ACCESSIBLE AUTONOMY: EXPLORING INCLUSIVE AUTONOMOUS VEHICLE DESIGN AND INTERACTION

FOR PEOPLE WHO ARE BLIND AND VISUALLY IMPAIRED

By

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Autonomous vehicles are poised to revolutionize independent travel for millions of people experiencing transportation-limiting visual impairments worldwide. However, the current trajectory of automotive technology is rife with roadblocks to accessible interaction and inclusion for this demographic. Inaccessible (visually dependent) interfaces and lack of information access throughout the trip are surmountable, yet nevertheless critical barriers to this potentially lifechanging technology. To address these challenges, the programmatic dissertation research presented here includes ten studies, three published papers, and three submitted papers in high impact outlets that together address accessibility across the complete trip of transportation.

The first paper began with a thorough review of the fully autonomous vehicle (FAV) and blind and visually impaired (BVI) literature, as well as the underlying policy landscape. Results guided pre-journey ridesharing needs among BVI users, which were addressed in paper two via a survey with (n=90) transit service drivers, interviews with (n=12) BVI users, and prototype design evaluations with (n=6) users, all contributing to the Autonomous Vehicle Assistant: an award-winning and accessible ridesharing app. A subsequent study with (n=12) users, presented in paper three, focused on pre-journey mapping to provide critical information access in future FAVs.

Accessible in-vehicle interactions were explored in the fourth paper through a survey with (n=187) BVI users. Results prioritized nonvisual information about the trip and indicated the importance

of situational awareness. This effort informed the design and evaluation of an ultrasonic haptic HMI intended to promote situational awareness with (n=14) participants (paper five), leading to a novel gestural-audio interface with (n=23) users (paper six). Strong support from users across these studies suggested positive outcomes in pursuit of actionable situational awareness and control.

Cumulative results from this dissertation research program represent, to our knowledge, the single most comprehensive approach to FAV BVI accessibility to date. By considering both pre-journey and in-vehicle accessibility, results pave the way for autonomous driving experiences that enable meaningful interaction for BVI users across the complete trip of transportation. This new mode of accessible travel is predicted to transform independent travel for millions of people with visual impairment, leading to increased independence, mobility, and quality of life.

DEDICATION

This dissertation is dedicated to Major. You were and always will be the best grad school pup-pup.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

1.1 Motivation

Fully Autonomous Vehicles (FAVs) represent a massive innovation to how people will interact

with and navigate the world. Catalyzed by the billions invested in the research and development of

these systems, FAVs are poised to dramatically transform our roadways by making them safer, more

efficient, and more accessible. Driving is one of the most dangerous activities people engage with every

day, leading to over 30,000 deaths per year in the United States alone (NHTSA, 2018). Given that 90% of

driving accidents can be attributed to driver error (Fagnant & Kockelman, 2015), research predicts that

our FAV future will result in a significant reduction – up to 90% – in traffic accidents and fatalities by

eliminating operator error (DOT, 2017; Koopman & Wagner, 2017; Liu et al., 2019).

Beyond the magnified safety differences, removing physical and sensory requirements needed

to operate a vehicle is predicted to result in transformative transportation access and improved quality

of life for those who cannot currently drive, including many older adults and people with visual

impairments (Anderson et al., 2014; Fagnant & Kockelman, 2015). There are 26 million people reporting

transportation-limiting disabilities in the United States and 49 million people who are blind worldwide

(Bureau of Transportation Statistics, 2021; World Health Organization, 2019). These underserved

transportation demographics undoubtedly stand to benefit greatly from the independence and mobility

that widespread implementation of FAVs will bring to bear. Consider, for example, the opportunity to

address decades-long underemployment rates for people with visual impairment (nearly 70%), which

stem significantly in part from journey-to-work challenges (McDonnall, 2011). Indeed, people with visual

impairment have long experienced limitations on travel, with as many as 30% not travelling

independently outside of their homes (Clark-carter et al., 1986). Although FAVs hold life-changing

potential to address these challenges, it is argued here that research and development efforts must first ensure this technology is designed with inclusive human usability and accessibility in mind.

Active research areas investigating the engineering requirements for FAVs to be safely implemented across a variety of driving scenarios, road conditions, and use-cases have largely overshadowed human-centered research in this domain. Over 90% of academic published work in the field has traditionally focused on these engineering and technical factors, whereas only 2% has focused on human factors (Rosenzweig & Bartl, 2015). Therefore, the underlying motivation of this dissertation research is that for society to reap the safety, efficiency, and accessibility benefits of FAVs, a concerted and principled effort must be undertaken to ensure that transportation technology is accessible and acceptable to their human passengers. The fallouts resulting from the lack of human-centered usability strategies for FAVs include the sum of lives lost at the wheel of traditionally operated vehicles, as well as the continuation of poor transportation access among underserved driving populations.

1.2 Research Trajectory

A critical contribution of the dissertation research presented here is the focus on FAV accessibility across the entire journey of FAV transportation. Given the prevailing assumption that FAVs will operate much like rideshare services operate today (Narayanan et al., 2020), FAV accessibility can and should be considered from the moment a user wants to order a ride to their arrival at the intended destination. Whereas the preponderance of human-vehicle interface research has pertained exclusively to in-vehicle design, this dissertation research explores accessibility across multiple stages of the FAV trip: first on a ride-ordering app, then while navigating to the vehicle, and finally during vehicle travel. This emphasis on complete trip accessibility was informed by an initial review of the literature and FAV policy, which was subsequently published in the *ACM's Transactions on Accessible Computing* (Fink et

al., 2021) which can be found in its entirety in Chapter 2 of this dissertation. These early results

informed, constrained, and guided the design and direction of later studies focused on comprehensive

FAV accessibility.

Two temporally distinct but interconnected sections of accessible FAV trips were identified to

structure this dissertation research program: 1.) Accessible Pre-journey Ridehailing, which includes

ordering an FAV via a smartphone-based application and navigating to the summoned ride safely and

efficiently and 2.) Accessible In-vehicle Interactions, including information access and interaction with

nonvisually dependent human-machine interfaces (HMIs). Six papers are the basis of this dissertation,

