological solution that builds off the museum’s existing Beyond The Visual app, started by the 2022-2023 MQP team in August 2022 (Zeolla & Vila, 2023). The app allows users to navigate to art pieces by providing voice commands indicating directions and utilizing an indoor positioning system devised of Bluetooth low energy beacons to triangulate users’ location. This functionality was added to the existing React Native app, while committing to accessible, research-based design. The app was user tested with visually impaired participants involved with Audio Journal in Worcester. This addition to the app aims to expand its usage within the museum and allow visually impaired persons (VIPs) to navigate and experience the museum without needing an in-person guide.
1 Introduction

Museums, as public institutions, have increasingly sought to enhance their accommodations and experiences for disabled visitors, either through wheelchair ramps, specially designed exhibits, or arranged guides (Lott, 2015). Concurrently, museums are integrating technology into their infrastructures, allowing visitors access to tools that make visits more convenient, accessible, or interactive (Decker & Alexander, 2015). As part of this broad initiative, the Worcester Art Museum (WAM) has already implemented new technologies into its exhibits like iPads, QR codes, and NFC tags. Driven by outreach from Worcester’s visually impaired community, the 2022-2023 MQP team pioneered accessible technology at the museum by developing an app for community members. App users can use the Beyond the Visual (BV) app to scan NFC tags next to art pieces and initiate audio logs describing each piece in detail. BV is available for Apple devices on the iOS app store, as well as Android devices on the Google Play Store (Museum, 2023a, 2023b). For phones that are not capable of scanning NFC tags, the information for each piece can still be found through voice commands in the app.

The museum sought to expand this app to facilitate indoor navigation for visually impaired persons (VIPs). To achieve this, the project team added functionality to the existing Beyond The Visual app to allow users to navigate to specific art pieces in the museum. By using Bluetooth low energy (BLE) beacons placed within the designated pilot area, the app tracks users’ locations and provides directions to the user-selected art piece.
2 Background

2.1 Beyond the Visual 2022-2023

In 2022, the previous MQP group created the Beyond the Visual app and included the following accessibility-focused features:

- Audio descriptions for art pieces, explaining the material used, what the piece depicts, and the piece’s history.
- Voice commands for navigating to different pages of the app.
- NFC scanning that allows users to touch their phones to tags placed next to museum exhibits. The information for that exhibit is then loaded on their phone.
- Color palettes to address colorblindness.
- Scalable elements and text to account for device-specific accessibility settings.

![Figure 1: Pages on the existing Beyond the Visual Application](image)

(a) Home page  
(b) Gallery page

Figure 1: Pages on the existing Beyond the Visual Application
The previous team recommended that a future team working on the application should develop a live navigation service that guided VIP users around the museum. They did preliminary research on the feature and possibilities for its development and integration into the existing Beyond the Visual app. They suggested that GPS would be unreliable in indoor environments, such as the WAM, and recommended that a Wi-Fi or Bluetooth-based navigation system would be preferable instead. These technologies often use signal strength from a transceiver to a user device as an indicator of the device’s position. By measuring the signal strength from multiple transceivers to the device, it is possible to estimate the device’s location through triangulation. The remainder of this section expands upon the previous team’s research into a live navigation service for VIPs and gives possibilities for its implementation.
2.2 Demand For a Navigation Feature for Visually-Impaired Visitors

VIPs have historically faced challenges in attaining navigation information in public and commercial settings. Common means of providing directions for visitors, such as maps and signage, can be ineffective sources of information for VIPs because of these mechanisms’ reliance on visual cues (Ponchillia et al., 2020). As such, VIPs have found alternate solutions for navigating outdoor environments, such as through the use of guide dogs and the processing of familiar auditory and tactile information (Ponchillia et al., 2020). The emergence of GPS technology since the 2000s has also provided VIPs with greater ease in navigating outdoor environments. The adoption of GPS services in personal devices, such as smartphones, allows VIPs to use software tools to follow step-by-step directions for reaching their destination (Ponchillia et al., 2020).

However, indoor navigation remains a considerable challenge for VIPs. GPS technology is generally unreliable in indoor spaces, leaving VIPs without their most effective tool for navigating unfamiliar spaces. One study performed in 2020 evaluated the preferences and concerns of 614 visually impaired adults in navigating indoor spaces. It found that information about locations of interest, such as elevators and bathrooms, was the most essential for VIPs, with over 90 percent of respondents identifying such information as important to know (Ponchillia et al., 2020). Over 75 percent of participants also indicated that knowledge of room numbers, information desk locations, and building entrances and exits were also important to be aware of (Ponchillia et al., 2020). Additionally, the participating VIPs identified museums as one of the most challenging types of indoor spaces to navigate (Ponchillia et al., 2020). When asked about desired features for an assistive application for indoor navigation, 98 percent of respondents preferred that an application include some form of verbal output as an accessibility tool (Ponchillia et al., 2020). A majority of participants indicated that knowing their current location, routing to a specific location, announcements of nearby points of interest, and knowing the distance and direction of a point of interest would be helpful features in such an application (Ponchillia et al., 2020).
2.3 Bluetooth-based Indoor Positioning

In recent years, BLE beacons have emerged as a popular alternative to GPS in navigating indoor spaces. BLE beacons are battery-powered, wireless devices that are typically small in size, affordable, and can communicate with personal devices, like smartphones, through the use of Bluetooth protocols (Spachos & Plataniotis, 2020). The Bluetooth signal strength of the beacons generally decreases with distance, meaning that the further away the connected device is, the weaker the Bluetooth signal will be (Spachos & Plataniotis, 2020). These beacons can measure the received signal strength (RSS) of this Bluetooth signal to a connected device. This measurement is referred to as the received signal strength indicator (RSSI) and can be used to estimate the distance between the beacon and device. When multiple beacons at varied locations are connected to the same device, their RSSI allows for the triangulation of the position of this device. Triangulation with BLE beacons has a fairly low error. One study testing BLE positioning using a triangulation algorithm with a Gimbal 21 beacon and Android phone found that the estimation was less than 3 meters 95% of the time at distances up to 5 meters away in a laboratory and less than 3.5 meters 95% of the time in a busy corridor.

Using BLE beacons for indoor navigation presents a number of considerations. A beacon’s RSSI has a greater error the further away the connected device is from the beacon, meaning estimating the distance between the beacon and device is more difficult as the distance increases (Spachos & Plataniotis, 2020). Additionally, beacons’ batteries must be regularly replaced, requiring some regular maintenance and upkeep costs. Battery life can range from a few weeks to several months depending on the make of the beacon. Additionally, increasing a beacon’s transmission power can increase the effective range of its RSSI, but also causes its battery life to drain quicker (Spachos & Plataniotis, 2020). A beacon’s RSSI is also susceptible to noise, such as the Bluetooth signals from other beacons and physical obstructions (Spachos & Plataniotis, 2020). A technique known as Kalman filtering can improve estimation accuracy in noisy environments, especially at greater distances. In the aforementioned study, Kalman filtering improved the max error to be within 2 meters in the laboratory and within 2.5 meters in the corridor.
2.4 WiFi-based Indoor Positioning

In addition to Bluetooth beacon technology, WiFi is also capable of approximating a device’s location within an indoor environment. Generally, these WiFi-based systems use the RSS from transceivers to the user device (Shang & Wang, 2022). Similarly to BLE beacons, Wi-Fi-based positioning can use triangulation to estimate the location of user devices. As this method makes use of existing Wi-Fi access points, it requires no additional hardware, making it an affordable option for incorporating indoor positioning in locations where Wi-Fi is reliable and multiple access points are within range (Yang & Shao, 2015).

