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The Autonomous Vehicle Assistant (AVA): Emerging technology design supporting blind and visually impaired travelers in autonomous transportation

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ABSTRACT

The U.S. Department of Transportation's Inclusive Design Challenge spurred innovative research promoting accessible technology for people with disabilities in the future of autonomous transportation. This paper presents the user-driven design of the Autonomous Vehicle Assistant (AVA), a winning project of the challenge focused on solutions for people who are blind and visually impaired. Results from an initial survey ($n = 90$) and series of user interviews ($n = 12$) informed AVA's novel feature set, which was evaluated through a formal navigation study ($n = 10$) and participatory design evaluations ($n = 6$). Aggregate findings suggest that AVA's sensor fusion approach combining computer vision, last-meter assistance, and multisensory alerts provide critical solutions for users poised to benefit most from this emerging transportation technology.

1. Introduction

Transportation systems that include fully autonomous vehicles (FAVs) hold the potential to revolutionize independence and mobility for people experiencing transportation-limiting disabilities. In the United States alone, this group represents over 25 million individuals with sensory, cognitive, and/or motor impairments that functionally limit travel (Bureau of Transportation Statistics, 2021). By affording additional transportation options for people who cannot or do not drive themselves, FAVs are expected to have outsized impacts for people with disabilities including increased workforce participation (United States Department of Labor, 2019) and overall quality of life (Claypool et al., 2017). Recognizing this opportunity, the United States Department of Transportation (USDOT) issued its inaugural Inclusive Design Challenge throughout 2020–22, with the goal of promoting solutions to barriers for people with disabilities across the complete trip of FAV-enabled transit. Fifty academic and industry led teams across the United States competed for a prize purse of $5 million, with solutions covering a range of cognitive, motor, and sensory challenges in current transportation systems. Ten of these teams were selected for a first-round prize and were subsequently invited to compete for the three winning positions in round two. This paper presents the cumulative research and resulting project of one of the winning second-round finalist teams focused on accessible transportation technology for people with visual impairment, the Autonomous Vehicle Assistant (AVA): Ride-hailing and localization for the future of accessible mobility.

FAVs have enormous promise for improving the independence and mobility of driving-limited populations, including people who are blind and visually impaired (BVI) and many older adults. For instance, consider that BVI people have experienced decades-long unemployment/under-employment rates of nearly 70%, impacted significantly by journey-to-work challenges and difficulties with transportation systems more generally (McDonnall, 2011). This problem will undoubtedly increase owing to the aging of the workforce, especially considering the

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strong correlation between age and visual impairment (CDC, 2020). While driverless vehicles could help address the myriad of travel-related challenges for BVI individuals, the potential solution space is complicated by FAVs being predicted to leverage ride-hailing models and services (Narayanan et al., 2020), which currently lack robust accessibility features when a human driver is no longer in the loop. Consider that BVI travelers often rely on rideshare drivers for critical wayfinding tasks to begin the trip, such as last-meter assistance to find the car or to determine that the correct car has been identified (Brewer and Kameswaran, 2019). Therefore, the question remains how BVI travelers will use FAVs when a human driver is no longer available to provide door-to-door assistance. We argue that new transportation technology is necessary that explicitly considers how to meet the needs of all users throughout the entire trip, from pre-journey planning to arrival at the intended destination. This end-to-end focus on accessibility differs both from the current emphasis of human-vehicle research, which almost exclusively focuses on in-vehicle interactions with sighted users, and from the fragmented assistive technology landscape. That is, the limited approaches to assistive navigation technology that exist generally only support discrete components of navigation (i.e., assistance in indoor, outdoor, or transportation settings in isolation) or specific tasks (e.g., accessing printed information on signage or providing route instructions), without providing a unified solution for access across the trip.

In order to address these problems, the AVA team undertook a user-driven design and development process guided by the following research questions:

1 What challenges do BVI users face when navigating to and localizing rideshared vehicles?
2 What solutions do potential BVI end-users suggest for these challenges?
3 How well do user-driven solutions (based on our team's prototypes) support door-to-door navigation?

Our process began with a series of BVI user interviews ($n = 12$) and a survey with current transit service providers ($n = 90$). These results, reviewed in Sections 2 and 3 of this paper respectively, informed the problem space for our team's approach and the iterative, user-driven design cycle, which culminated in AVA's ride-hailing and localization features. Fully reviewed in Section 4, AVA leverages a unique combination of computer vision and smartphone-based accessibility features to seamlessly assist BVI passengers during pre-journey planning, travel to pick-up locations, and vehicle entry processes. We then engaged users through a formal navigation study ($n = 10$), Section 5, and prototype and design evaluations ($n = 6$), Section 6, to assess the efficacy of AVA in supporting FAV-enabled transit among this demographic. The results of these efforts demonstrate strong support for AVA to meet the needs of BVI users in driverless transportation systems with broad impacts for future mobility..

1.1. Complete trip accessibility in FAVs for BVI users

The Complete Trip initiative by the USDOT aims to promote door-to-door mobility for all travelers by considering every segment of a trip, from pre-journey planning to arrival at the intended destination (DOT, 2020b). When considering accessibility, the core concept of the complete trip is that if any segment of the journey is unusable or compromised, then the trip as a whole cannot be completed. Indeed, emerging frameworks for inclusive transportation design emphasize the importance of considering access needs during each phase of the trip (Detjen et al., 2022). Although a small but growing body of work has begun to consider Level 5 (fully autonomous) vehicles for use among BVI users through survey, interview, and focus group methodologies, few projects have sought to design solutions for the trip itself (Dicianno et al., 2021; Fink et al., 2023b). Interview and focus group projects, for example, have indicated the need for new interfaces that translate the assistance drivers provide in current ridesharing services to FAVs for BVI users (Brewer and Ellison, 2020; Brewer and Kameswaran, 2018). Assistance can and should be provided for a range of problems that BVI users face using rideshares, including locating a ride, navigating after the ride, and accessing the underlying rideshare apps and technology (Brewer and Kameswaran, 2019; Kameswaran et al., 2018). The extant survey research has emphasized evaluating attitudes towards FAVs among BVI respondents, with results suggesting positive views of FAVs, tempered by concerns regarding safety, affordability, accessibly designed technology, and policymaking (Bennett et al., 2020; Brinkley et al., 2020). Indeed, federal and state policies surrounding FAV accessibility for BVI users has also been the focus of related research, with findings indicating policy gaps that fail to promote accessibility and on-road user testing among people with disabilities in FAVs (Brinkley et al., 2019a; Fink et al., 2021).

To address the disconnect between policy and research, as well as the dearth of research exploring tangible technology solutions for the trip, the USDOT's Inclusive Design Challenge sought to spur technology innovation and disseminate the results to policy stakeholders (DOT, 2020a). Teams built on encouraging results from the few existing examples of human-machine interfaces for BVI users like the audio and speech-input based ATLAS project (Brinkley et al., 2019b). Teams also designed new interfaces that provide end-to-end considerations for a range of motor and sensory disabilities, including people with visual impairment by providing screenreader accessible elements and voice-based control (Martelaro et al., 2022). Given the emphasis of the challenge on user engagement throughout the design process, our development of the Autonomous Vehicle Assistant (AVA) began by building on the existing survey and interview research from the literature to identify specific problem/solution pairings for scoping the project, as described in the following section.

2. Initial problem identification

To better conceptualize the problems facing our intended user group and best inform our solution, the AVA team began by distributing a survey to ITN*America* drivers (https://www.itnamerica.org/), a nationwide nonprofit transportation service for disabled and older adults, with the mean age of members being 80 years old. The logic behind this effort was that many older adults experience age-related visual impairment, with incidence rapidly increasing given changing population demographics (CDC, 2022). As people age, reduced visual acuity, contrast, and attention present significantly heightened safety risks during travel-to-transit scenarios including accidental trips, falls, and serious injury. Even minor changes in vision can lead to falls with devastating consequence (NIA, 2023); an estimated 10% loss of vision increases an individual's likelihood of falling by 20% (Reed-Jones et al., 2013). Beyond these pervasive health and safety concerns, vision loss and fear of falling can drastically limit quality of life by reducing an individual's willingness to travel independently (Curl et al., 2020). Indeed, Americans over the age of 65, in aggregate, take roughly 90% fewer daily trips than adults 25–64 (Shen et al., 2017), contributing to detrimental impacts like social isolation and increased rates of depression among this demographic (Mooney, 2003; Roberts et al., 1997). This lack of independent travel coincides with the previously discussed unemployment rates and journey-to-work challenges experienced by people with visual impairment more generally – consider that 30% of BVI people are estimated to never leave their home independently (Clark-carter et al., 1986) and that this demographic experiences a disproportionate amount of stress around safe and efficient travel (Golledge, 1993). Given the high incidence and unfortunate impact on travel of visual impairment among older adults, our goal with this initial survey was to better understand challenges facing users who rely on assistive travel services.