which consisted of ten studies that explored these two pillars of research (depicted in Figure 1).
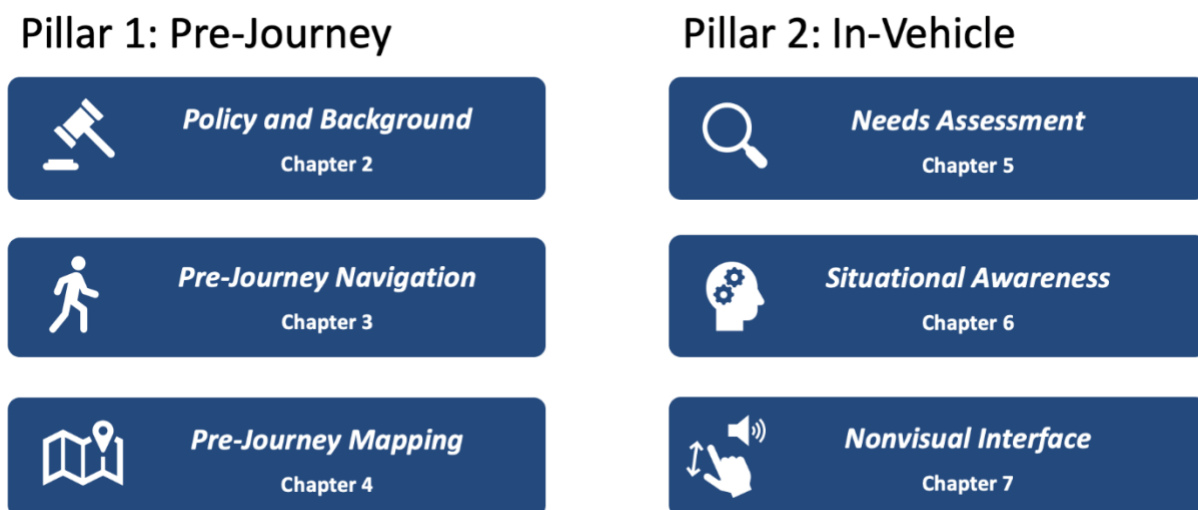
Figure 1. Research overview depicting topics of six papers presented in this dissertation research.

The following sections detail the research questions and methodological tools for each of the

studies presented in this dissertation.

1.3 Pre-Journey Research Questions and Methods

A common misconception is that transportation begins and ends in the vehicle. For millions of people who cannot or do not drive, the steps prior to vehicle travel (i.e., finding a ride, navigating to it, and entering safely) are just as important for a successful journey as riding in the vehicle itself. Recognizing this misconception and lack of research support, the USDOT initiated new sponsored programs investigating the complete trip, including the inaugural Inclusive Design Challenge (DOT, 2020; Inclusive Design Challenge, 2020). Our group's work competing in the Inclusive Design Challenge was selected as one of three winning teams, with proceeds supporting this dissertation research. The following section describes the research questions guiding the principled trajectory of dissertation research presented here.

1.3.1 Policy and Background

Too often new technology is developed without adequately considering the ways in which policy systems have capacity for, or will react to, fundamental change as a result. Transportation is not immune from this phenomenon, with autonomous driving technology making almost daily headlines in conflict with current roadway rules and regulations. As such, we began this research program with a core supposition: that transportation stakeholders must transcend the status quo by considering new ways to approach self-driving vehicle design in tandem with state, local, and federal policy.

We posited that although fully autonomous vehicles (FAVs) hold the potential to transform mobility for people with disabilities, there are likely legacy laws or lack of policy support that would inhibit their use by non-drivers. Thus, the research questions guiding the first published paper presented in this dissertation (Chapter 2) were the following:

1. What is the current policy landscape governing the use of fully autonomous vehicles?

This research question was addressed by reviewing both state and federal policy efforts in the United

States. State-level policies were identified using databases from the Insurance Institute for Highway

Safety, the National Conference of State Legislatures, the Governors' Highway Safety Association, as well

as legislative tracking tools on individual state websites. Federal policy efforts were identified using the

legislative tracking tool for the U.S. Congress, the Department of Transportation's Series of Automated

Vehicles Reports and related news media. Results, provided in full in Chapter 2, indicated that a lack of

cohesive federal policy has led to myriad state laws that often restrict use of highly autonomous vehicles

by users with disabilities. These results led to our second research question:

2. How does the current user research connect with potential policy solutions and future work?

Though not addressed by a formal methodology, this research question involved comparing the related

FAV BVI user research with relevant policy and upcoming policy efforts alluded to in the USDOT's

Automated Vehicle Reports.

Contributions from this paper, presented in full in Chapter 2, include policy analysis of what

assumptions are made about BVI travel (access, independence, technical supports, and safety

protocols), as well as review of ongoing accessibility research in this domain. Results identified

opportunities to update accessibility policy like the Americans with Disabilities Act (ADA) in terms of the

complete trip of transportation. Furthermore, results indicated the critical importance of designing of

new multisensory interfaces to achieve safe navigation across the trip.

1.3.2 Pre-Journey Navigation

A key result from the initial Policy and Background paper (Chapter 2) was that new multisensory

solutions are required to support safe and efficient navigation across the complete trip of FAV-based

transportation for BVI users. This critical unmet need led to a multiyear effort on our prototype solution,

the Autonomous Vehicle Assistant (AVA), which was the basis for our submission and winning prize in the Inclusive Design Challenge. AVA is a nonvisual ridehailing and localization app for autonomous vehicles that assists users in pre-journey tasks including ordering a ride, safely navigating to the ride, locating the ride, and entering the ride.
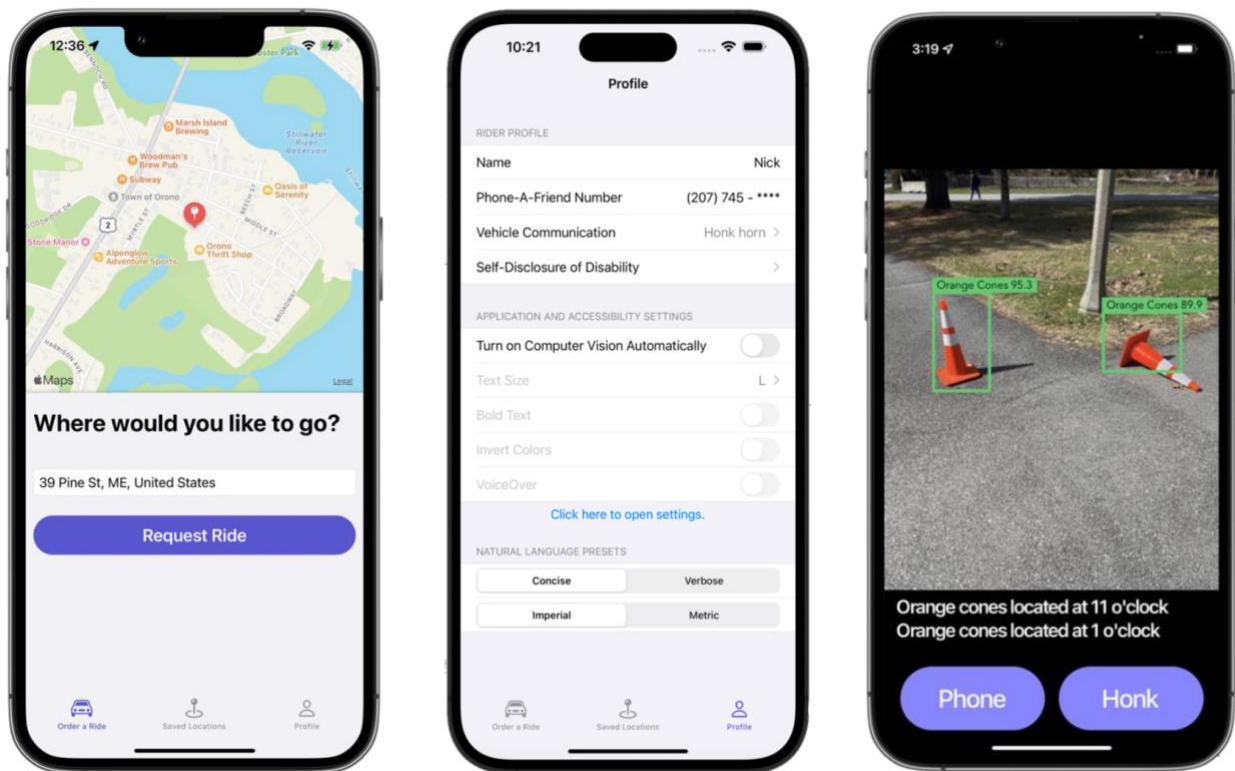
Figure 2. From left to right: AVA's ride ordering screen, user profile screen, and safe navigation screen.