Conversely, Wi-Fi-based positioning can be ineffective in areas where Wi-Fi connection is weak or there are a limited amount of access points. A single access point can estimate device location using a combination of a Wi-Fi signal's time of arrival and angle of arrival. The time of arrival allows for the estimation of the distance between the access point and receiving device, and the angle of arrival allows for the estimation of the direction in which the device is located (Yang & Shao, 2015). However, attaining the angle of arrival requires special hardware that is not present on most models of Wi-Fi access points (Yang & Shao, 2015). This method also is prone to error in complex indoor environments. When there are physical obstructions between the access point and receiving device, the Wi-Fi signal often takes multiple paths to the device, resulting in multiple times and angles of arrival, thus making the distance and direction to the device difficult to determine (Yang & Shao, 2015).

2.5 Ultra-Wideband based Indoor Positioning

Ultra-wideband (UWB) is a viable option for indoor positioning. UWB has a high data rate which can reach 100 Megabits per second (Mbps). This high bandwidth allows for very accurate positioning. The low frequency of UWB pulses can enable the signal to effectively pass through objects and walls (Alarifi et al., 2016). UWB also consumes low power on the transmitter which can improve the battery life while the receiver does the more complex tasks.
2.6 Inertial based Indoor Positioning

Inertial based Indoor positional tracking is one approach to indoor positioning that uses a method called dead-reckoning. "Dead-reckoning is the process of determining one’s current position projecting course and speed or elapsed distance from a known previous position." (Munoz Diaz et al., 2019). This means that all tracking is done through the inertial sensors (consisting of accelerometers and gyroscopes) of whatever smartphone is used for navigating, making this method infrastructure-free. This is convenient, but has the downside of being a less accurate method for indoor positioning. Inertial sensors are susceptible to gyroscope drift, which reduces accuracy over time. Often times, this technology is used as a hybrid with other technology to reset the positioning error that accumulates over time.

2.7 Vision based Indoor Positioning

Vision-based navigation is a technology that relies on computer vision algorithms and cameras to enable precise location tracking and navigation. This approach simulates the way humans perceive and understand their surroundings by processing visual information. In vision-based navigation, cameras capture real-time images or videos of the environment, and software analyzes these visuals to determine the user’s position and orientation. By comparing the captured images to pre-existing maps or landmarks, the system can accurately pinpoint the user’s location and assist in guiding them to their destination.

2.8 Existing Solutions for Visually-Impaired Museum Visitors

2.8.1 American Museum of Natural History: Explorer App

In 2010, the American Museum of Natural History (AMNH) in New York published an app to provide information and real-time routing to specific exhibits for museum-goers (Grobart, 2011). According to the app’s download page on the Apple app store, users can receive step-by-step instructions on how to reach certain exhibits or other points of interest. This includes highlighting accessible-only routes for users who need to reach exhibits strictly through paths that avoid staircases in favor of elevators, lifts, and ramps.
Museum director Matt Tarr points out that the app purposefully gears itself toward the experience of naturally finding interesting exhibits alongside guidance to specific ones. The app recommends nearby exhibits to users by prompting them for their interests, as well as provides information about exhibits that are not otherwise physically shown (Fenton, 2016). Including an additional educational perspective on museum navigation may make traveling the museum with the app in-hand a more interactive, and therefore, more essential experience for users.

From a technical standpoint, the navigation feature operates on a backbone of roughly 700 Bluetooth beacons that are spread throughout the museum’s exhibits. A user’s position is triangulated from these beacons, which allows the app to detect the ”hall” they are located in and, roughly, their position in that hall (History, 2010). In some cases, the architecture of an exhibit prohibits the beacons’ signals from reaching a user’s phone and muddles the connection of the app and accuracy of the positioning system. To remedy this, the museum recommends moving to a new position a short distance away, which potentially provides an opportunity for a better signal and more acute location tracking (History, 2010).

2.8.2 Live Visual Interpreter: Aira App

Aira (Access to Information Remote Assistance), launched in 2015, is a service app that connects visually impaired users to live agents. Users enable their device cameras to provide a video feed to the agents, who then describe, help users navigate, or answer users’ questions about their surroundings (”Aira.io”, n.d.).

Aira is available for individual users at a monthly cost. They have nine tiers of payments, ranging from $25 USD for 15 minutes per month to $1160 for 800 minutes per month (“Aira Offset Prices”, n.d.). Aira also partners with over 170 organizations that pay to provide free-of-charge service to community members. Organizations include museums, universities, airports, and other enterprises (Aira, n.d.). For example, the Museum of Science in Boston uses the free Aira service as an alternative to sighted guide tours and for the ”reading of exhibit labels and instructions” (MOS, n.d.). For organizations with fewer resources than the AMNH, subscribing to Aira’s services presents a more cost-effective option for VIP accessibility support.
2.8.3 Non-digital Accessibility Options

In lieu of or in addition to app-related offerings for museum navigation, many museums offer non-digital accommodations for VIPs. For example, the WAM offers events geared specifically toward VIPs, like tours where tour guides describe pieces in exceptionally thorough detail, similar to the experience created in Beyond The Visual (Garland, 2023). Furthermore, The Metropolitan Museum of Art offers exhibits and special events where visually impaired visitors can touch the art pieces. Some of these events cover rotating exhibits on specific dates and have limited space for participants (Met, 2023). Others, like tours through their “touch collection” of pieces can be arranged in advance on an individual basis (Met, 2020). All of these experiences are generally free to visitors and offer a reliable way to engage with the museum. However, these experiences are limited to a predetermined set of exhibits. A specially reserved tour or accessible tool is required for VIPs to get a holistic experience without additional in-person support.

The Museum of Science addresses this issue with a comprehensive guide to navigating the museum available on their website (MOS, 2023). The guide begins with detailed descriptions of how to get to the museum based on different transportation methods, as well as the layout of the main entrance and paths to take from there. Following this, there are sections for each wing of the museum, with descriptions for each level, including navigation paths to each level using stairs, elevators, or wheel-chair ramps. The exact directions of each path are specified based on where one enters the level. There are indicators to help visitors identify which gallery or hall they are in, and there are descriptions for the materials of the floor and nearby objects in each area.

One proposal put forth by Meliones and Sampson for increasing the accessibility of three museums in Greece includes a combination of digital and physical support tools (Meliones & Sampson, 2018; Vaz et al., 2020). Their app uses BLE beacons to determine when a user enters an approximate location and alerts them of the exhibit they have entered. Then, using the app device’s accelerometer, the app can determine how many steps users have taken into that exhibit, allowing it to provide estimated guidance to specific art pieces. This guidance is aided by textured paths on the ground for VIPs to follow with their canes (Vaz et al., 2020). Having a mix of physical and technological mechanisms for self-guided touring broadens the number of visitors who will be comfortable with this system. For those who are new
to digital navigation, including a traditional aspect to the experience adds a reliable fallback option.
3 Methodology

This section outlines the team’s methods and approach to implementing an indoor positioning system for the WAM. This includes the development methods and organization tools used in order to integrate the necessary app features into the Beyond the Visual application.