As a mobility-as-service (MaaS) provider, an advantage of seeking input from ITN is that its users have experience with the model that FAVs are likely to utilize (Narayanan et al., 2020), with related research indicating the benefits that MaaS models can provide for older adults in terms of mobility and independence (Bayne et al., 2021). While the majority of assistive transportation literature focuses on the client or user experience, the extant research has indicated the valuable perspective and roles that MaaS drivers can provide in relation to understanding user needs (Brewer et al., 2019). As such, of interest in the initial survey was determining and validating the problems derived from the related research that users may face when navigating to a summoned vehicle, including identifying falling hazards, finding the correct vehicle, and localizing its door handle. This section provides the methods and results for this effort.

2.1. Methods

The survey instrument developed and used in this work (Appendix A) was deployed remotely by Qualtrics (https://www.qualtrics.com/) to 331 ITN*America* volunteer drivers geographically dispersed across the country in nine states where the company has its most established network and driver base: Maine, Connecticut, Pennsylvania, Delaware, Tennessee, Kentucky, Oklahoma, Missouri, and California. The survey resulted in 90 complete responses. Questions included four 5-point Likert style questions (1-Strongly Disagree to 5-Strongly agree) assessing the challenge for passengers to navigate to the vehicle, avoid obstacles on the way to the vehicle, find the vehicle, and find the door handle. These items were derived from the existing ridehailing literature (as reviewed in Section 1.1) and the personal experience of one of the authors on this paper who is himself congenitally blind. Participants were also asked two open-ended, long-answer questions that aimed to identify how drivers communicate with passengers when challenges occur during navigation to the vehicle, as well as what information is effective.

2.2. ITNAmerica survey results

Results from the survey validated the presence of challenges during navigation to summoned vehicles. Importantly, 62 (69%) of ITN drivers generally agreed (53 somewhat agreeing and 9 strongly agreeing) that navigating to the vehicle can be challenging for their passengers and 59 (66%) generally agreed (with 53 somewhat agreeing and 6 strongly agreeing) that avoiding obstacles or potential hazards can be challenging for passengers. Although fewer participants agreed that finding the vehicle is a challenge (31 (34%)), 'somewhat agree' was the most frequent response with 27 responses, followed by neither agree nor disagree (22), somewhat disagree (20), strongly disagree (17), and strongly agree (4). Finding the door handle was rated as the least problematic, with 41 participants generally disagreeing (46%) vs. only 29 (32%) generally agreeing that this was a problem for their passengers. This result may well have been impacted by ITN passenger visual status, since many older adults with age-related visual impairment retain usable vision. Fig. 1 summarizes these data.

When considering the long-answer questions, all but four participants, 86 (96%), reported that they use some form of additional guidance to help passengers to the vehicle, with verbal and audio-based communication being the most common approach. We interpret this finding as providing support for the development of new accessible approaches to FAV-related technology that incorporate multimodal assistance during travel-to-vehicle tasks, as developed and studied here in AVA. Many drivers, 51 (57%), also noted that it was helpful to provide some information about the vehicle (e.g., size, color, make, and/or model of the vehicle) to assist passengers in locating the vehicle and to prepare for entering it safely depending on its size or height.

3. Problem-solution pairings

Building on the problems identified from the driver survey (Section 2), our team conducted a series of user interviews with blind and visually impaired (BVI) participants ($n = 12$). Our goal was to explore the pre-journey and travel to transit needs of both BVI users and older adults and to identify problems that should be considered in our development of AVA. Participants in these initial interviews brought to light several unmet needs in future FAV services and suggested solutions that helped focus AVA's design.

3.1. Methods

Twelve participants were recruited from our group's established network of BVI participants who have previously participated in our research or who responded to an email advertisement that was distributed to these contacts. Participants represented a broad range of age ($M = 44.83$, $SD = 17.15$) and vision loss (details are provided in Table 1). The interviews were approximately thirty minutes in length and followed a semi-structured format with both prepared questions and follow-up questions from the researchers (prepared questions can be found in Appendix B). Questions centered on participants' day-to-day

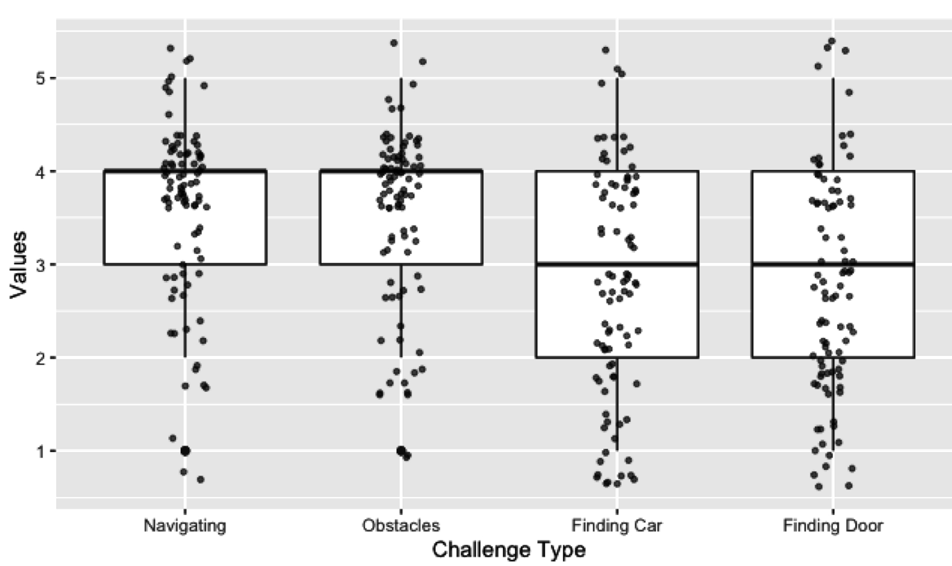

Fig. 1. Likert scores for each challenge type question in survey with ($n = 90$) transportation service drivers.

Table 1
Summary of Participant Demographics and Provided Problem-Solution Pairings.