Four studies were conducted as part of AVA's iterative development and are provided in full in the paper entitled The Autonomous Vehicle Assistant (AVA): Emerging Technology Design Supporting Blind and Visually Impaired Travelers in Autonomous Transportation, submitted for publication in *The International Journal of Human – Computer Studies.* This paper is presented in full in Chapter 3 of this dissertation and was guided by the following research questions.

1. What challenges and problems are experienced by current transit users with disabilities?

This research question was addressed via a survey distributed to 331 drivers working with ITN*America*, a nationwide nonprofit focused on providing transportation solutions for people with disabilities and older adults. The survey resulted in 90 complete responses and assessed pre-journey challenges for passengers on the way to the vehicle using 5-point Likert style questions, as well as long-answer questions intended to identify issues and challenges that should be addressed in assistance systems when there is no longer a human driver in the loop. Results, as reported in Chapter 3 of this dissertation, provided valuable insight regarding safety when navigating to the vehicle and the need for new multimodal assistance. As such, the second research question for this project sought to identify solutions via suggestions from users regarding multimodal and accessible assistance.

2. What solutions do potential end-users suggest for identified problems in future FAVs?

A series of interviews with (n=12) BVI users was conducted in accordance with this research question focusing on user experiences with current rideshare services. Participants offered proposed solutions to problems in future autonomous rideshares, which resulted in our identification of a series of problem-solution pairings reported in Chapter 3 of this dissertation. These problem-solution pairings informed the multisensory design of the AVA App, which was evaluated via the third and fourth research questions.

3. How effective is AVA's sensor suite in supporting navigation to a summoned vehicle?

While not the purview of this dissertation research (the study addressing this research question was led by collaborator and committee member Dr. Stacy Doore at Colby College), results supported AVA's sensor fusion approach combining GPS, ultrawideband, and LIDAR sensors designed to support safe navigation to the vehicle. These results encouraged subsequent user testing via Research Question Four.

4. How accessible is AVA as a ridehailing, obstacle avoidance, and vehicle localization solution?

Research question four was addressed through a formal prototype evaluation with (n=6) BVI users. Participants were tasked with using AVA across the suite of pre-journey functions, beginning with ordering a ride via the accessible user interface, then avoiding obstacles using computer-vision and multisensory alerts, and ending with locating the car through the sensor fusion approach designed by Dr. Doore's team. Throughout these tasks, participants were scored on their ability to safely avoid obstacles and find the vehicle door handle using AVA. Post-test interviews were also conducted with participants. Both qualitative and quantitative results from this evaluation (reported in full in Chapter 3) demonstrated strong support from users in terms of AVA's utility to address pre-journey challenges with autonomous vehicles. Contributions from the paper resulting from this work include a detailed description of the technical development and inclusive design of the first known travel-to-autonomous-transit solution for BVI users.

1.3.3 Pre-Journey Mapping

After the success of the AVA project and Inclusive Design Challenge competition, we sought to continue improving pre-journey transportation outcomes for people who are blind and visually impaired. In addition to ongoing work with AVA that is beyond the scope of this dissertation, we investigated pre-journey needs in current, human-operated rideshare services and how these needs may translate to future autonomous systems. An important area of differential information access between BVI users and their sighted peers involves accessing and understanding the vehicle's travel behavior while waiting for a ride. That is, on current ridesharing apps, sighted users often rely on a visually-dependent map displayed on the app to understand where the vehicle is along its route, how far it is from them, and its intended (or often unintended) arrival location.

When rideshared vehicles arrive to unintended or unanticipated locations (e.g., when parking spots are full, or construction or one-way traffic patterns deem it necessary), sighted users can use the visual map to quickly understand where it has arrived and travel to the new location. To solve this same problem, BVI users, lacking access to that visual map, are left with calling and relying on the driver for assistance. This begs the obvious question as to how this problem will be addressed when there is no longer a human driver to provide that assistance. As such, we built on our group's previous work with nonvisual haptic maps rendered on touchscreen devices (Palani et al., 2020, 2022) to design and evaluate a vibro-audio mapping solution that enables users to track a vehicle's route and arrival location in real time using haptic and audio cues.
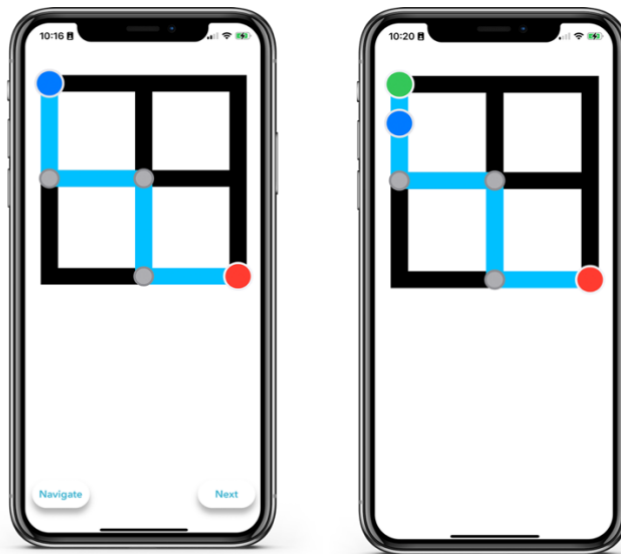
Figure 3. Vibro-audio maps showing the vehicle indicator at the start location (left) and moving (right).