3.1 Goal

The Worcester Art Museum’s goal is to make their museum more accessible to visually impaired persons. The museum has already taken steps to work towards this goal through guided tours specifically for visually impaired people and the existing implementation of the Beyond the Visual app. To continue in this pursuit, the addition of indoor positional tracking within the app will enhance VIPs’ ability to navigate the museum without the direct assistance from staff-guided tours.

3.2 Project Management

The team chose to use the Agile methodology as the basis for organization and project management. The Agile methodology is an industry standard for software engineering because of the highly conceptual and quickly changing nature of software (Coram and Bohner, 2005). The team decided to meet at a consistent time each weekday for a daily scrum. During these scrums, each team member discussed what they had worked on since the last scrum, any roadblocks that are stopping them from completing tasks, and what they plan on working on next. These scrums were necessary to keep clear communication between team members and hold each other accountable.

There are many useful project management software tools available on the Internet. The team chose to use Jira as a project management tool. Jira is popular among software development teams for its extensive features that support the Agile methodology. Some of the key features that the team used during development were the Planning Timeline and the board. The board is used to add both functional and non-functional tasks. Tasks can be placed in the “done”, “in progress”, or “to do” categories depending on their status, and are categorized by “epics”. An epic is a term used in Agile to describe a large and high-level user story or work item that represents a significant and substantial piece of work. Epics are typically used to group
related user stories or tasks together, providing a higher-level view of the work that needs to be done. The team divided the contents of the project into 4 epics: preparation, navigation feature, testing and revising, and the final report. These epics are visible in the timeline section of Jira, which clearly shows the schedule for the project.

![Jira Board](image1)

**Figure 3: Jira Board**

![Jira Timeline](image2)

**Figure 4: Jira Timeline**

The team also had a weekly group meeting with their sponsors, advisor, and the EcoTarium MQP team to present their work, as well as gain insight from the EcoTarium MQP team’s presentations. In addition to these group meetings, the team had separate weekly meetings with their sponsors for clear communication on objectives and expectations.
3.3 Indoor Positioning System Technologies

There are many different types of technologies to implement an IPS system. IPS can be sub-categorized into (1) self-positioning, (2) infrastructure positioning, and (3) assisted by self-directed infrastructure (Coram and Bohner, 2005). The previous MQP recommended focusing on infrastructure positioning in their report for future work. After doing more research into these technologies, the team agreed to focus on infrastructure positioning. Self positioning techniques like the use of inertial measurement units (IMU) on their own can become less accurate over time when not used in a hybrid approach with other technologies. Assistance by self-directed infrastructure does not work for this project for a few reasons. First, vision based tracking relies more heavily on the user’s ability to see the navigation prompts on the screen which makes it less accessible for VIPs. Second, Computer vision involves the development of more complex software. This leads to high accuracy but is not in the scope of the project timeline.

3.4 Piloting IPS with Bluetooth Low Energy Beacons

After deciding on infrastructure positioning as primary IPS technology, the team spent time looking into hardware options for WiFi, Bluetooth, and UWB beacons. The criteria for selecting a beacon were accuracy, cost, battery life, range, ease of implementation, scalability, and maintenance. In the piloting phase, the team was less concerned about battery life and maintenance.

Based on the criteria for the beacons, as well as further discussion with the project’s sponsors, it was decided that pilot testing would start with the Gimbal series 10 BLE beacons. These beacons are five dollars a piece and small in size (1.6 inches x 1.1 inches x 0.2 inches) which is convenient for testing and initial setup. This small size allows for easy and temporary installation, since these beacons can be mounted with tape. However, the battery life for these beacons is relatively short. When configured to follow the iBeacon protocol, these beacons only last for 2-3 weeks. When the piloting stage is complete, these beacons will be replaced with a more permanent hardware option that has a longer battery life. Below in Figure 5 are the specifications of the top three hardware options based on the criteria.
Figure 5: Specs of initial hardware options

WiFi based positioning is a viable option that the team may implement into BV in the future as a hybrid approach alongside BLE beacons. The WAM already has Aruba WiFi access points set up on all floors of the museum. On their own, these access points do not provide accurate enough readings for a full implementation of indoor navigation. However, if used in conjunction with the existing implementation with BLE beacons, it could further improve the navigation accuracy.

3.5 Initial Testing

In order to initially deploy the navigation feature at a manageable scale, the team first worked with the WAM to define a small pilot area in which to deploy a small number of beacons. This allowed the team to work through any initial challenges that might arise upon first attempting to integrate the navigation feature into the app in an isolated and controllable manner. The WAM purchased an initial order of ten Gimbal Series 10 beacons for the purpose of this initial testing. Before deploying the beacons in the museum, the team tested them in their personal spaces to ensure that they would catch as many issues interfacing with the hardware as possible before museum staff installed the beacons on-site.

The team and the WAM representatives decided upon the 201, 204, and 206 rooms as the pilot area. The team identified a number of benefits to using these rooms for this purpose. There are existing Beyond the Visual NFC tags located in rooms 201 and 206, allowing the team to test the integration of the navigation system with the existing app features. Additionally, these rooms
Figure 6: Map of the Worcester Art Museum’s second floor
have large amounts of open space and see regular but generally moderate foot traffic, which should minimize the amount of noise present while reading the RSSI of the beacons while also serving as useful indications of how physical obstructions might affect signal strength.

The team then measured some of the dimensions of the rooms using a tape measure that the WAM provided. This allowed the team to get a sense of potential positioning options for the beacons to try to attain maximum RSSI clarity. Additionally, this gave the team an option of systematizing the navigating system by incorporating a grid coordinate system. The navigation system could offer specific directions to a user by checking if they were in a specific square within the coordinate system.

Next, with the help of WAM personnel, the team set up the beacons at temporary locations within the pilot area in order to assess the accuracy of the location readings using various beacon positioning configurations. The team also took measurements of the locations of the beacons within the pilot area rooms in order to precisely define their locations within the coordinate system.

### 3.6 Additional Beacon Purchasing

Because of the Gimbal 10s’ low battery life when configured with the iBeacon protocol, the team further explored other beacon options after initial testing. The team and the WAM decided to purchase 3 additional beacons of the MBS02 model from the manufacturer Minew. These beacons were affordable, at only about $10 USD per beacon. A third-party performance evaluation of various BLE beacons conducted by Aislelabs found that a similar model, the Minew MS54V3, had an estimated battery life of almost 3 months using the iBeacon protocol (2017). These beacons are slightly larger than the Gimbal 10s, at 2.2 inches x 2.2 inches x 0.91 inches (n.d.), but are still small enough to be discreetly placed around the museum. Below is a breakdown of the MBS02’s specifications provided by Minew’s website.
3.7 Application UI Mock ups

Before development on the application, the team made a few mock ups using the online tool Figma (https://www.figma.com/downloads/). Figma is a free online tool for creating high fidelity prototypes. When creating the mock ups, the team referenced the previous MQP team’s research on accessibility features for developing the UI for an application.

Figure 8 highlights the initial application flow that the team had in mind. Sub figure (a) shows an update of one of the already existing pages. On this page, the user can search for art pieces in the selected exhibit. The mock up includes a button at the top of the page that redirects the user to a page for navigation to the exhibit. Sub figure (b) shows the initial design for the navigation page. It includes text directions, as well as a graphic to display directions. Although it is not possible to represent audio in the mock up, the team planned on the addition of voice-over for key events in the directions. At the bottom of the screen, there is a button to cancel the directions as well.
as a button to redirect the user to sub figure (c). The page in sub figure (c) gives an overview of the key directions in the route.