Participant	Age	Extent and Etiology	Specific Problems	Participant Proposed Solutions
1	43	Low-partial vision. Glaucoma.	Difficulty finding vehicle when it arrives, especially in crowded environments. Obstructions in the way of vehicle entry. Confirmation that it is the correct vehicle.	A way to self-identify their impairment to the vehicle to receive additional assistance. A way for the vehicle to "talk the passenger in" like a human driver.
2	69	Only light sensitivity. Retinopathy of prematurity.	Locating vehicle door, avoiding hazards on entry, silence of electric vehicles.	A way to elicit a noise from the vehicle. A way to confirm the correct vehicle has been found.
3	66	Total blindness. Retinopathy of prematurity.	Locating vehicle door, entering the vehicle properly given its size and potential hazards in the way, knowing if at the correct vehicle.	A way for the "AI to talk to me" not only to confirm at the correct vehicle but to alert about environmental hazards.
4	64	Light perception. Unknown etiology: Autoimmune or viral process.	Knowing what type of vehicle is for guide dog and to determine how to enter, navigating to the vehicle, knowing "which one is mine".	Feedback from a device to know if "hotter or colder" from vehicle and an auditory confirmation when next to it. Highlight door runners and other entrance assistances on larger vehicles.
5	38	Some light perception. Lebers congenital amaurosis.	In busy areas, it will be difficult to know where the vehicle is, no one to "roll the window down" and confirm arrival, silence of electric vehicles.	A tone that the user can hear with a hotter and colder pitch that increases in frequency when oriented to the vehicle. Vibration to support sound.
6	35	Partial vision. Optic nerve atrophy.	How the vehicle will locate the passenger and vice versa, accuracy of GPS.	Confirmation of GPS location with an accessible map. An audio confirmation of correct vehicle. Ways to interact with vehicle if it arrives in unpredicted location.
7	21	Legally blind. Partial distance vision. Neurofibromatosis.	Trying to locate the car. Being able to distinguish which is the correct car so "I don't get in the wrong one."	Auditory sound to let you know where the car is. Auditory confirmation of correct vehicle.
8	30	Total blindness in one eye. 8° of vision in the other. Retinitis pigmentosa.	Trying to locate the car. Getting in the wrong car. Knowing it's the right one.	N/A
9	32	Some light perception. Lebers congenital amaurosis.	Identifying the vehicle. Knowing where the vehicle is. Knowing which door to use.	Using a sound to identify the vehicle. Participant mentioned using new ultra-wideband for directions to the door like "15 feet at 2′oclock."
10	48	Light perception and some high-contrast vision at close distances. Lebers congenital amaurosis.	Correctly locating and identifying the right vehicle. Being able to identify hazards between location and the vehicle	A way to know how far away the vehicle is and a clear identification of the pick-up location. Something that allows communication with the vehicle.
11	27	Total blindness. Posterior-polymorphous corneal dystrophy.	Finding a vehicle. Knowing which vehicle is yours. Getting into the vehicle.	Pressing a button to honk the horn or have the AI talk.
12	65	Total blindness in one eye. 20% peripheral vision in the other. Glaucoma.	Being able to explain where exactly you want to be dropped off or picked up.	Asking the car to park in a particular location.

experience with transportation, what challenges they faced, and how they imagined FAVs could best address these challenges. Our research team used transcriptions of the recordings (with informed consent from participants) to discuss, summarize, and couple problems and solutions each participant suggested, as provided in the results section below.

3.2. User interview results

The user interviews resulted in a set of solutions that participants proposed to guide AVA's design. Summarized in Table 1, the problem-solution pairings included ways to safely navigate to the vehicle, avoid obstacles on the way, find the vehicle, and find the door handle. Participants prioritized solutions that incorporated multisensory interaction with audio, voice, and augmented visual information. Participants also noted new ways to give the vehicle information (e.g., where to park) and to receive information (e.g., if it arrived in an unpredicted location).

4. The Autonomous Vehicle Assistant (AVA)

Using the problems identified from both the transportation service driver survey and the user interviews, as well as the proposed solutions in the interviews, our team began designing initial prototypes for AVA. The starting tenet of our project argued that successful travel involving FAVs must incorporate a unified, end-to-end accessibility solution. As previously mentioned, this differs from most assistive navigation technologies, which provide a fragmented travel experience (e.g., isolated indoor, outdoor, or transportation assistance). By contrast, our goal was for AVA to represent a robust, complete trip solution that was designed from the onset to be accessible and highly scalable. Another innovation of our approach was the use of a multisensory user interface (UI). Whereas most assistive technology uses only one mode of information (e.g., speech UIs for BVI users) to provide information access, we modeled AVA's design using suggestions from our user interviews and best practices related to multisensory design. AVA's multisensory, bio-inspired UIs were designed to promote inclusion across the spectrum of ability, as all information input/output between the user and system could be tailored to meet user needs, abilities, and preferences.

4.1. Technical approach

To support the first stages of FAV travel, AVA enables a fully accessible ride summoning and travel-to-transit experience that leverages a suite of *Assistive Navigation* and *Obstacle Avoidance* features. For ride summoning, we developed a user profile system (Section 4.1.1) that not only individualizes the accessibility requirements of the UIs across these functionalities (e.g., speech, haptic, and visual settings), but also for determining interaction between the user and the FAV once it arrives. The Assistive Navigation Module (Section 4.1.2) is engaged upon vehicle arrival and guides users using a novel sensor-fusion approach, providing multisensory directions and real-time navigation cues. To do so, AVA leverages ultrawideband (UWB) sensors, which increase distance and direction precision over traditional GPS-only approaches. This is important because GPS systems equipped on modern smartphones lack precision (Merry and Bettinger, 2019), which present significant problems when attempting to navigate to and localize discrete objects without the use of vision. To improve safety and situational awareness, AVA also uses a unique real-time computer vision solution (Section 4.1.3) to detect and recognize a user-driven set of navigational hazards (e.g., ice, cones, guy wires, overhanging branches). An object detector based on YOLOv5 (Jocher et al., 2022) was trained on a custom dataset and deployed on mobile phones to achieve real-time object detection (training methods and testing results are provided in full in Section 4.1.3). Information from the object detector is conveyed via audio descriptions and haptic alerts to complement existing mobility aids (i.e., dog guide or long cane), while high-contrast visual bounding boxes are superimposed to support people with low-vision. These bounding boxes are designed to augment environmental hazards for people with usable vision to reduce the risk of trips or falls while traveling to the vehicle. Supporting people across the continuum of visual impairment, from low-vision and residual functional vision, to those with no usable vision, is both a practical and critical aspect of AVA given the wide range of vision loss for this population and the previously discussed high incidence of age-related visual impairment, prevalence of falls among older adults during travel-to-transit, and opportunity to improve transportation outcomes among this demographic using FAVs.

4.1.1. Pre-Journey planning

Development began with the design and prototyping of AVA as an accessible ride-hailing solution for FAVs. The underlying app and architecture is developed using XCode and Swift, a design decision that leverages the numerous accessibility features available in Apple's iOS ecosystem and maximizes inclusion of our target community, where over 70% of BVI users use iOS (WebAIM, 2021). The overall ride ordering process works similarly to current ride-hailing platforms: users enter a destination via a VoiceOver compatible text entry field, request a ride, and wait for it to arrive. Fig. 2 (left) depicts the ride-hailing screen from an early AVA prototype.

An important innovation of this initial work was our team's design and validation of AVA's rider profiles. Depicted in Fig. 2 (right), the profile system enables users to convey information to the FAV service

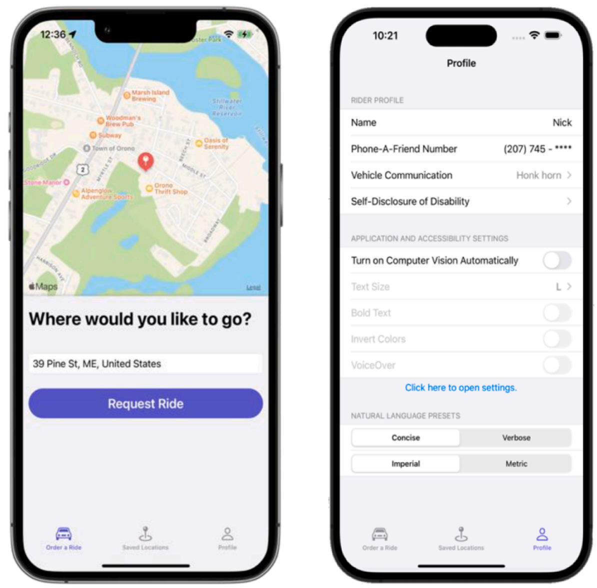

Fig. 2. (left): A view from the AVA ride hailing screen. Fig. 2 (right): A view from the AVA rider profile screen.

that not only aids the user experience by feeding directly into the phone's native accessibility settings (e.g., changing text size, color, and VoiceOver settings), but also specifies aspects important to subsequent parts of the journey and communication between the user and FAV. For example, if a user indicates they have a visual impairment, the FAV can 'know' that it must provide more information about exact vehicle location and identification, so the user can easily find and uniquely identify their vehicle (or send a larger vehicle if they indicate having a guide dog). These issues were frequently mentioned as concerns in our user interviews (provided in Table 1). As it will no longer be possible to communicate with human drivers for assistance using FAVs, profile options can also help determine presets for the subsequent Assistive Navigation component (AVA's process for assisting users to the ride once it has arrived). This is done by changing whether instructions are concise or verbose, given through language, haptics, using the enhanced computer vision overlays (or all of these), as well as other multisensory UI variants. These options also control how and what information should be presented to the user once inside the vehicle.