A key innovation of the approach, depicted in Figure 3, is that the haptic vehicle indicator moves in real time, providing constant spatial updates to the user as the vehicle makes progress along the route. Results from this work were submitted for publication in the *Proceedings of the 15th International*

ACM Conference on Automotive User Interfaces (Auto UI '23), which is presented in full in Chapter 4 of this dissertation, guided by the following research question.

RQ: How do vibro-audio maps compare to the nonvisual information in current rideshare apps? This research question was addressed through a user study with (n=12) BVI rideshare users. Participants experienced two conditions, the vibro-audio map condition and a condition designed to represent the nonvisual information currently available in ridesharing apps (i.e., time and distance estimations). The study utilized a think-aloud method, a common approach in early human interface design (Jaspers et al., 2004), where participants were tasked with stating out loud their thoughts in relation to the vehicle's behavior. Participants were also instructed to inform the experimenter 1. When the vehicle was halfway to them, 2. As soon as they thought the vehicle might be delayed, and 3. As soon as they thought the vehicle might arrive to a different pickup location than indicated by the route. The time difference between participants' responses and the actual halfway point, delay point, and route deviation were calculated and compared between conditions using within-subject t-tests. Finally, participants were asked several Likert-style and long answer questions gauging usability and likeability of the solution. Results demonstrated initial support for these vibro-audio maps as a pre-journey solution, as well as suggestions for improving our prototypes. Contributions of this research, reported in full in Chapter 4 of this dissertation, include the first known dynamic vibro-audio map enabling real-time nonvisual tracking of objects. Beyond the real-time vehicular mapping applications of this technology, as studied here, dynamic tracking of on-screen elements has extensive implications for future accessible user interfaces, such as within data visualizations (e.g., for animated time-series bar charts), wayfinding applications (e.g., for vibratory real-time compasses), multimedia applications (e.g., for tracking progress bars on videos and songs) and accessible games for entertainment.

1.4 In-Vehicle Research Questions and Methods

Once the vehicle has been ordered, mapped, navigated to, and entered safely, the next step for inclusive transportation is ensuring that interactions in the vehicle can be accessed without vision. Unfortunately, the common approach of using touchscreens in vehicle displays renders most current interactions and information about the vehicle's behavior inaccessible without the use of vision. To address this problem, this phase of dissertation research investigated both the information needs of BVI users in FAVs, as well as the aspects of the trip over which users desire interaction and control. Three papers (two published and one in revision) characterized this work, which culminated in a patented gestural-audio interface in collaboration with Toyota Research Institute. The following section summarizes these efforts and provides the guiding research questions and methods.

1.4.1 Needs Assessment

A core tenet of this dissertation research is that user experiences with current ridesharing services can, in part, inform the use of future autonomous vehicles. However, replacing the human driver with an algorithm will undoubtedly result in key differences for both the information needs and interaction requirements in FAVs. Assuming this non-1:1 translation, we sought to explore the information and interaction needs among rideshare users and compare these needs with self-reported predictions for future FAV use. This work was submitted for publication in *Transportation Research Part F: Traffic Psychology and Behaviour* (see Chapter 5 of this dissertation) and is currently in revision. The following overarching research question guided these efforts.

RQ: How do current information and interaction needs in rideshares compare to future FAVs? The research question was addressed via a survey with (n=187) BVI ridesharing users. Likert-style questions centered around identifying the importance of information about the trip, as well as

interaction with the human driver in current rideshares vs. the AI-agent in FAVs. These data were

reported for both legally blind participants and the larger sample of users with moderate to severe

visual impairment. Key contributions of this research, provided in full in Chapter 5, included results

indicating high importance among users across the range of visual impairment for access to

environmental/contextual information (particularly information about the route and the vehicle's

behavior along the route) throughout the trip with FAVs. We interpreted this finding as providing strong

support for the design of new interfaces to promote nonvisual access and understanding of route-based

information in FAVs.

1.4.2 Situational Awareness

Building on our finding that new interfaces are needed to promote access to environmental and

contextual information about the trip (termed situational awareness in the literature), we sought to

design and evaluate a new interface to promote effective route learning among BVI users. One emerging

nonvisual interaction technique gaining traction in the automotive domain is ultrasonic haptic feedback.

Through the device pictured in Figure 4 (left), users can feel shapes projected in mid-air on their palm,

which we leveraged to create haptic intersection abstractions, depicted in Figure 4 (right).
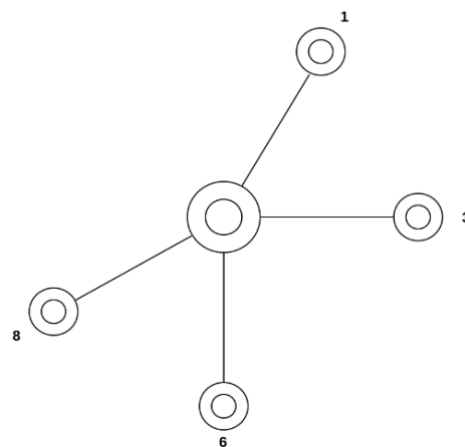
Figure 4. Left: The Ultrahaptic device (Ultraleap, 2023). Right: Experimental intersection abstraction.

The results of this effort were published in *HRI '23: Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction* (Fink et al., 2023) and are presented in full in Chapter 6 of this dissertation. The following research questions guided this work.

1. How effective is ultrasonic haptic information for situational awareness without vision?

To address this research question, we compared the ultrasonic haptic intersection abstractions with the gold standard for nonvisual spatial mapping: embossed paper maps. Fourteen participants were tasked with feeling the intersection abstractions in both conditions (haptic and embossed), with the goal of identifying the number of roads and the clockface position of each of these roads. Results indicated comparable accuracy between conditions with relatively small effect sizes. The contributions from the paper resulting from this work, presented in Chapter 6, included the encouraging evidence for the use of ultrasonic haptic interaction to promote nonvisual situational awareness, which we further evaluated through the second research question.

2. Can ultrasonic haptic situational awareness be used to initiate nonvisual control?

Following the initial user study, our group was interested in the extent to which the information conveyed by the ultrahaptic device could translate to actionable behavior. A proof-of-concept was designed leveraging hand-tracking and gestural recognition, which enabled an operator to feel the haptic intersections and control a 1/10th size robot vehicle using gestures. Though not formally analyzed, the concept was deemed successful: the operator could feel and understand the intersections with enough time to intervene and direct the robot vehicle using the pre-defined gestures. These informal results paved the way for the culminating paper in this dissertation research program, as discussed in the following section.

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1.4.3 Nonvisual Interface

A common misconception of fully autonomous vehicle design is that the human passenger will be or should be taken completely out of the loop of vehicle control. We all make on the fly decisions when travelling – we might add a stop along the route to pick up a snack and use the restroom or change the route entirely to take the scenic route or avoid traffic – and it stands to reason this will also be the case in FAVs. The question becomes what kind of control will be important for people in future autonomous transportation systems and how to enable that control nonvisually. As such, the culminating work in this dissertation program sought to build on our previous success in conveying situational awareness to design and evaluate a novel interface for nonvisual control in FAVs.