Figure 8: Initial UI mock ups for Application


4 Implementation

This section covers the implementation of the features and concepts introduced thus far into the application. This includes the team’s development timeline, integration of the art piece navigation feature, and enhancements to preexisting features.

4.1 Project Structure and Workflow

For project management, the team relied heavily on Jira. Jira was used to keep track of all the major components of the project. The project was broken into three main components in Jira: Application features, the final report, and logistical planning.

During A term, the first 7 weeks of the project, the team focused mainly on the Introduction, Background, and Methodology chapters of the report. Most of the background research was for choosing the best option for indoor navigation tracking. This included both the positioning technique as well as the hardware needed for implementation. The team also reviewed the 2022-2023 MQP team’s report, became familiar with the codebase, and set up local environments to begin development.

For B term, the team spent the majority of the time working on implementing the new features into the application, as well as planning and conducting the user study. By the end of B term, the implemented features were nearly complete. The team had a few bugs regarding the navigation features that they resolved at the beginning of C term. Figure 9 shows the number of Jira tasks completed over the course of A and B-term. Generally, tasks were created as often as prior tasks were completed.
In C term, the team focused on implementing bugs discovered and suggestions received through user testing in the application. Another major goal was ensuring the complete compatibility of the app with Android and iOS devices. The team also worked on improving the accuracy of the IPS system, finishing this report, analyzing user study results, creating the MQP poster, preparing material for marketing the application, and publishing the application to the Google Play Store and Apple App Store.

4.2 Application Features

4.2.1 BLE Beacon-based Device Positioning

The team moved forward with BLE beacons as the sole signal providers for the app. The WiFi access points in the museum could potentially be utilized, were the scope of the project expanded to further areas of the museum. However, their lack of signal strength and sporadic placement made beacons a necessary choice. Building on measurements taken in initial testing, the team took complete measurements of the room dimensions, placement of NFC-tagged art pieces, placement of floor obstructions (statues, seating, etc...), and doorway dimensions to create a to-scale representation of the pilot area in Google Drawings. This mapping, shown in Figure 10 is in feet and is used
to determine the coordinate values of beacons, doorways, and NFC tags in relation to each other and the pilot area as a whole.

Each BLE beacon is configured to share confidential Universally Unique Identifiers (UUIDs) that let the app know which Bluetooth signals to treat as relevant. Many non-beacon devices also emit Bluetooth signals, thus it is important to differentiate between extraneous hardware and the museum’s beacons. Individually, each beacon stores a unique combination of major and minor values that contain data about the beacon’s location in the museum. These identifiers, as well as power measurements and RSSI readings, are stored in advertisement packets. These packets are emitted by beacons once every 100ms, as per the iBeacon protocol standard, such that applications or other beacons can pick up their signal.

The app parses the packets of all eligible beacons and stores their RSSI readings. After a pre-determined scanning period, the app pauses its search for beacons. For each received beacon, a Kalman filter is applied to its series of RSSI readings to eliminate noisy values and determine an accurate RSSI value, representative of that beacon. That final RSSI value is then passed as RSSI to Equation 1, which outputs the distance, in meters, from the beacon to the mobile device running the app. This is a modified version of Equation 1 from Spachos and Plataniotis (Spachos & Plataniotis, 2020). $TxPower$ refers to the RSSI value of the beacon from 1 meter away, a previously identified value known by the app.

$$10^{(TxPower - RSSI)/(10*2)}$$

Once the readings of all beacons have been processed, the app identifies the three beacons with the closest distances to the app’s mobile device. The coordinates of these beacons are read in from the back-end and passed, along with the distance values, to a trilateration function. This function determines the intersecting point of the three beacons using their distances from the mobile device (11) and outputs the location of the mobile device with respect to the pilot area. From here, the location of the device is used to determine the shortest path to an art piece, the user’s proximity to an art piece, and the user’s progress along the path.
Figure 10: Scaled recreation of the European Galleries (Pilot Area)
Initially, the team used a react-native library that could scan (range) BLE devices on both iOS and Android. For Android, this included beacons. However, on iOS, beacons cannot be treated as general BLE devices, meaning the app was unable to retrieve data from the museum’s iBeacons. Thus the team transitioned to a new library that allows both Android and iOS devices to range beacons by using the required CoreLocation framework for iOS.

4.2.2 Voice Control Efficacy Improvements

While testing the voice navigation system within the application, the team noticed that the speech recognition system previously implemented in the app was susceptible to slight inaccuracies in parsing the speech data, which resulted in the voice navigation being ineffective. For instance, when the team tried saying the phrase “navigate to Woman at Her Toilette” from the home screen to bring the user to the navigation page for the piece, the device often interpreted the audio as ”navigate to women at her twilight” instead. Phonetically, the two phrases are very similar, but since it is not an exact match, the app did not take the user to the navigation page. To improve upon this, the team used the Fuse.js library’s fuzzy search feature, which identifies two blocks of text as a match if they are similar enough to each other. Using this, the app can now identify phrases close to the target phrase
and send the user to the correct page.

4.2.3  Indoor Navigation page from Voice Control

As mentioned in Section 4.4.2, the team added new functionality to the voice commands on the home screen. Users can add keywords to a voice command to get directions to an art piece. The keywords include phrases such as "navigate to", "get me directions to", "get directions to", "give me directions to", "direct me to", "go to", "get me to", and "take me to". Adding these keywords to a voice command will open the map page and give directions to the specified art piece.

4.2.4  Floor Plan

Given that the indoor positional tracking system only encompasses a few rooms on the second floor, the team added the official WAM floor plan into the application interface to assist with building-wide traversal, as seen in Figure 12. With this feature, non-VIPs and guides of VIPs can now visualize their location within the building context, offering a clearer understanding of their surroundings and aiding navigation.
4.3 Museum Location Database

Using the measurements the team took of the pilot area and the locations of the beacons and NFC tags therein (see sections 3.5 and 4.2.1), the team extended upon the project’s preexisting MongoDB database by creating a collection representing the physical layout of the pilot area. This database lists the x, y, and z values of each beacon and NFC tag within the pilot area as defined by the coordinate system, in which x is the distance in meters from the West to East according to the map, y is the distance in meters from
South to North, and z is the height above the floor in meters. It also contains information about the dimensions of each of the three rooms in the pilot area, listing the x and y values of the 4 corners of each room. Additionally, each room contains a number of waypoints positioned where the pathfinding node labels are in Figure 10. The team picked these waypoints to represent specific areas in the rooms that were generally clear of obstructions and would be suitable spaces for users to walk through. The database also labels the doorways between rooms and lists their center points on the coordinate system.

4.3.1 Pathfinding System

Using the location database described in Section 4.3, the team implemented a pathfinding feature that can take the user from their current point in the pilot area to the location of an NFC-tagged art piece within the pilot area. To do this, the team used the location data to build a graph data structure, as shown in Figure 13. The waypoints and doorways act as nodes in the graph. The database also includes information about the paths between these nodes. If you can walk directly from one node to another, there is an edge between the two nodes in the graph, where the edge weight is the Euclidean distance between the nodes’ center points.

In order to take the user from their current location to the desired NFC-tagged art piece, the app first computes which nodes the user’s device and NFC tag are closest to. It then uses Dijkstra’s algorithm to find the shortest path between these two nodes by finding the path with the smallest edge weight (Mehlhorn, n.d.).