4.1.2. Assistive navigation

Once a ride has arrived, users are prompted to begin AVA's assistive navigation mode. Assistive navigation consists of overlapping positioning sensor data, real time navigation features, and a multisensory UI (i.e., high contrast visual information, natural language descriptions, and haptic cues) to make finding an FAV safer and more accessible to people with visual impairments. The navigation component is designed to guide the traveler from the beginning of their route (i.e., from the door of their house, entrance of a store, designated pick-up spot at the airport, etc.) to the vehicle's door handle. To do so, AVA navigation includes a suite of wayfinding and object detection features that dynamically update based on the user's real-time distance to their ride. Fig. 3 provides a high-level overview of the user interface elements and sensor fusion used to support navigation assistance.

Navigation begins by finding a route between the user's current position and the vehicle's arrival location. For routing directions, we made use of the iOS directions in the MapBox API (Mapbox, 2023), which updates its mapping data from the open-source OpenStreetMap (OSM) database (OpenStreetMap, 2023). This API enables us to provide visual, auditory, and haptic feedback based on the route to guide the user to the vehicle and to customize any changes needed to update the routing information in real time. Customized directions are snapped to

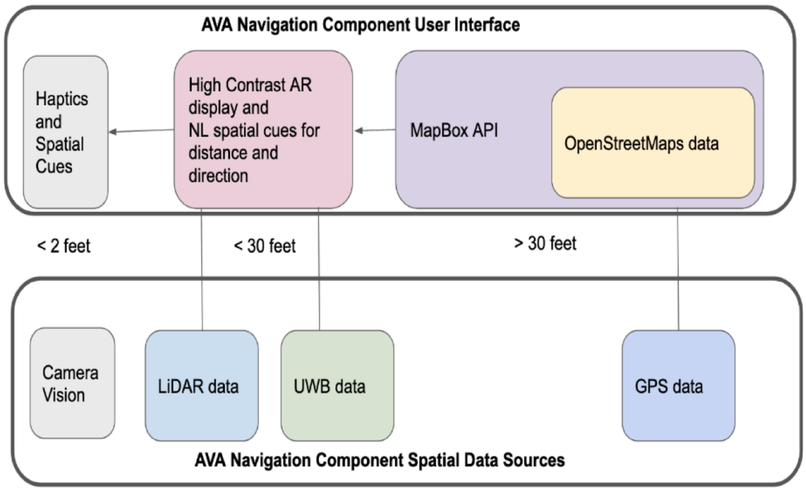

Fig. 3. High-level architecture of the AVA navigation component.

known sidewalks and pedestrian paths, with GPS used to determine where the user is located along the route. OSM also has a point-of-interest feature which takes the user's current location and can download data on nearby OSM data objects. This enables AVA to provide the user with distance and direction to the vehicle, which is presented first through a verbal pre-navigation overview and then continually updated thereafter. Previous studies have found that BVI users often benefit from these pre-navigation route summaries but would also like the ability to customize the level of detail, which we have implemented in AVA (Aziz et al., 2022).

AVA's route-finding and initial pre-journey summary rely on OSM and GPS. However, as mentioned previously, the accuracy of Assisted GPS (A-GPS) systems used on modern smartphones lack precision, with horizontal accuracy between 5 and 8.5 m and vertical accuracy between 6 and 12.5 m (Massad and Dalyot, 2018; Zandbergen and Barbeau, 2011), which is inadequate for supporting BVI localization and targeting. For instance, existing outdoor A-GPS systems do not have the precision to support targeting of environmental elements with small spatial extent, e.g., a vehicle's door or its handle. By contrast, the UWB sensor used in AVA development (Decawave now Qorvo DM3000EVB) allows for short-range communication under 10 m, distance measurements accurate to within 0.1 m accuracy, and angular direction measurements accurate to 5°, all of which are critical for last meter localization (Dotlic et al., 2017). UWB sensors also use a radio signal with both a high frequency (500 MHz) and a high bandwidth (2–3 GHz) that makes them less susceptible to interference compared to Bluetooth beacons and GPS, which can be influenced by multipath errors caused by the signal bouncing off of buildings, trees, and the ground. The main advantages of UWB are its sub-centimeter accuracy, resistance to interference, and ability to provide directional information: while other technologies may have access to one or another of these (e.g., Bluetooth low-energy beacons), none but UWB have the advantage of all of these features. These combined advantages make UWB ideal for AVA, since it is accurate enough to guide a user to the vehicle and target a specific door handle, while also being sufficiently reliable to be used in a human-centered system, where near-perfect reliability is critical. As our interviews reenforced, BVI travelers want to be able to quickly and accurately localize the door handle without the need to search around with their hand on the vehicle, which is perceived as awkward and potentially stigmatizing, as well as being dirty. This last-meter localization is a known challenge for smartphone-based targeting among BVI users (Manduchi and Coughlan, 2014), which pushed our team to explore our sensor-fusion approach.

One limitation of UWB is that both distance and directional accuracy decrease when the sensor is out of line of sight, including when being blocked by obstacles (e.g., people, other vehicles, or walls). In practice, direction measurements are rarely available outside of a 30–40° deviation from the camera module, which greatly limits the range in 3D space where the UWB sensor can be effective. To compensate for this, AVA uses a solution that combines UWB measurements with Apple's Augmented Reality (AR) feature, which is supported by LIDAR, Camera, Gyroscope, and Accelerometer data to keep track of the UWB position even when it fails to provide accurate distance and direction data. Taken together, AVA's novel sensor-fusion approach is a significant improvement over solutions relying exclusively on traditional GPS with broad implications for supporting inclusive navigation.

The visual UI used in AVA's assistive navigation component is designed using best practices for multimodal systems supporting low vision users (Giudice, 2018). The visual interface uses high contrast, large font, with simple text cues to alert the user to the arrival of the FAV and to show its distance and direction information, depicted below in Fig. 4. The visual cues are coordinated with customized natural language spatial information for conveying distance and direction, which are provided in quantitative metrics (> 2 feet) as well as linguistic concepts (clock positions, "nearby", "within", etc.). This description logic is consistent with what BVI people are taught in current orientation and mobility (O&M) training and congruent with current theories from multimodal spatial cognition (Giudice and Long, In Press). An important innovation here is that the auditory information is presented via spatialized audio (i.e., the audio is heard as if it is coming from a specific 3D location in space that corresponds with the distance/direction of the video) when used with earbuds or headphones, which again was a design decision derived from the multimodal spatial cognition literature. That is, spatialized audio cues have been demonstrated to best support route guidance for BVI navigators (Loomis et al., 1998) and to increase navigation performance by as much as 50% over non-spatialized speech-only cues, while also reducing cognitive load (Giudice and Tietz, 2008; Klatzky et al., 2006). When the user nears the vehicle, the interface provides an additional set of confirmatory haptic cues that increase in intensity based on proximity, finally sending a pulsing signal when the door handle is located.

4.1.3. Obstacle detection and avoidance

Our initial survey and user interviews (summarized in Section 2 and 3), elucidated that BVI users frequently encounter obstacles and potential hazards when navigating to current transportation and desire accessible information relating to those obstacles. As such, throughout assistive navigation, users have the option of turning on AVA's obstacle avoidance module that utilizes a unique computer vision solution implemented using the phone's onboard camera. Information from the

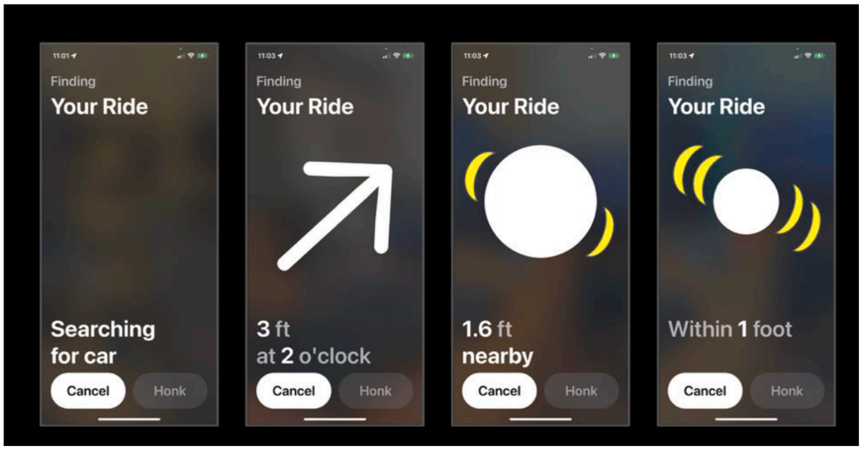

Fig. 4. AVA navigation component interface interactions at near distance to door handle localization.

object detector is passed to users via multisensory audio descriptions and haptic alerts to complement existing mobility aids (i.e., guide dog or white cane).