Figure 5. Nonvisual control interface using spatialized audio, gestural interaction, and haptics.

The interface (depicted in Figure 5) leveraged evidence from this research program and related work to combine spatialized audio, ultrasonic haptic feedback for situational awareness, and gestural recognition for nonvisual control. Published in the *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Fink et al., 2023), and presented as Chapter 7 of this dissertation, the paper consisted of three user studies guided by the following overarching research questions.

1. What types of vehicle control are important for blind and visually impaired users in FAVs?

The first research question was addressed through a survey and interview session with (n=23) BVI users. Participants were asked to imagine riding in a fully autonomous vehicle and to rate the importance of several different types of vehicle control based on existing literature and expert guidance at Toyota Research Institute. Results from a Friedman's test and post-hoc corrections (available in full in Chapter 7 of this dissertation), indicated strong support for control across the battery of control types, with altering the route rated as the most important control type. Though preference for altering the route was not surprising to us, the high desire for control across driving actions – even when told the vehicle could safely and legally automate all driving actions – was a major contribution of this initial study and contributed to the title of the paper, *Autonomous in Not Enough.* The second study sought to build on these initial results by identifying how control could be initiated through an emerging nonvisual interaction technique: mid-air gestural interaction.

2. What gestures are intuitive and natural for common driving control tasks for BVI users?

Whereas the proof-of-concept demonstration in the Situational Awareness study (section 1.4.2 above) relied on a pre-defined set of gestures to use for controlling the robot vehicle, in this study we predicted performance could be improved and training requirements reduced for our prototype interface if we identified a set of gestures that were intuitive for users. To do so, a user study with (n=15) BVI participants was conducted in which participants were tasked with performing gestures for each of the

driving tasks identified as important from the initial survey and interview study. Video analysis from 210 recorded gestures focused on commonalities between gestures in terms of movement, handshape, and repetition. The result was what we believe to be the first inclusively designed gesture set for autonomous vehicle control and is available in full in Chapter 7. A subset of these gestures focused on altering the route was utilized for the third and final study in this paper, guided by the following research question.

3. How desirable and easy to use is a gestural-audio system for BVI users to control FAVs?

To address this final research question, we conducted a user study with (n=8) BVI participants. Again, participants were tasked with imagining riding in a fully autonomous vehicle, with their goal being to intervene in the vehicle's behavior and direct the vehicle to a nearby coffee shop. Using the ultrasonic haptic device, participants could feel the intersection they arrived to and then could hear and sort through information about the streets using gestures identified from the previous study. Importantly, all participants successfully navigated to the coffee shop and reported high ease of use in post-test Likert survey questions. Moreover, the vast majority of participants agreed or strongly agreed that they would want to use the system. We interpret these results as providing strong evidence for the utility of our gestural-audio interface for promoting situational awareness and nonvisual control in automated vehicles for people with visual impairment. The combined results, reported in full in Chapter 7, include important contributions to the field in terms of the high levels of control desire among BVI participants, the first inclusively designed mid-air gesture set for autonomous vehicle control, and strong support from users for gestural-audio interaction.

1.5 Summary

Our driverless future will have widespread and transformative benefits in terms of safety, efficiency, and accessibility. Not only do fully autonomous vehicles (FAVs) have the potential to save lives and promote convenient travel, but this new driving technology is also poised to dramatically improve independence and mobility among millions of people experiencing transportation-limiting disabilities. In order to realize these benefits, however, new approaches to meaningful information and accessible interactions across the complete trip are necessary for widespread implementation among these demographics. The dissertation research presented here leverages a novel conceptualization of FAV travel that considers accessibility by addressing known challenges with pre-journey tasks and previously inaccessible in-vehicle interactions for blind and visually impaired passengers. Results from ten studies across six papers contribute to the single most comprehensive and award-winning research program focused on BVI accessibility in FAVs, with ongoing industry and advocacy organization support. The following chapters provide this research in full.

CHAPTER 2: Fully Autonomous Vehicles for People with Visual Impairment: Policy, Accessibility, and Future Directions

Contribution statement: The following paper was published in *ACM Transactions on Accessible Computing (TACCESS)*. My role on this paper as first author included the initial ideation, all policy and background research, and formation of future work based on the current state of research and landscape of state, federal, and local policy. Representing the main contribution of the paper, the latter formed the basis of our discussion and informed, guided, and constrained the remainder of this dissertation research program. I presented the results of this effort at The 23rd International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS 2021) on October 20th, 2021.

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Fully Autonomous Vehicles for People with Visual Impairment: Policy, Accessibility, and Future Directions

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A significant number of individuals in the United States report a disability that limits their ability to travel, including many people who are **blind or visually impaired (BVI).** The implications of restricted transportation result in negative impacts related to economic security, physical and mental health, and overall quality of life. **Fully autonomous vehicles (FAVs)** present a means to mitigate travel barriers for this population by providing new, safe, and independent travel opportunities. However, current policies governing interactions with the **artificial intelligence (AI)** 'at the wheel' of FAVs do not reflect the accessibility needs articulated by BVI people in the extant literature, failing to encourage use cases that would result in life changing mobility. By reviewing the legislative and policy efforts surrounding FAVs, we argue that the heart of this problem is due to a disjointed, laissez-faire approach to FAV accessibility that has yet to actualize the full benefits of this new transportation mode, not only for BVI people, but also for all users. We outline the necessity for a policy framework that guides the design of FAVs to include the concerns of BVI people and then propose legislative and design recommendations aimed to promote enhanced accessibility, transparency, and fairness during FAV travel.

CCS Concepts: • **Human-centered computing** → **Accessibility technologies**; *Accessibility*; • **Social and professional topics** → **Governmental regulations**; *Computing/technology policy*; *Government technology policy*;

Additional Key Words and Phrases: Autonomous vehicles, accessibility (blind and visually impaired), transportation policy, accessible design, artificial intelligence

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1 INTRODUCTION

Fully autonomous vehicles (FAVs) represent the future of accessible transportation by affording safe and flexible mobility for individuals who are limited by current transportation modes due to disability. Unfortunately, the policy landscape guiding the development of FAVs does not adequately consider the needs of transportation-limited populations, particularly those of people who are **blind and visually impaired (BVI)** and many older adults experiencing age-related visual impairments. While the predicted benefits of autonomous transportation have resulted in extensive media fanfare and advocacy by BVI stakeholders, the extant literature offers little clarification for designers and researchers to conceptualize the ever-evolving FAV legal ecosystem and its implications for accessibility. To succeed, we argue that the road ahead for accessible design must include policy promoting the small but growing body of work examining BVI perceptions, needs, and concerns with respect to FAV technology. This article starts by reviewing the current state of FAV policy as it relates to BVI accessibility. Based on these data, we then present recommendations to: (1) eliminate state level laws that discriminate on the basis of disability; (2) extend relevant sections of Part 37 of the Americans with Disabilities Act to FAV related technology; and (3) revise and reinstate the Vehicle Performance Guidance for Automated Vehicles. By discussing our recommendations in concert with existing policy recommendations and current work regarding the expectations and concerns of BVI people, the paper offers a pragmatic and user-driven approach for promoting accessible FAV technology and related policy development. Ultimately, we argue that should technology be reimagined to include the considerations presented here, the future will be bright for current transportation-limited populations who stand to benefit so greatly from autonomous vehicles using FAVs as their core transportation platform.