This solution is effective because it allows the pathfinding process to account for slight inaccuracies when estimating the device’s location, a given in any indoor navigation system. By attempting to direct the user to the general area of the art piece within about 1 meter, the pathfinding algorithm operates on a realistic scale of precision. There is also the benefit of being able to manually define the edges between nodes, which can be useful in the occurrence that the layout of the pilot area is altered, such as if an art piece or piece of furniture is added that acts as an obstruction between two previously connected nodes.
Generating Directions for the User

One of the most important features of the navigation system is giving the user easy-to-understand and effective directions to navigate to their destination. The app’s target demographic contains people of varying levels of technical expertise, so the directions do not assume the user has any familiarity with the underlying technical concepts of the pathfinding system. Based on the resulting path between the user and their desired NFC tag as generated by the algorithm described in Section 4.3.1, the app generates a list of step-by-step directions for the user in text based on the distance and direction they should move to navigate between waypoints and doorways. These directions deliberately omit visual cues to address the needs of those with significant enough visual impairments that they cannot rely on any visual stimulus as a reference for navigation. Instead, the directions instruct the user to turn a specific amount to the right or left and walk a designated number of steps. Figure 14 shows an example of the text for a specific direction being displayed on the navigation page.

The team decided to utilize steps as the primary unit of measurement.
rather than a more exact unit, like feet, in order to make the distances more intuitive for users to understand, enhancing their ability to comprehend and follow navigation instructions. Additionally, acknowledging the needs of visually impaired individuals, the team incorporated the feature of obstruction details upon entering a room. This enhancement serves to alert users to potential obstacles or hazards within the room, facilitating safer and more accessible navigation experiences.

![Figure 14: An example of the text for a direction on the navigation page](image)

The team also researched different methods to maximize the accuracy of the device positioning. The team discovered that the inaccuracies that occurred in the app’s calculations during testing were primarily due to the unreliability of beacon RSSI values from certain distances. According to Gimbal, and corroborated by the equations used in the app, as RSSI increases, the potential distance of the device increases at a logarithmic rate (Admin, 2023). This means that the error on the distance calculation grows rapidly after 20 feet and even more substantially after 35 feet because the RSSI value becomes less descriptive. To offset this, the team experimented with adding 4 new Minew beacons to Room 201 of the pilot area. The beacons were placed
uniformly throughout the room, allowing the device to always be within 35 feet of the necessary amount of 3 beacons. The team found that this did increase the accuracy of the distance calculations and would suggest that future inaccuracies in exhibits could be remedied by this same method.

4.4 User Interface and User Experience Updates

Integrating the navigation feature seamlessly into the existing app structure was crucial for ensuring the feature was accessible and consistent with the behavior of the rest of the app. The team was committed to adhering to the guidelines and structures that the previous WAM MQP group put into place, especially as it related to accessibility. Whenever possible, the team tried to use preexisting screens, menus, and voice control interfaces to implement the navigation feature. This resulted in the team deviating slightly from the initial UI mockups to create a more consistent look and feel to the app as well as to increase accessibility. The team also iterated upon the preexisting design of various UI elements throughout the app to further enhance the user experience.

4.4.1 Navigation Page Architecture

To ensure that users with significant visual impairments can use the navigation page as easily as possible, the page contains only a few components that are large and vertically organized so that they can be clearly identified, especially when using a screen reader. If the beacons find that the device’s position is within the pilot area, the navigation page displays the current step-by-step direction described in Section 4.3.2 at the top of the screen. If they cannot find the device or estimate its position as outside the pilot area, it alerts the user that the directions are not available. If the positioning system detects that the device has moved to another node, the current direction is updated automatically with the direction for the new node. The user can click on the speaker icon below the direction text to have the device’s text-to-speech system read out the direction. Once the user is near the NFC-tagged piece they are navigating to, the page will redirect to the Art Piece Description page, as if the user scanned the NFC tag at that art piece. At any point, the user can click on the ”Art Piece Description” button to go to this page as well. Pressing the ”End Navigation” button sends the user back to the home page.
4.4.2 Common Application Flows to the Navigation Page

Users can get to the navigation page from the home screen by clicking the "Navigate to Art Piece" button, located below the "Help" button, as shown in Figure 16a. Pressing this button will send the user to a page with all the art pieces the user can currently navigate to, which are currently "Woman at Her Toilette" and "The Repentant Magdalen," since these are the two NFC-tagged pieces within the pilot area (Figure 16b). Similar to the lists for exhibits and art pieces elsewhere in the app, this list is filterable by different parameters, such as the title of the piece, the creator of the piece, and the date the piece was created. It also has voice control functionality. Clicking on one of these art piece items will send the user to the navigation page for the art piece (Figure 16c).
(a) "Navigate to Art Piece" button on home page

(b) Selection of art pieces it is possible to navigate to

(c) Navigation page tries to load directions based on the art piece selected

Figure 16: Getting to the navigation page from the home page button

Users can also click on the preexisting microphone button in the bottom right corner of the screen to use speech recognition to get to the navigation page for a specific art piece as shown in Figure 17. For instance, clicking the microphone button, saying "navigate to the Repentant Magdalen," clicking the microphone button on the voice control page, and then hitting confirm will send the user to the navigation page for the Repentant Magdalen. There are also multiple phrases that work in place of "navigate to" for this function, such as "get me directions to the Repentant Magdalen," "go to the Repentant Magdalen," and "take me to the Repentant Magdalen" to allow users to use whatever form feels most natural, rather than requiring them to remember once specific phrase.
Figure 17: Getting to the navigation page using voice control from the home screen
4.4.3 Audio Player Interface

To simplify the audio player for visually impaired users, the team streamlined the preexisting playback speed controls into a dropdown menu. Recognizing the importance of play/pause and skipping functions, the team relocated this feature to the end of the audio player interface. Pressing the playback button shows speed options ranging from 2.0x to 0.8x that alter the playback rate of the audio player. The audio pitch is adjusted based on the speed such that the audio stays decipherable as the speed changes.

![Figure 18: Updated Audio Player](image)

4.4.4 Changes to Accessibility Features

In an effort to enhance the accessibility of the app for visually impaired users, the team enlarged the font size of the back button and revised several
accessibility labels to be more clear. For instance, in the audio player, the label to indicate that the button served the dual function of pausing and playing the audio is clarified better.

![Enlarged font size to back button text](image)

Figure 19: Enlarged font size to back button text

Furthermore, the team simplified the voice control UI flow to make it more intuitive for users using screen readers. The preexisting voice control flow involved pressing the voice control button, then pressing the microphone button to have the app listen to speech, pressing the microphone button again to stop the app from listening, and finally pressing ”Confirm” or ”Cancel” to resolve the given voice input. The team changed the flow such that after pressing the voice control button, the microphone button is automatically pressed and the app starts listening for input immediately, as shown in the upper middle image of Figure 17. Removing the extra step of pressing the microphone button saves time for the user and simplifies the flow.
4.4.5 Standard Vision Mode

To increase the ease of use of the app for non-visually impaired users, the team added a separate coloring pattern option in which the color of an element depends on its context rather than alternating between two colors. The user can toggle between vision modes by clicking the color palette customization button on the home screen. The color palette customization popup now also includes a switch for toggling between vision modes, as shown in Figure 20a. As the primary goal of the application is servicing VIPs, low vision mode is enabled by default. Like with the color palette selection, the user’s vision mode preference is stored on the device so it persists even if the user closes the app. As shown in Figure 20b, using standard vision mode configures the home screen elements such that the palette customization and voice control buttons are the primary color in the palette and the menu buttons are the secondary color. This pattern persists when the user changes the color palette, as shown in Figure 20c.