AVA's obstacle detection leverages a deep neural network object detector that classifies a set of common objects experienced in day-to-day travel: traffic cones, overhanging branches, guy wires, and ice. Based on additional user feedback, the solution also detects door handles to assist in the final meter of travel and support targeting behavior. To work, the phone's camera collects video frames in real-time as the user walks along the path. These frames are sent to AVA's deep neural network model that runs on-device in the iPhone's processing core for dynamic obstacle detection. The object detector based on YOLOv5 (Jocher et al., 2022) has three main components: a backbone, a neck, and a head. Given the input frame, the backbone first aggregates and forms image features at different granularities with a convolutional neural network (Bochkovskiy et al., 2020). The neck then mixes and combines the features of various granularities from the backbone with a series of DNN layers. Finally, based on the combined features from the neck, the head performs the object detection and outputs the size and location of bounding boxes of the detected obstacles with its corresponding class predictions (Redmon et al., 2016).

To train the detector, we first built a dataset with images of door handles, traffic cones, overhanging branches, guy wires, and ice. We collected 1000 images in total with 200 images for each object and created the bounding boxes and labels for the objects in each image. In the dataset, 900 images were used for training and 100 images were used for testing.

YOLOv5 has different versions (such as large, medium, small, etc.) with different model sizes. To perform real-time detection on a resource-limited mobile phone, we used a YOLOv5s model, which is a small version YOLOv5 with only 7.2 M parameters and 16.5GFLOPs of computations for input images with size 640 × 640. The advantage is that it can achieve real-time detection with 34 frames per second (FPS) on an iPhone. During model training, we adopted various data augmentation techniques (such as mosaic augmentation, copy-paste augmentation, mixup augmentation, etc.) to improve the model's generalization ability and reduce overfitting. To enhance the model's performance, several sophisticated training strategies were adopted, such as multiscale training, warmup and cosine learning rate scheduler, exponential moving average, mixed precision training, etc.

After training, we tested the model with our test set. As shown in Table 2, the detector can detect and classify the objects accurately with high precision and recall. Also shown in Table 2 are the mean Average Precision (mAP) under different thresholds of Intersection Over Union (IOU). The mAP@0.5:0.95 (i.e., the average precision for IOU from 0.5 to 0.95 with a step size 0.05) is 0.695, demonstrating that the objects are accurately identified and located with bounding boxes. Although we adopted a small version YOLOv5, it detects reasonably well in practice, as the dataset is still small with a limited number of classes and images, meaning there is no need to use more complex models. In the five target objects trained, the traffic cones and ice are detected more accurately with relatively higher mAP@0.5:0.95 since the features of the two objects (such as the cone shape and eye-catching colors) are easy to recognize. The detection performance of the overhanging branches is somewhat worse, with relatively lower mAP@0.5:0.95, since the branches are more variable due to many different tree species, tree ages, the season, etc. As such, more data may be needed for the model to extract their shared features for greater precision.

Table 2
Detection Performance of the Trained Detector on the Test Set.

Class	Precision	Recall	mAP@0.5	mAP@0.5:0.95
All	0.957	0.942	0.972	0.695
Door Handles	0.952	1	0.996	0.679
Traffic Cones	0.938	1	0.996	0.804
Guy Wires	1	0.958	0.996	0.625
Overhanging Branches	0.9	0.75	0.892	0.582
Ice	0.959	1	0.995	0.813

When the obstacle is detected, it is labeled with a bounding box together with the class label (e.g., traffic cone, door handle, etc.) that is also delivered via dynamic clockface positions using spatialized audio. That is, as the user moves the phone, the clockface positions are updated (and spoken) in real time along with their distance from the user. The high-contrast bounding boxes (depicted below in Fig. 5) are included to promote access among the high percentage of BVI users with usable vision, e.g., most older adults. This may sound like an obvious design decision, but it is actually quite rare in the design of assistive navigation technology. Despite the huge range of visual impairment, from mild to total vision loss, the preponderance of technology design for BVI users focuses exclusively on nonvisual interfaces aimed at supporting people with total blindness, a design decision that ignores the 90–95% of legally blind people with residual functional vision (see Giudice, 2018 for discussion). Incorporating visual information as a redundant, multisensory component of our UI increases inclusion by avoiding this common design flaw. Further expanding the multisensory user experience, Fig. 5 also depicts two buttons in the Obstacle Avoidance module: "Phone" and "Honk."

The phone button is an important error-handling feature that allows users to call a pre-defined friend in case there is an emergency, which is registered via the "phone-a-friend" field in the rider profile (Fig. 2). The "honk" button is a customizable UI element that enables users to elicit multimodal cues from the vehicle by either sounding the horn, flashing the lights, or both. These design decisions were added in direct response

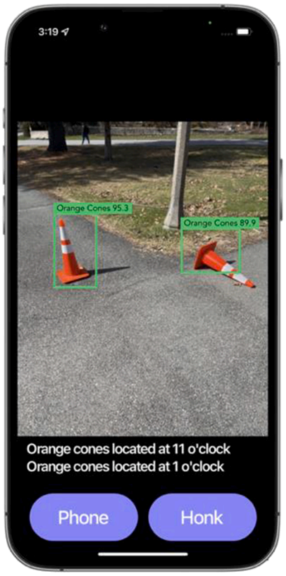

Fig. 5. AVA's Obstacle Avoidance module.

to user input and feedback we received throughout user interviews and are important as they allow direct targeting of the vehicle by the user as they navigate toward it. We believe that the ability to trigger known perceptual cues to indicate vehicle location is an important feature that couples the app to the physical environment (i.e., the user's position relative to the vehicle's position) and will be critical for localizing FAVs when there is no longer a human driver to provide this assistance.

5. UWB navigation study

To evaluate the extent to which AVA performs its intended functions, our team conducted a series of user tests and prototype evaluations. These user studies investigated both the accessibility of AVA's UI elements and its practical use in guiding users from their point of origin to a summoned vehicle. Results, discussed in the following, suggest strong performance, usability, and potential for adoption among the target user group. As discussed in Section 4, AVA's Assistive Navigation component is designed to guide users directly to the vehicle door handle by leveraging a unique handoff between GPS-based navigation and UWB last-meter guidance. The goal of this study was to evaluate the effectiveness of our UWB approach between the user's point of origin and the vehicle arrival location compared to traditional GPS-only navigation.

5.1. Methods

The study protocol consisted of several study phases, which began with participants taking a pre-study survey to capture basic demographic data. Sighted participants ($n = 10$, self-reported $F = 9$, age 18–22) were recruited from a small liberal arts college in the United States. All were blindfolded during the study, a common approach in early-stage human-subject research exploring the feasibility of nonvisual applications (see Giudice, 2018 for discussion).

A practice phase with the app and blindfold was utilized to familiarize participants with the process and ensure that they were comfortable. After this phase, participants were tasked with navigating to the door handle of a nearby vehicle (20 feet) using AVA's UWB or GPS sensor, depending on the experimental condition. The navigation trials took place outside of the science center on campus. Participants were led out of the building with a blindfold and positioned at the origin point (Fig. 6) approximately 20 feet behind the target vehicle (2019 VW Tiguan sedan).

Participants were instructed that they would need to use the natural

Fig. 6. Origin, destination, and intended route used during the navigation study.

language (NL) directions from the AVA navigation app to find the target rear car door handle as quickly and accurately as possible. The participants were blindfolded inside the building and handed the phone when they reached the origin. A sighted guide was situated behind them with a hand on their shoulder to provide a safety measure and let them concentrate on navigating using the phone as the primary source of information to find the door handle. The app would then send either the GPS-based directions or the GPS+UWB-based directions depending on experimental condition. The order of the two trials was randomized and participants were assessed on their ability to navigate successfully and on their task completion time (seconds). Finally, a post-test was conducted asking about user satisfaction with the app functionality and features.