In the United States alone, there are over 25 million people who report experiencing travel limitations due to a disability, one third of whom assert that they do not leave their homes as a result of these limitations [United States Bureau of Transportation Statistics 2018]. Additionally, there are 26.9 million adults—roughly one tenth of the country's population over the age of 18-reporting some degree of visual impairment [American Foundation for the Blind 2019]. Recent statistics from the World Health Organization detail that there are 2.2 billion people who experience some form of visual impairment worldwide [World Health Organization 2019]. Of these, approximately 36 million experience blindness and 216 million have some form of moderate to severe visual impairment [Bourne et al. 2017]. The foregoing demographic measures can be expected to dramatically increase as populations age rapidly both worldwide and in the U.S., where 10,000 people turn 65 each day [United States Census Bureau 2019] and age continues to be a significant risk factor for experiencing visual impairment [World Health Organization 2019]. As visual impairment often restricts an individual's ability to drive, these figures suggest that there are at least 25 million people within the U.S., and approximately 253 million individuals worldwide, who stand to benefit greatly from the new, safer mobility options yielded by the implementation of FAVs. These benefits can be expected to have broad impacts in terms of supporting increased independence, employment, economic stability, physical and mental health, recreation, and overall enjoyment and quality of life.

The remainder of this article is organized as follows: In Section 2 we briefly review the current state of FAV technology. Section 3 reviews related work concerning BVI perceptions of FAVs and existing policy recommendations. Section 4 outlines the current state and trajectory of FAV policy. In Section 5 we propose future directions with policy recommendations, and in Section 6 we ground our discussion in the context of current problems with FAV consumer acceptance and user trust at large. Finally, in Section 7, we conclude by describing limitations and recommending future work.

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2 CURRENT STATE OF FAV TECHNOLOGY

The proliferation of FAV development and related technologies means driving tasks are increasingly being transferred from a human operator to a computer. The current state of the art for consumer grade **autonomous vehicles (AVs)** involves semi-autonomous operation, where vehicles have the ability to automate specific aspects of the driving process (e.g., lane switching, speed maintenance, and braking) without driver intervention. These operations are considered Level 3 autonomy, with levels for AVs ranging from no assistance (Level 0) to fully autonomous operation (Level 5) [SAE International 2018]. The core tenant of consumer grade semi-autonomous operation is that the driver is ultimately responsible and must always be able to assume vehicle control with sufficient transition time to ensure safe operation [National Highway Traffic Safety Administration 2013]. Fully autonomous operation, as we discuss here, is performed without any human direction or intervention. FAVs can be considered a subset of AVs, and throughout this paper, the term AVs will be used when referring to vehicle autonomy between Level 3 and Level 5, with FAV used to refer specifically to Level 5 autonomy. FAV technology is currently available in commercial shuttle operations active in New York, Detroit, the University of Michigan, Las Vegas, Orlando, and many cities worldwide [EasyMile, 2020; May Mobility 2020; NAVYA 2020; United States Department of Transportation 2018]. The prevailing assumption is that as FAVs become available to consumers, vehicles will operate much like rideshare services are operated today, but without the constraints of a human operator [Narayanan et al. 2020]. This undoubtedly will result in FAVs leading to increased mobility, particularly in rural regions and those with poor public transportation networks. For instance, people who were once limited by the timeframe and reach of bus routes, railways, and human-operated rideshare services will be able to travel without relying on new infrastructure or the availability of human drivers. FAVs will also inevitably be safer than traditional, manually-driven technology, while providing much needed opportunities for populations limited by current transportation modes, including BVI people and older adults [DOT 2020a; Fagnant & Kockelman 2015]. The increased safety of this new class of transportation can best be illustrated through predictions that FAVs will reduce traffic related accidents by up to 90% [Koopman & Wagner 2017; Liu et al. 2019; National Highway Traffic Safety Administration 2017]. These factors will undoubtedly confer many benefits relating to increased mobility, independence, and social engagement for underserved demographics.

3 RELATED WORK

The following offers background on BVI perceptions of FAVs, current ridesharing services (which closely mimic the predicted rollout of FAVs), and existing FAV policy recommendations.

3.1 BVI Perceptions of FAVs

A small but growing body of research investigating accessible FAV technology and its perception by BVI individuals provides useful insight into the needs and concerns that are currently lacking from policy in this domain. Interest in this work has been shared by media and advocacy groups who largely echo the need to design accessible FAVs for people with visual impairments. This section details both the user research exploring BVI perceptions of FAVs, as well as the public interest pieces that offer useful insight in this regard.

In a 2020 study involving both a survey of 516 respondents and a subsequent series of focus groups with 38 people who are blind and low vision, Brinkley and colleagues explored opinions and concerns among individuals with visual impairments regarding FAVs [Brinkley et al. 2020]. The survey results from the study revealed that the vast majority of respondents (88.87%) view FAVs positively (50.18% extremely positively, 30.44% moderately positively, and 7.75% slightly

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positively), with more than 90% expressing interest in FAV ownership. Importantly however, 94.3% reported being concerned about laws preventing people with visual impairments from operating FAVs. This sentiment was reiterated in the subsequent focus groups, with a majority of participants (55%) mentioning concerns regarding discriminatory laws that would prevent FAV operation among BVI people. Furthermore, when considering the accessible design of FAVs, more than half of focus group participants believed that the needs of individuals with visual impairments were not being adequately considered in the design of this technology. Although survey respondents were more optimistic about accessible FAV design, those with higher educational attainment echoed these concerns. The authors offered advertising efforts by Google's Waymo, which depict a blind user operating one of their vehicles, and prior experiences with other technology as possible explanations for the mismatch in perceptions of accessible FAV design. While a minority of focus group participants (37%) mentioned that technology currently exists to solve accessibility problems, several concerns emerged related to vehicle localization and orientation. For instance, more than half (53%) of participants mentioned the importance for people with low vision to be able to verify correct vehicle arrival destinations. Other features of interest included tools to locate the vehicle in congested areas, parking guidance, and real-time information regarding the vehicle's operation. Of particular interest to the topic of this paper, results from the focus groups suggested the usefulness of smartphone-based interfaces for BVI people, with many participants noting a desire to use current accessibility features built into their phones to control an FAV. Additionally, a large majority (71%) of participants mentioned the capability for dictation input as a primary interaction mode but, recognizing concerns about the accuracy of speech input and the battery life of cell phones, mentioned the potential for in-vehicle touchscreens to serve as a backup form of interaction. This sentiment was controversial however, with many blind participants noting the inaccessibility of current touchscreens, even when considering voiceover capability.