(a) Switch for toggling between vision modes

(b) Standard vision mode using the default color palette

(c) Standard vision mode using an alternate color palette

Figure 20: Examples of standard vision mode in the app
5 User Study and Results

A user study was conducted at the WAM on December 9, 2023. With the help of Harry Duchesne at Audio Journal, the team was able to recruit five VIPs and one non-visually impaired person for testing. The also team performed another round of user testing at the WAM on January 21, 2024 with two non-visually impaired users. All participants tested the application on Android devices supplied by the team. An Expo local development build was downloaded on the Android devices for testing. Only Android was tested since the iOS build for the application was not ready for testing at the time.

5.1 Study Procedure

Before the team conducted testing, the user study was approved by the WPI Institutional Review Board (IRB). The consent form can be found in Appendix A, the statement of research methods in Appendix B, and the questionnaire in Appendix C. All participants were required to sign the consent form before participating in the study. For those with severe visual impairments who could not read the consent form, a student investigator read the contents of the consent form out loud and answered any questions the participants had before signing. The statement of research methods outlines and explains the purpose of the task list and questionnaire. The study questionnaire includes non-identifying questions regarding the demographics of the participants, as well as the participants’ feedback on the tested features of the application.

Testing was performed on-site at the WAM and followed the guided procedures detailed in ???. Testing consisted of two task sets. Task Set 1 was performed seated in the Lancaster Room. Users were first asked to get to the description page for the art piece "Woman at her Toilette" from the home screen in two different ways: navigating through the menus using touch and using voice commands and saying "Woman at her Toilette.” They were then similarly asked to get to the navigation page for "Woman at her Toilette” using a long press feature, which worked by pressing the ”Art Piece” button on the home page, clicking on the "European Galleries” exhibit, and then long pressing on the ”Woman on Her Toilette” button. Lastly, they were similarly asked to get to the navigation page for "Woman at her Toilette” by using voice commands and saying ”Navigate to Woman at her Toilette.” In Task Set 2, users started at the doorway leading to Room 201 from the
hall. They were then asked to walk to “Woman at her Toilette” using the directions provided by the app’s navigation page. Once they got to the piece, they were asked to get to the art piece description page by using the NFC tag on the wall and then by using their preferred method from Task Set 1. The users then repeated this process starting from “Woman at Her Toilette” and then walking to “The Repentant Magdalen.” After performing these task sets, the participants then answered the prompts in the questionnaire with the assistance of a student investigator.

5.2 Results of the User Study with Visually Impaired Subjects

All of the VIPs had some form of print impairment, with one indicating that they had partial print impairment and three indicating that they had full print impairment. Additionally, three testers indicated that they were partially blind. Two of the testers used a cane and/or a personal aide to navigate public spaces.

As part of the questionnaire, the team asked the study participants to evaluate the quality and ease of use of the main features of the app under test and the overall app experience on a scale of one to five, with one being the lowest quality and five being the highest quality. Figure 21 shows the average rating among VIPs for these features. VIPs were generally very satisfied with the overall experience of the app, giving it a 4.25 rating on average. They were particularly happy with the voice control efficacy, giving it a 4.50 rating on average. However, participants had difficulty with the voice control UI flow. This involved pressing the voice control button, then pressing the microphone button to have the app listen to speech, pressing the microphone button again to stop the app from listening, and finally pressing “Confirm” or “Cancel” to resolve the given voice input. When using a screen reader, participants had trouble identifying that after pressing the voice control button, the microphone button had to be pressed to start listening. This is indicated by the voice search feature being given an average rating of only 3.50 by VIPs. The team later iterated upon the design of the voice search feature so that the microphone button did not have to be pressed to start listening, as specified in Section 4.4.4.
Trouble with the text-to-speech system was a commonality, with VIPs giving it an average rating of 2.00. Many testers indicated that various buttons were too small and/or cluttered to locate using text-to-speech, such as the back button in the top left corner of the screen. They also mentioned that some accessibility labels were unclear. The team addressed these concerns by increasing the back button size and revising some of the accessibility labels, as described in Section 4.4.4. The team observed that some visually impaired participants encountered difficulties while utilizing the audio player as well. Two issues stood out in the audio player user interface: the arrangement of buttons and accessing the playback speed. Users could adjust the playback speed using separate forward and back arrows, which proved unintuitive for those relying on screen readers. Many said that there were too many buttons for playback speed options and that certain speeds, like 0.25, were not useful. This led the team to simplify the audio player page. The updated version is described in Section 4.4.3. VIPs also generally had difficulty using the long press feature to get to the navigation page for an art
piece, leading the team to remove this feature from the app. Additionally, all of the testers used iOS in their day-to-day lives and not Android, which made using the text-to-speech system on Android, TalkBack, slightly more difficult. Multiple testers said that iOS had better accessibility features for VIPs than Android in general and that a large majority of VIPs use iOS devices instead of Android.

VIP testers had difficulty using the app to navigate to art pieces, with the navigation feature getting a 1.75 average rating. At the time of user testing, the navigation directions used feet instead of steps as a measurement of distance. One common comment was that the use of feet in the directions was unintuitive. Testers were not sure how to count the footage they were traveling with their steps, which often led them to overestimate the distance they needed to walk in a particular direction. In general, they felt that the directions were too specific and robotic. This led the team to change from feet to steps as a distance measurement, as described in Section 4.3.2. Some participants said they would prefer to be given more general information, such as obstructions in the room they were navigating through, in order to get to the art piece. The team added the obstruction descriptions to the directions outlined in Section 4.3.2, which were not present in the app at the time, in response to this feedback. Many also had difficulty getting the NFC tag reader to work. However, the response about the art piece descriptions themselves was generally very positive, with the testers feeling that it enhanced their experience.

5.3 Results of the User Study with Non-Visually Impaired Subjects

As shown in Figure 22, non-visually impaired testers were generally satisfied with the overall experience of the app, giving it a 4.33 average rating. As non-visually impaired testers did not need to use TalkBack/VoiceOver and the text-to-speech system in general to navigate the app, they did not provide ratings for these features. In general, non-VIPs found the app more intuitive to use, especially regarding navigating to the art pieces using the app, giving that feature an average rating of 4.00. They also found the quality of the directions to be quite high. This was expected, as non-VIPs can rely on their vision to make up for small inaccuracies in the navigation system. For example, non-VIPs still generally overestimated the distance to traverse in a
particular direction, often taking fewer steps than the estimated amount indicated by the app. However, non-VIPs rating the navigation-related features highly suggests that the general idea and flow of the directions themselves and the navigation experience as a whole are fairly intuitive. In general, confusion over app features among non-VIP testers was due to miscellaneous bugs, such as the microphone not working on one of the test phones and an error message displaying as a direction text, which was later corrected. One non-VIP suggested the inclusion of a floor map. Two of the non-visually impaired participants of the user study mentioned that they were confused by the alternating color pattern present in the app. One tester thought that the color of an element indicated something about its function instead of being a purely visual distinction. To address this, the team implemented standard vision mode, as previously discussed in Section 4.4.5. Multiple non-VIPs also said that they would use the app upon visiting the museum again, as they enjoyed the art piece descriptions and found it convenient to not have to get close to the piece to read the physical description on the wall.