5.2. GPS navigation results

In the GPS trials, all 10 participants failed to complete the task of navigating to the vehicle's door handle (0% task completion). One participant made contact with the vehicle but did not find the door handle because the GPS indicated that they were not in fact at the vehicle, causing confusion. Measurements from the GPS sensor were highly variable, with distance to the vehicle varying between 5.7 to 71.9 feet and angular direction to the vehicle varying 215.7° (Table 3), despite participants starting from the same location and orientation in each trial for the designated route.

Applying the GPS data to an aerial view of the experiment location shows where the app believed the user was relative to the vehicle (Fig. 7). The blue line takes numerous turns away from the vehicle and does not converge on a particular location, which mirrors the paths

Table 3
Descriptive Statistics for GPS data.

GPS	n	M	SD	Range
Starting Distance (ft)	10	30.0	20.2	5.7–71.9
Starting Direction (°)	10	−65.7	80.0	(−172.8)–80.0

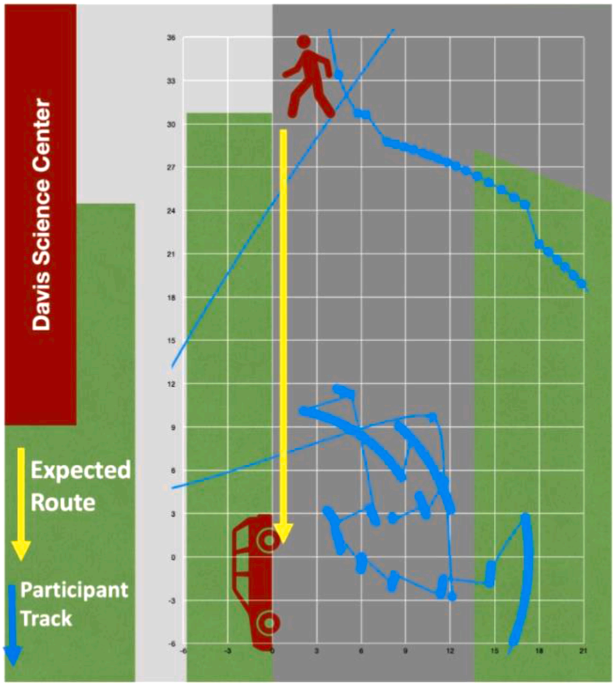

Fig. 7. Single participant GPS sensor data (units in feet).

participants took who were unable to make contact with the vehicle.

Taken together, these data illustrate that GPS alone was not sufficient for navigation to the vehicle. Trials were stopped when the researcher determined the participants were either 1) far enough out of range of the car to not be able to use the inaccurate GPS signal to find their way back to the car, or 2) they had traveled completely in the wrong direction and were heading into dangerous walking conditions. The GPS trials were stopped by the researcher on average at 55.3 s (range 38–78 s).

5.3. GPS+UWB Navigation Results

In the GPS+UWB trials, 9 out of 10 participants successfully navigated to the target door handle of the vehicle (90% task completion). From the start of the trials, participants completed the navigation tasks with the help of the UWB sensor in an average of 48.8 s (range 33–75 s). This is in comparison to 17 s (range 16–18 s) for a baseline non-blindfolded walk to the vehicle from the same starting position. This baseline non-blindfolded time is considered optimal performance and does not account for the hesitancy often associated with sighted participants being blindfolded. The sole participant that failed to find the door handle using the help of the UWB sensor self-reported in the post-study survey that they did not fully understand how to use the clock directions delivered by AVA, despite being able to complete the practice session in an indoor setting.

When considering the accuracy of the UWB sensor, the starting distance ranges were within 21 to 29 feet away from the vehicle as measured by the UWB and the starting directions varied by just over 60° (Table 4).

Applying the UWB data, indicated by the blue line, to an aerial view of the experiment location, shows where the app believed the participant was relative to the vehicle (Fig. 8). The route converges on the vehicle within the last meter, unlike the GPS data which did not converge on any particular location.

Table 4
Descriptive Statistics for UWB Data.

UWB	n	M	SD	Range
Starting Distance (ft)	10	25.1	3.2	21–29
Starting Direction(°)	10	6.4	23.9	(−5.53) - 56.74

Taken together, the marked difference in navigation task completion results between the UWB and the GPS sensors are unequivocal and provide strong support for our decision to use the layering model of sensor information to provide AVA with UWB distance and direction data in addition to GPS data.

5.4. Post-experiment survey results

The post-experiment survey consisted of six open response questions that gauged the helpfulness of the app, which navigation cues were most helpful or confusing (e.g., NL audio directions, spatialized audio signals, vibro-haptic cues), and overall satisfaction with the spatial information provided by the app. Question responses were open coded based on common themes such as specific app feature satisfaction, points of confusion, and multisensory spatial information cues. Aggregate results suggest participants were satisfied overall with the functionality and features of the app. Participants specifically mentioned the utility of the natural language spatial updating features with both distance and direction of the target, the use of clock-based references, and the haptic confirmation signal communicated by the phone when the door handle was within 1 meter in the GPS+UWB trial.

Some illustrative user comments included:

- P3: “Hearing consistent updates on the location of the car relative to me was the most helpful feature. It was also nice to use clock-based directions because I don’t know right and left.”
- P4: “The most helpful feature was the haptic response when we are facing the correct direction and when we are close to the handle.”
- P5: “The audio descriptions were helpful because they gave me a magnitude (sic direction) and direction to help direct my path. Also, the haptic feature was nice to help me know I was on the right path as I was moving. It took me a minute to get familiar with the clock-

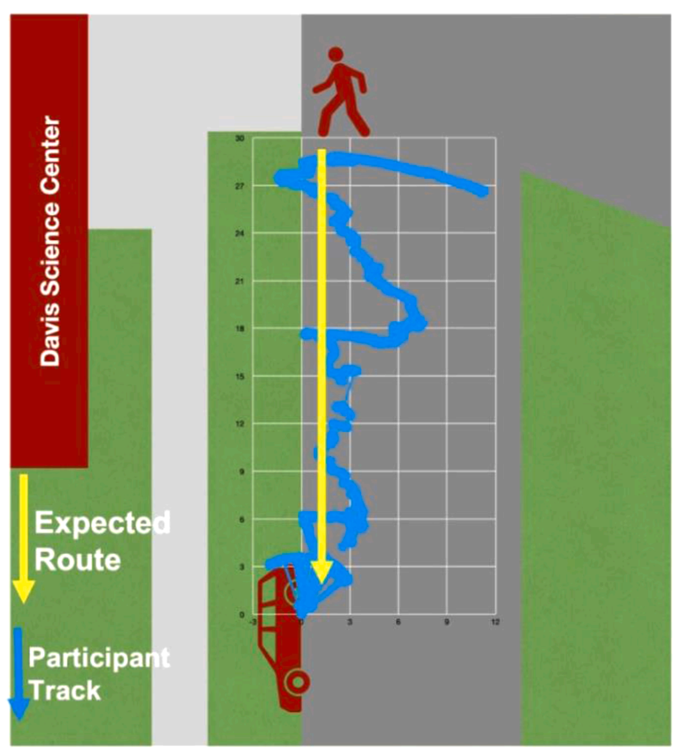

Fig. 8. Single participant UWB sensor data (units in feet).

based direction descriptions, but they were really helpful at the short range."

Participants shared several parts of the app that they considered to be the most confusing or difficult features. Relevant responses included that the speed at which directions were given was often too fast and difficult to process quickly, their fear of falling or tripping (even with a research guide to steady them), the combination of the multisensory information when within a meter of the target door handle, and knowing exactly when to reach for the target door handle.

Illustrative comments:

- P9: "The fact that the system interrupts itself mid-direction to change itself. Maybe it should give directions less frequently? Also nervous about elevation changes on the ground and tripping."
- P3: "It was hard for me to find the doorhandles when I got to the car. Also, it's difficult to intuitively understand when one is close enough to begin to reach for the car handle."
- P6: "How quickly [AVA] said the next command so it was hard to hear what she said."