Bennett, Vijaygopal, and Kottasz found in a 2020 survey of 211 BVI respondents in the UK that BVI attitudes toward FAVs were characterized by hope for increased independent and convenient travel, tempered by skepticism that FAVs will be designed to meet the needs of people who are blind [Bennett et al. 2020]. Skepticism included both the design of FAV technology, as well as a lack of trust in state agencies responsible for accessible policy and advocacy. The open-ended responses from this research also indicated that BVI people have concerns regarding safe travel, entry-exit processes, and affordability. Although skepticism did not significantly predict willingness to travel in FAVs, the authors suggest that these respondents may hold a favorable disposition towards FAVs, despite their skepticism.

A 2018 focus group of 15 BVI participants by Brewer and Kameswaran investigated perceptions between AVs and FAVs, the influence of control when using these vehicles, and the ways in which tactile and voice-based designs can support BVI AV navigation across varying levels of vehicle autonomy [Brewer & Kameswaran 2018]. The authors led design-based activities where participants were asked to solve challenges by thinking about and creating either tactile or voice-based artifacts using props. Examples of tactile solutions included a compass for contextual awareness and vibration-based indicators for obstacle avoidance. Voice-based solutions included audio feedback when interacting with control elements in the vehicle (e.g., the door handle) as well as conversational solutions that mimicked current virtual assistants (e.g., Apple's Siri) and GPS. The authors found that both approaches can contribute to feelings of independence across various levels of autonomy, but concerns were raised about potential malfunctions with these solutions. The focus groups also illuminated the connection and tension between control and independence, demonstrating that participants desire accessible control mechanisms (e.g., feedback to the driver/passenger) that can facilitate independence but vary depending on the individual and the level of vehicle automation. The authors offer recommendations that advocate

for conversational user interfaces and route planning features (e.g., an audio-based GPS system), voice-based object identification in the vehicle (e.g., feedback when interacting with control elements), and tactile/vibration-based solutions (e.g., the tactile compass) for understanding, reflecting on, and changing plans in dynamic driving environments.

News outlets have also revealed perceptions towards FAVs among BVI people. For instance, a 2018 Associated Press report reviewed early efforts by Google's Waymo to build excitement for people with disabilities while contrasting these efforts with skeptical sentiments from the BVI community. Although the report offered encouraging results from a University of Florida project by Brinkley and colleagues, entitled Atlas [Brinkley, Posadas, et al. 2019], the author cast uncertainty on academic research translating into automotive development efforts. A BVI consultant for Waymo offered, "Autonomous vehicles aren't being designed for blind people; we're one of the beneficiaries of the technology…I'm patiently waiting" [Dearen 2018]. Advocacy groups echo the concerns of BVI people related to FAVs, as exemplified in the 2016 MIT Technology Review report entitled *The Blind Community Has High Hopes for Self-Driving Cars.* The report detailed efforts by the Perkins School for the Blind, the National Federation of the Blind, and the American Council of the Blind to advocate for FAV policy and development to include BVI considerations, citing a belief among BVI people that the community cannot assume auto-manufacturers will consider their needs [Woyke 2016]. It is worth noting that efforts to address these concerns have increased in recent years, as exemplified by Waymo's December 2020 presentation regarding research into FAV accessibility for people who are blind in 2020's Sight Tech Global [*Accessibility from the Wheels Up* 2020] and a September 2020 MIT podcast demonstrating dialogue between FAV accessibility research and **original equipment manufacturers (OEMs)** [MIT Technology Review 2020]. It remains to be seen, however, if these efforts will impact negative perceptions among BVI people regarding accessible FAV development.

The emerging research surrounding the perception of FAVs among BVI people suggests cautious optimism. While people who are blind and low vision have high hopes for the independence that FAVs are purported to afford, these hopes are tempered by concerns and skepticism related to development efforts to make the technology accessible, as well as policy and laws potentially limiting or failing to encourage BVI use-cases. Results from this body of research, as described above, suggest that BVI people desire FAVs to include a combination of audio-based and haptic/tactile interfaces that can be readily implemented on existing smartphone applications. In-vehicle touchscreens employing magnification and tactile (vibration-based) access can also serve as supplemental channels, especially for those with some residual vision. Common concerns across the corpus of available user research with BVI people suggest that solutions must consider the complete journey of driving by including supports for locating, entering, and exiting the vehicle, as well as accessible operational information during driving.

3.2   BVI Travelers and Ridesharing Services

As previously mentioned, current predictions among major auto-manufacturers situate the roll-out of Level 5 FAVs to prioritize ride-sharing and ride-hailing models, termed **mobility-as-a-service (MaaS).** Therefore, one advantage of the MaaS ecosystem is that existing ride-hailing services (e.g., Uber and Lyft) provide a useful proxy for understanding the unique challenges and needs that BVI people may experience during the widespread implementation of FAVs. Studies investigating the ways in which people with visual impairments experience ridesharing services offer a lens through which to conceptualize FAV travel.

Brewer and Kameswaran's 2019 study involving 16 interviews with BVI rideshare users revealed the interplay between independence and trust formation during experiences with services like Uber and Lyft [Brewer & Kameswaran 2019]. The authors identified the critical role the driver

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plays to facilitate entry and exit processes for BVI people (e.g. using convenient drop off locations), environmental awareness during driving (such as landmarks and potential obstacles at the destination), and trust building through conversation and social contracts. The authors also found that locating the vehicle, even when communicating with the driver, was often referred to as the most difficult process when using ridesharing services. These results offer useful insight into the challenges that BVI people will face in MaaS systems when a driver is no longer at the wheel.

In a 2019 study involving 18 interviews with drivers of rideshare services with experience driving people with visual impairments, Brewer, Austin, and Ellison explored the different forms of physical and relational labor that drivers engage in to support BVI passengers [Brewer et al. 2019]. Physical forms of labor included helping people enter and exit the vehicle, as well as walking them to their destination. Emotional and relational labor included conversing with passengers to respond to their needs and building a relationship over multiple trips. Drivers indicated that most passengers with visual impairments would self-disclose their disability to receive additional assistance and that this was appreciated and useful, especially at the beginning and end of the trip. Although this process of self-disclosure could help ameliorate challenges for BVI people by enabling proactive assistance from the driver (e.g., finding and entering the vehicle), the authors noted that self-disclosure is not without its disadvantages. For example, some drivers admitted to not wanting to accept rides with guide dogs, while others mentioned the possibility of taking advantage of those with visual impairments by driving longer routes to increase the fare. The authors concluded by proposing means through which passengers could selectively disclose their disability (i.e., through a profile in a ridesharing app), as well as ways for this information to be shared with drivers to limit the potential for discrimination.