![Average Quality of Features as Assessed by Non-Visually Impaired Users](image)

Figure 22: Average Quality of Features as Assessed by Non-Visually Impaired Users
5.4 Overall Testing Results

VIPs and non-VIPs rated the overall app experience, voice control, and finding art pieces and directions through the app menus very similarly, as shown in Figure 23. All but one of the testers only used an iOS device in their day-to-day lives, with the other tester using Android instead. One common trend among all the testers was the very high reception of the art piece descriptions, which suggests that this feature is useful to the general population of museum visitors. The feedback from both VIPs and non-VIPs led to the various changes described in Section 4.4.

![Figure 23: Average Quality of Features as Assessed by All Users](image-url)
6 Future Work

6.1 Improve Location Tracking Accuracy

To improve the location tracking accuracy, the team recommends expanding upon the existing algorithms used to interpret the BLE beacon signals and supply directions. Techniques like fingerprinting and Kalman filtering can be explored to improve positional estimates. Integrating inertial sensors like accelerometers and gyroscopes with Bluetooth beacons could improve accuracy, especially in areas with limited beacon coverage or signal interference, by tracking the movement of the device. Furthermore, re-investigating alternative positioning technologies such as Ultra-Wideband (UWB) or Wi-Fi RTT could offer more precise indoor localization capabilities if the mentioned strategies above aren’t sufficient.

6.2 Expansion of Pilot Area

Expanding the pilot area poses several challenges. Scaling up the deployment of Bluetooth beacons to cover larger areas, such as entire floors and buildings, requires careful planning and execution. Future developers should take into account factors such as cost, infrastructure compatibility, and maintenance. Cost considerations include both the initial investment required for deploying additional Bluetooth beacons as well as the maintenance of those beacons like changing the batteries. Infrastructure compatibility poses a challenge, as the deployment expansion must contend with various building layouts and potential sources of signal interference, necessitating careful planning and possibly retrofitting existing infrastructure to ensure optimal performance. Retrofitting beacons would involve keeping the backend up-to-date with beacon locations and adding new beacons would mean expanding the floor map, which also may involve updating beacon data. Balancing these challenges requires a strategic approach that accounts for budgetary constraints, technical feasibility, and long-term sustainability to successfully expand the pilot area while maintaining the reliability and effectiveness of the indoor positional system.

Expanding the indoor positional system to a three-dimensional area with multiple floors presents another step in complexity from the current pilot area, which only encompasses a few rooms on a single floor. One challenge involves adapting the system’s algorithms and infrastructure to accurately
track users’ positions across multiple floors. This requires addressing challenges such as distinguishing between floors and handling transitions between floors. Infrastructure compatibility becomes even more crucial in a multi-level environment, as the system must contend with potential sources of signal interference across different floors. Ensuring consistent coverage and accuracy throughout the entire building, including stairwells and elevators, demands careful planning.

6.3 Recreating Floor Plan

The team designed the floor plan using Google Drawings and taking meticulous measurements of the pilot area. Expanding the pilot area would mean potentially reevaluating the x and y axis of the map. Google Drawings was sufficient for the current scale of the project, but issues like keeping walls to scale, giving wall rectangles width, and having to use rectangles to determine the position of a node on the map prevent this from being a sustainable solution. Ideally, a suitable software would include the ability to dynamically expand the x and y axis, maintain measurements of walls and obstructions in feet while keeping accurate scale, and be capable of expansion along the z-axis. One option is AutoCAD by Autodesk, used by architectural students and professionals. WPI provides licenses for Autodesk software for free.

6.4 Improving Trilateration

The trilateration calculation used in the app depends only on the x and y values of each beacon, excluding the beacons’ z-values. The height of each beacon is important because the device exists in a 3D space and to most accurately calculate distance, all three dimensions should be used. For the pilot area, most of the beacons are at the same height, which offsets the potential influence of the z-value on trilateration. However, if the pilot area were to grow, beacons may be placed at different heights to account for the varying dimensions of each exhibit. 3D trilateration formulas were explored for this version of the application, however, the app did not consistently produce accurate results and the team continued with 2D trilateration due to the scope of the project.
References


Garland, A. (2023, September 6).


Appendix A: IRB Consent Form

Informed Consent Agreement for Participation in Worcester Art Museum Accessibility App Study

Student Investigators: Timothy Connors, Theo Coppola, Randolph Dyer
WPI Faculty Advisors: Rodica Neamtu, Email: rneamtu@wpi.edu
Student Investigators Alias: gr-wam-mqp-23@wpi.edu
Title of Research Study: Worcester Art Museum App User Study
Sponsor: Worcester Art Museum

Introduction:
You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the Study:
The Worcester Art Museum is working with WPI to enhance their existing mobile app and make the museum more accessible to navigate for visually impaired visitors. We are the student team responsible for developing and testing the application on Apple iOS and Android devices. Our overall goal is for users to use the app effectively, and ensure that our new museum navigation feature works as intended. Visually impaired people are the focus of this study, but we would also like people with no or minimal visual impairments to participate in the study. We will be writing a report and analysis of our findings.

Procedures to be followed:
- For participants with significant visual impairments, we will provide a read-aloud service for all study materials, including this consent form. This service will be conducted by a qualified individual who will read the content aloud to you in a clear and understandable manner.
- You will be given the opportunity to ask any questions you may have during the read-aloud session. Our team is here to address any concerns and provide additional information as needed.
- By participating in this user study, you acknowledge that the expected duration of the study is approximately 1 ½ hours or less. We value your time, and every effort will be made to ensure that the study is conducted efficiently while still obtaining valuable insights.
- We will provide iOS and Android devices to use in-person, as well as instructions on how to open the test version of the app.
- You will be asked to perform some tasks regarding using the app while navigating our test area. The test area is three of the rooms in the museum’s European exhibit.
- Testing will involve physically walking through the museum while using the app. It will also involve using the app while seated in-place.
- You will be asked to state out loud your thought process when using the app, as well as your opinions on various features of the app.
- At the end, you will be asked to answer a set of questions.
- Your identity and responses to individual questions will be kept confidential.

**Risks to study participants:**
Standard risks associated with using smartphones and navigating rooms.

**Benefits to research participants and others:**
You will be helping the Worcester Art Museum be more accessible for all visitors.

**Your participation in this research is voluntary.**
Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

**Record keeping and confidentiality:**
Our report will be made available online at digital.wpi.edu. It will include analysis and statistics regarding the intuitiveness of our app and user satisfaction with the app. Only the student investigators will have access to the data collected in the questionnaire, which will be stored on a secure Worcester Polytechnic Institute OneDrive server. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

**Compensation or treatment in the event of injury:**
This study involves minimal risk of injury. You do not give up any of your legal rights by signing this statement.