Overall, these data demonstrate that participants valued both the spatialized updating and the haptic information provided by AVA, as well as the natural language navigation route overview prior to beginning the navigation task to find the vehicle. They reported that the speed of the direction and distance information given by the voice-based assistant was often difficult to process quickly and there was perhaps too much overlap in the haptic and audio information when within less than 1 m to the target door handle. Taken together, the quantitative trial results and the qualitative survey results of the blindfolded sighted participants ($n = 10$) provide strong evidence that the sensor fusion approach (GPS+UWB) adopted to provide layered multisensory spatial information (NL audio, vibro-haptic, spatialized audio) in the AVA app was sufficiently effective for a subsequent prototype evaluation with BVI users.

6. Task-driven prototype evaluation

6.1. Methods

Given the encouraging results from the Assistive Navigation user study with blindfolded sighted participants (Section 5), our team undertook a full prototype evaluation of AVA covering the breadth of its features with ($n = 6$) blind and visually impaired users. Participants for this study (age 21–65, 3 guide dog users, 3 cane users) were drawn from the same group who gave input in our initial interviews (Section 3) and represented a wide range of visual impairment, from legally blind with significant residual vision to total blindness (see participants 7–12 in Table 1). Participants were tasked with using AVA across its intended functionalities and began by exploring the rider profile, then initiated the assistive navigation module, identified and avoided an obstacle on the way to the vehicle, and concluded by reaching the door handle. Throughout the trip, the study utilized a think-aloud method (Jaspers et al., 2004), where participants were asked to provide a stream of consciousness relating to two key aspects: 1. The perceived usefulness of AVA's features and functionality and 2. The accessibility of the user interface elements. This qualitative input was intended to provide important supplemental information evaluating AVA in addition to the data resulting from a navigation task participants engaged with after providing their thoughts on the profile. The navigation task involved using AVA to navigate to a vehicle in an unfamiliar location (i.e., parked beyond a different door and in a different parking area from where they arrived to participate in the study). The route to the vehicle was highly similar to that used in the earlier navigation trials (as provided in Fig. 6). Participants were told to imagine that they had summoned a fully autonomous vehicle and that they were to walk to it 'as if' they were going for a ride. The process began by leading participants to the exit of the building before they heard a pre-navigation summary describing the vehicle's location in relation to their own. Participants then began navigating to the vehicle using the natural language directions provided by AVA's Assistive Navigation module to complement their normal mobility aid (e.g., cane or dog). To increase the realism of the task, and to evaluate the accuracy and utility of obstacle avoidance, a traffic cone was positioned as an obstruction in the center of the path. Participants were told by the experimenter that there might be obstacles in the path that they should identify out loud and navigate around, but not what type of obstruction or where it might be located on the route. The experimenter measured if the obstacle was identified and avoided, as well as if the participant reached the vehicle's door handle without assistance. After completing the task, participants were engaged in a short post-test interview to complement the task usability results.

6.2. Prototype evaluation results

Both qualitative and quantitative results from the prototype evaluation demonstrated support for AVA's intended functionality as an accessible FAV summoning and localization tool for our core user demographic. When engaging with the user profile, all six participants were able to complete the fields and submit the profile in its entirety. Feedback from all participants suggested that the profile was useful and accessible. Furthermore, all participants indicated they would be likely to use the profile system (despite it being optional), given the customization that it enables for the UI and interaction with the vehicle. The think-aloud method also revealed several useful insights. Importantly, when implementing this evaluation, the AVA "Phone-A-Friend" option only allowed one entry. This initial decision was based on our conceptualization of an emergency contact being an important safety feature. While participants mentioned that they liked this feature, it was suggested that we undertake the "hotlist" approach, where multiple numbers can be registered in case someone is unavailable to answer. Participants also suggested that this feature could tie into existing video-based accessibility services with live agents (e.g., Aira: https://aira.io).

After exploring the profile, participants undertook the navigation task. Importantly, every participant identified the cone correctly and navigated around it successfully (without contact) based on AVA feedback. Since we continued to utilize the think-aloud method throughout the navigation task, participants also pointed out that they could use AVA to identify the overhead branches along the path. While not part of the task itself, the enthusiasm that was evident during this process was encouraging of the additional benefits to situational awareness that AVA is able to provide and motivated our subsequent focus on expanding the set of recognizable hazards to include, for example, guy wires and other head-height or overhanging objects that are traditionally extremely hard to detect using standard mobility aids (Giudice, 2018). Once around the cone, participants proceeded to the vehicle using AVA's unique handoff between GPS-based and UWB-based sensors in the Assistive Navigation module. Again, all participants used AVA to find the vehicle and door handle. Taken together with the earlier UWB navigation findings, these results demonstrate strong evidence supporting AVA's intended functionality.

Finally, during the post-test interview, participants were asked if they would be likely to use AVA to summon and navigate to FAVs. Four of the six participants definitively said they would use AVA, while the other two participants noted that they would use AVA in certain situations (e.g., at night or in an unfamiliar location). Following these answers, we asked participants about other potential implementation scenarios. A consistent response across participants was the desire for AVA's features to be included in other applications. Representative quotes included:

- P3: "It could be a plugin app that adds those features directly to Uber or Lyft, so you don't have to keep going back and forth."

- P5: "I'll almost always take one app that does 5 things pretty well over 5 apps that do the same thing really well"
- P2: "I don't want to be using multiple different applications if I don't have to. It becomes annoying going back and forth between things."

These results, as well as the enthusiasm for AVA to detect a range of objects and hazards during typical navigation, inform future directions for AVA that focus on extending the app, both in terms of the hazards it detects (i.e., terrain perturbations like curb cuts and potholes), and across form factor. Future work in this regard is provided in the following section.

7. Discussion

New accessible transportation technology is needed to harness the benefits of fully autonomous vehicles and promote mobility among the millions of people experiencing transportation limiting disabilities. Contributions of the AVA project, described in this paper, include a novel technology solution addressing experimentally validated problems among underserved populations. The Study 1 survey results (n = 90) informed a set of common problems experienced by both blind and visually impaired (BVI) users and older adults in travel-to-transit scenarios, specifically related to navigating to the vehicle and avoiding obstacles in the path. Subsequent user interviews (n = 12) in Study 2 complemented these initial data by identifying the importance of multisensory technology solutions to address these problems. The resulting Autonomous Vehicle Assistant (AVA), developed and guided by these data, was then evaluated in a navigation task with blindfolded sighted users (n = 10) and via a prototype evaluation with BVI participants (n = 6). Though results with AVA were distinctly positive, some limitations should be recognized in terms of sample size and methodologies used that can be addressed in future work. First, in order to demonstrate the utility of accessible travel-to-transit solutions like AVA, additional work across user group and in-situ context is needed, opposed to in controlled experimental scenarios with relatively small sample sizes, as was done here. The question remains, for example, how GPS-UWB fusion will work "in the wild" where user attention is split and environmental hazards are amplified. This project also did not cover the range of challenges experienced by users or identified in our informal analysis of user interviews. More robust qualitative work with formal analyses is needed in the future to further identify user-driven solutions across the complete trip of transportation. Extensions of these efforts, namely to include more user groups, proactive training programs, and future form factors (as reviewed in the following), will be critical for preparing for the next generation of accessible navigation technologies harnessing FAVs as the core transportation platform.