**For more information about this research or about the rights of research participants, or in case of research-related injury, contact:**
WPI Faculty Advisor: Rodica Neamtu, Email: rneamtu@wpi.edu or
WPI IRB Manager: Ruth McKeogh, Tel. 508 831-6699, Email: irb@wpi.edu or
WPI Human Protections Administrator: Gabriel Johnson, Tel. 508 831-4989, Email: gjohnson@wpi.edu

By signing below, you acknowledge that you have been informed about the study, and consent to be a participant in the study described above. By signing this consent form, you affirm that you are 18 years of age or older. Participation in this study is limited to individuals who meet this age requirement. If you do not meet the age requirement, please do not proceed with participation. Make sure that all of your questions are answered before signing this form. You are entitled to retain a copy of this consent agreement.
Printed Name

Study Participant Signature

Date: _________________

Witness Signature (As applicable)

Date: _________________

Investigator Signature

Date: _________________
Appendix B: Statement of Research Methods

1. User Study

In order to get adequate feedback on our implemented app features, we will need to conduct a user study. We hope to find out which features are intuitive and accessible for visually impaired persons, and which features we could improve upon. We plan on testing the accessibility of the user interface and voice control commands, as well as the indoor navigation feature within the app.

We plan on using the think aloud protocol to obtain information from the participants. We will first explain to the participants the task description, which will include navigating to different pages within the app, and using the app to find different art pieces and navigate to the pieces in the museum. For each task, we will incrementally give them instructions when necessary.

1.1 User study tasks

The following describes each of the tasks we plan to give to participants. The first set of tasks will be tasks that participants can complete without physically moving around the museum and involve successfully using the app’s menus. The second set will be tasks that require participants to move between rooms in the testing area of the museum and use the app to find art pieces.

Task Set 1:

1. Open the application
2. Open the description page for the art piece “Woman at her Toilette” through touch
   a. Press the “Art Pieces” button on the home menu
   b. Press the “European Galleries” button on the Location of Art Piece menu
   c. Press the “Woman at her Toilette” button
   d. Press the audio playback button to play a description of the piece
3. Open the description page for the art piece “Woman at her Toilette” through voice command
   a. Press the microphone button on the home menu to activate voice command
   b. Say “Woman at her Toilette”
4. Open the directions page for getting to “Woman at her Toilette” by long pressing
   a. Get to the European Galleries page by pressing buttons on the menu or by voice navigation
   b. Press the “Woman at her Toilette” button for two seconds
5. Open the directions page for getting to “Woman at her Toilette” through voice command
   a. Press the microphone button on the home menu to activate voice command
   b. Say “Navigate to Woman at her Toilette”

Task Set 2:
1. Navigate to the doorway leading to Room 201 from the hall.
2. Open the directions page for getting to “Woman at her Toilette” as outlined in task set 1, step 4 or 5 based on preference.
3. Navigate to the art piece in-person
   a. Get information for that art piece:
      i. By scanning an NFC tag
      ii. By the preferred method from either step 2 or 3 in Task Set 1.
4. Starting from the piece “Woman at Her Toilette”:
   a. Repeat steps 2-3 for the art piece “The Repentant Magdalen”

2. Questionnaire

   After the think aloud session, we will administer a questionnaire to get more information from the participants such as their opinions on the specific features, as well as the overall app experience. This will also give us a chance to collect demographic data such as their level of visual impairment and will not include any identifying information.
Appendix C: Study Questionnaire

The Worcester Art Museum’s app user testing study will consist of approximately 10 volunteers supplied by the local nonprofit for the visually impaired, Audio Journal. Participants will receive a description for each task first, then enact the task, which will include navigating to different pages within the app, using the app to find different art pieces and navigating to the pieces in the museum. No volunteer will be asked to spend more than the time allotted for testing, and risks associated will be standard to operating a smartphone and navigating public spaces.

Task List:
- Find a few specific art pieces in the app's user interface
  - Navigate to the art piece in-person
  - Get information for that art piece:
    - Through the menu
    - By scanning an NFC tag
- Test the native Talkback or VoiceOver implementations

Question List:
1. Which accessibility options did you use when navigating the app? Check all that apply
   - TalkBack or VoiceOver
   - Text to Speech
   - Audio Descriptions
   - Voice Control
   - No Accessibility Options
2. In your day-to-day life do you use an iOS device, Android device or Both?
   - iOS
   - Android
   - Both
3. When testing the application did you use an iOS device or an Android device?
   - iOS
   - Android
4. Have you been to the Worcester Art Museum before?
   - Yes
   - No
   a. If yes, what was your method of navigating the museum? Check all that apply
      - Tour guide
      - Smartphone app
      - Museum map from website
      - Personal aide
5. Have you previously used other accessibility apps, such as the Audio Journal app or the Worcester Art Museum app?
   - Yes
   - No
   
   a. If you answered yes above, then please list which apps you have used in the past.

6. What is your level of visual or print accessibility needs?
   - No accessibility needs
   - No additional needs beyond glasses
   - Color blindness
   - Partial blindness
   - Full blindness
   - Partial print impairment
   - Full print impairment

**Numerical Ratings:**
Rate the following app features on a scale from 1 to 5, with 1 meaning the feature was unintuitive and difficult to use and 5 meaning the feature was intuitive and easy to use.

<table>
<thead>
<tr>
<th>Unintuitive</th>
<th>Intuitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

1. If you used any of the features listed, rate the ease of use and quality of those features.
   
   a. Accessibility features
      i. Android TalkBack or iOS VoiceOver
      ii. Voice Control
      iii. Text to Speech
   b. Finding art pieces and directions via the app menu
   c. Navigating to art pieces
   d. Quality of the directions provided
   e. Using voice search
   f. The overall app experience

**Open Response Questions:**

1. How was your experience using the navigation feature? Did you run into any issues while navigating to the art pieces?
2. Did the app features work like you expected? If not, which features did not work like you expected? (using the art piece menu, voice control, guided navigation to the art pieces)
3. Did you have any difficulty using the app? If yes, what was difficult?
4. Would you use this app in the future when visiting the museum? If so, would you use the navigation feature?
Appendix D: Guided Procedures

INCREASING ACCESSIBILITY AT THE WORCESTER ART MUSEUM

GUIDED PROCEDURES

1. The team will introduce ourselves and our goals for the application
2. The team will then provide our informed consent document to participants. For visually impaired participants, we will read the document aloud.
3. The team will ask participants to perform a variety of tasks while seated and while walking around the museum testing area. The tasks are as follows:

Seated tasks:

Task Set 1:
1. Open the description page for the art piece “Woman at her Toilette” through touch
   a. Press the “Art Pieces” button on the home menu
   b. Press the “European Galleries” button on the Location of Art Piece menu
   c. Press the “Woman at her Toilette” button
   d. Press the audio playback button to play a description of the piece
2. Open the description page for the art piece “Woman at her Toilette” through voice command
   a. Press the microphone button on the home menu to activate voice command
   b. Say “Woman at her Toilette”
3. Open the directions page for getting to “Woman at her Toilette” by long pressing
   a. Get to the European Galleries page by pressing buttons on the menu or by voice navigation
   b. Press the “Woman at her Toilette” button for two seconds
4. Open the directions page for getting to “Woman at her Toilette” through voice command
   a. Press the microphone button on the home menu to activate voice command
   b. Say “Navigate to Woman at her Toilette”

Walking tasks:

Task Set 2:
1. Navigate to the doorway leading to Room 201 from the hall.
2. Open the directions page for getting to “Woman at her Toilette” as outlined in task set 1, step 4 or 5 based on preference.
3. Navigate to the art piece in-person
   a. Get information for that art piece:
      i. By scanning an NFC tag
      ii. By the preferred method from either step 2 or 3 in Task Set 1.
4. Starting from the piece “Woman at Her Toilette”:
   a. Repeat steps 2-3 for the art piece “The Repentant Magdalen”