7.1. Multimodal solutions across the complete trip to promote inclusion

Results of this research identified a set of navigational hazards, concerns, and solutions that people with visual impairments will likely experience when navigating to fully autonomous vehicles when there is no longer a driver in the loop to provide assistance, including obstacle avoidance, accurate vehicle identification, and localization of vehicle entry. While the existing BVI literature had already identified some of these issues in current rideshares (i.e., locating a ride and navigating after the ride) (Brewer and Kameswaran, 2019; Kameswaran et al., 2018), our results provide strong evidence for these problems extending to older adults and future FAVs among BVI users. We argue that the value and innovation of our work demonstrates the extent to which complete trip navigation is a cross-cutting problem with shared solutions that can be capitalized on to maximize impact among multiple groups and sensory challenges. That is, the benefits of an inclusive transportation solution can be realized for all users, especially when imbued with a customizable UI (as we do here), as many – if not most – people, irrespective of visual status, have trouble finding their ordered rideshare vehicle in unfamiliar or busy locations (e.g., at the airport or in busy parking lots like a grocery store). To maximize inclusion, our results from the navigation study indicate that solutions to these problems should leverage a combined sensor-fusion approach (e.g., UWB/GPS techniques as we did here), with multisensory cues (i.e., audio and haptics) that are specifically designed to support accurate and safe navigation. This finding is in line with related research suggesting the importance of multisensory interfaces with FAVs (Brewer and Kameswaran, 2018; Fink et al., 2021; Fink et al., 2023a), which we designed and tested here with one of the first known prototypes for travel-to-transit scenarios. Results from our prototype evaluation indicated enthusiasm for extending the CV obstacle detection feature to include more hazards and objects. Thus, we envision that as data sets improve for machine learning, solutions like AVA can and should be extended to recognize a range of environmental hazards, from head-height objects that a white cane or guide dog do not recognize, to terrain perturbations, steps and curbs, and other common tripping hazards, which would improve safe and independent navigation among a broad range of older adults and BVI users. We recognize, however, that future work is needed with larger sample sizes across demographics to demonstrate viability of our approach among a wide range of users and abilities. While our prototype evaluation and navigation study demonstrate that a technology solution like AVA is a successful proof-of-concept, we also envision the need for extensive user training among this demographic to ensure safe real-world implementation (as discussed in the following section).

7.2. Navigation training for FAVs

New technology solutions supporting accessible use of FAVs among BVI users will undoubtedly improve mobility and transportation options among this significantly underserved demographic. We argue, however, that to maximize user safety and adoption, transportation technology like AVA must be implemented in parallel with new techniques for user training. Much like was found with new nonvisual interfaces for in-vehicle interaction in FAVs (Fink et al., 2023a; Fink et al., 2023b), user training can improve performance and increase user satisfaction. Indeed, our participants noted in the navigation trials that interacting with AVA became easier with time, but did not always feel intuitive (e.g., P5 mentioning getting used to the clock-face positions and P3 struggling with the last meter haptic assistance). This is logical given that AVA, in-part, uses haptic navigation cues, which related research has suggested users are not very familiar with but can improve with over time (Palani et al., 2022). To address this unfamiliarity, our team is actively engaging orientation and mobility (O&M) instructors and experts about the ways in which AVA can be used to support navigation training. The innovation here is that, if adopted, the next generation of O&M professionals will be skilled to teach BVI travelers about the value of, and best ways to use, FAVs proactively, instead of reactively, as is all too often the current practice with new technology. The results of this future work and broadened participation would be a first-of-its kind training set for FAV navigation among people with sensory impairments, an area of significant unmet need. As such, we argue that the time is now for future work to focus on user training in FAVs, as Level 5 vehicle development is where technology evolution and transformative change should intersect in the sphere of accessible transportation, representing the golden grail for increased independence and mobility for people with disabilities.

7.3. Accessibility across form factor

Post-test interviews from our prototype evaluation elucidated that one way that AVA (and the assistive technology ecosystem as a whole) could be improved is by implementing accessibility features across app and device. Participants mentioned, for example, not wanting to have to switch between the many feature-fragmented accessibility apps to navigate from door to door. We interpret this finding as evidence that a future hardware and software agnostic approach would enable users to utilize AVA's functionality within their ridesharing app of choice, in-line with related research advocating for users to utilize their existing devices (Fink et al., 2021). Furthermore, this approach would pave the way for AVA and related solutions to be readily implemented on future hardware. We recognize (and advocate) that the future of BVI navigation will likely involve hands-free and head-referenced camera-based displays (e.g., smart glasses). However, despite the practical benefits demonstrated in related assistive navigation work with these displays (Zhao et al., 2020), we argue that there is immediate benefit to leverage existing accessibility features and sensory capabilities on current smartphones. That is, in order to maximize technical efficacy, immediate benefit, and adoption likelihood, continuing to develop software solutions such as AVA that can be readily implemented today on existing user hardware and integrated into current O&M training services, and tomorrow in FAVs and smart glasses, is both practical and needed.

Conclusion

This paper summarizes the user-driven research and development cycle of the Autonomous Vehicle Assistant (AVA), an accessible ride-hailing, navigation, and vehicle localization application developed and supported by the USDOT's Inclusive Design Challenge. Results from a ($n = 90$) survey with transportation service drivers and ($n = 12$) initial user interviews identified our team's problem space and multisensory design solutions. Based on this guidance, we developed the AVA prototype, with user study results ($n = 10$ and $n = 6$) demonstrating strong support for AVA as an accessible and inclusive solution to barriers surrounding FAV use among people with visual impairment. We provide these results in conversation with related literature and the need for future work centered on user training and form factor agnostic implementation. By prioritizing these efforts, complete-trip transportation system harnessing accessible FAVs will have broad impacts for independence and mobility both on current devices and in future implementation scenarios.

CRediT authorship contribution statement

Paul D.S. Fink: Conceptualization, Writing – original draft, Writing – review & editing, Methodology, Data curation, Formal analysis, Visualization, Funding acquisition. **Stacy A. Doore:** Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Xue Lin:** Methodology, Software, Validation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Matthew Maring:** Software, Investigation, Resources. **Pu Zhao:** Data curation, Software, Validation, Writing – review & editing. **Aubree Nygaard:** Software, Visualization. **Grant Beals:** Software, Visualization, Resources. **Richard R. Corey:** Supervision, Conceptualization, Funding acquisition. **Raymond J. Perry:** Software, Supervision, Resources. **Katherine Freund:** Methodology, Resources. **Velin Dimitrov:** Resources. **Nicholas A. Giudice:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We acknowledge support on this project from the United States Department of Transportation's Inclusive Design Challenge Stage I and Stage II prizes.

Appendix

A. Survey distributed to ITNAmerica drivers

To what extent do you agree with the following statements:

1 Navigating to the vehicle can be challenging for my passengers

Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
○	○	○	○	○

2 Safely avoiding obstacles and potential hazards can be challenging for my passengers

Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
○	○	○	○	○

3 Finding the vehicle can be challenging for my passengers

Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
○	○	○	○	○

4 Finding the door handle can be challenging for my passengers

Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
○	○	○	○	○

5 If you notice passengers are experiencing challenges when navigating to or finding your vehicle, how do you communicate with them?
6 What additional information about you or your car would you like to be able to convey to your passengers before you pick them up?

B. BVI user-interview guide

1 To begin, we'll go over some demographic information. Can you please tell us the extent and etiology of your vision impairment?
2 What is your age?
3 Do you use a mobility aid (cane or dog, magnification device, etc.)?
4 What is your overall perception of the rollout of fully autonomous vehicles?
  a What are you excited about?
  b What are you worried about?
5 Can you explain what your current day to day transportation experience is like? What challenges or difficulties do you face?
  a Do you utilize public transportation? If so, how much? What challenges or difficulties do you face using public transportation?
  b Do you utilize ride-hailing services like Uber or Lyft? How about taxis? If so, how much? What challenges or difficulties do you face using these services?
6 Can you walk me through your typical process for navigating to a ride that you're taking, whether that's a friend's car, taxi, public transit, etc.
7 How do you determine that you have found the right vehicle?
8 What is it like for you to enter a vehicle once you've arrived to it? Is there anything that you try to keep in mind in terms of logistics? For example, finding the door, knowing you are at the right door, or avoiding hazards upon entry like curbs or oncoming traffic.
9 Transitioning a bit here, what accessibility features do you utilize on the technology that you use? For example, text-to-speech, vibration, large print.
  a Which of these features do you think are most helpful?
10 Now imagine being able to summon a self-driving car directly to your house or apartment. What features do you think would be most helpful on an app that helped you summon the car? What do you think would be helpful beyond what's made?
11 Are there any challenges that you could imagine facing when the car arrives, without a human in it?
  a What challenges do you predict you might face when trying to find the vehicle and navigate to it?
    i How might these challenges differ if you are at home versus out in a busy environment, or in an unfamiliar place?
  b What challenges do you predict you might face when entering the vehicle?
    i How might these challenges differ if you are at home versus out in a busy environment, or in an unfamiliar place?
12 Finally, we just want to give you the chance to share any additional thoughts on how an app could support you in ordering a ride, finding a ride, and getting into it. What do you think the app should do, and what specific features do you think it could include?

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