The foregoing research echoes several of the challenges that emerged in studies investigating BVI perceptions of FAVs. Vehicle location, entry and exit processes, information relating to the driving environment, and the ability to disclose a disability are all critical considerations for rideshare services that are also relevant to accessible FAV design and related policy. Indeed, Brewer and Ellison extended the results from their ridesharing studies in a 2020 report to analyze how to support people with visual impairments in FAVs [Brewer & Ellison 2020]. This report offered several design recommendations for the future of FAVs in accordance with the rideshare studies including the importance of voice-based interfaces for environmental awareness and entry and exit, ways to connect passengers to other humans to increase trust, and ethical approaches for self-disclosure of disability. While these recommendations are important to the future design of FAVs, the following section illustrates a critical disconnect between the accessibility needs revealed by the literature and policies guiding development.

3.3 Policy proposals

Despite significant advocacy by BVI stakeholders and growing research interest and support from the **Department of Transportation (DOT)** in examining autonomous vehicle accessibility, such as through the Inclusive Design Challenge [DOT 2020b], as of 2020, only one article to our knowledge has sought to examine the FAV regulatory environment as it pertains to people with visual impairments. Brinkley and colleagues' 2019 article detailed the legislative and policy landscape surrounding AVs as of 2018 [Brinkley et al. 2019]. In addition to noting state laws in response to a lack of federal legislation, the authors found that a promising 2016 initiative by the **National Highway Transportation Safety Administration (NHTSA),** the **Vehicle Performance Guidance for Automated Vehicles (VPGAV),** was ultimately abandoned in the DOT's 2017 *Automated Driving Systems: A Vision for Safety 2.0 (Automated Vehicles 2.0)* in the name of spurring innovation. The authors called for a reinstatement and revision of the VPGAV in the 2018 *Preparing for the Future of Transportation: Automated Vehicles 3.0* to include a dedicated

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section on accessibility. Although we agree that enforceable policy with a dedicated section on accessibility is essential to promoting widespread FAV use, the article did not detail what a dedicated section might look like, or what specific considerations should be included.

A significant contribution of the work presented here is to take on the mantle of reviewing the legislative and policy developments in the quickly moving FAV timeline after Brinkley et al.'s publication. Much has changed since 2018, both in terms of the regulatory environment, as well as what we know about FAV accessibility as a result of the survey, focus group, and ridesharing research with BVI users. Unfortunately, the VPGAV was not reinstated in *Automated Vehicles 3.0*, nor was it reinstated, much less discussed, in the 2020 *Ensuring American Leadership in Automated Vehicle Technologies: Automated Vehicles 4.0.* Although we echo support for Brinkley et al.'s call to reinstate the VPGAV, we do so with specific recommendations derived from the emerging BVI user research. We also expand our recommendations to include similar sentiments from a recent policy brief concerning FAV accessibility at large [Fink & Giudice 2021], applicable sections from the **Americans with Disabilities Act (ADA**) of 1990, and the SELF DRIVE Act of 2020 to provide a comprehensive road ahead for accessible FAV policy.

4   CURRENT STATE OF FAV POLICY

We argue that legislative efforts should be expanded to guarantee that FAV use is both legal and accessible to those with visual impairments. To achieve this goal, policy development informed by the user research with BVI people would realize the full potential of this transformative technology. Such an expansion would undoubtedly help assuage the skepticism related to discriminatory FAV laws revealed in prior literature, while also promoting widespread and beneficial FAV usage among BVI people. Before providing our recommendations in detail, however, it is necessary to review policy efforts to date as context for proposed expansions.

4.1   Scope and Selection

The policies reviewed in this work include both state and federal efforts in the United States. Although BVI skepticism with regard to FAV policy extends beyond the United States, as evidenced by Bennet et al.'s [2020] previously discussed survey in the UK, policies outside of the United States are beyond the scope of this paper. State-level policies were identified using databases from the Insurance Institute for Highway Safety, the National Conference of State Legislatures, and the Governors Highway Safety Association, as well as legislative tracking tools on individual state websites. Federal policy efforts were identified using the legislative tracking tool for the U.S. Congress, the Department of Transportation's series of Automated Vehicles Reports, and related news media.

4.2   State Policy

FAV policy has thus far been characterized by a piecemeal mosaic of state-specific laws focusing on a critical qualifier: driver licensure. As of January 2021, 30 states have passed legislation or enacted executive orders regarding autonomous vehicle testing or deployment. Of these, 25 states currently address whether a passenger must be licensed, 11 of which definitively require a driver's license in all situations, and 7 of which require a driver's license dependent on the level of vehicle automation [Insurance Institute for Highway Safety 2020]. Table 1 illustrates the state laws and provisions that include driver's license requirements in autonomous vehicles. 'Yes' denotes that the state requires an operator with a driver's license even in a fully autonomous vehicle. It is worth noting that some of these laws (e.g., Michigan's) enable remote operation of the vehicle, where the licensed operator can monitor vehicle performance and assume control from a designated location.

A primary consideration for policy is whether FAVs should require a driver's license when manual driving is unnecessary. We argue that the answer is no. Laws requiring a driver's license in

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Table 1. State Laws and Provisions that Include Driver's License Requirements
in AVs (adapted from Insurance Institute for Highway Safety, 2020)

State	AV Driver's License Requirement
Arizona	Dependent on level of vehicle automation
Arkansas	Yes (effective 8/1/21)
Connecticut	Yes
District of Columbia	Yes
Florida	Dependent on level of vehicle automation
Georgia	Dependent on level of vehicle automation
Illinois	Yes
Iowa	Yes
Michigan	Yes
Nebraska	Dependent on level of vehicle automation
Nevada	Dependent on level of vehicle automation
New Hampshire	Yes
New York	Yes
North Carolina	Dependent on level of vehicle automation
North Dakota	Dependent on level of vehicle automation
Ohio	Yes
Utah	Yes
Vermont	Yes

FAVs are ultimately unnecessary, imposing needless limitations on the populations poised to benefit most from the technology (i.e., people who are unable to pass a driver's test because of visual impairments). The logic here is that FAVs are designed to forego the in-vehicle elements that enable traditional driving, including steering wheels, gas pedals, and other control mechanisms [Choksey 2020]. In other words, FAVs are predicted to eliminate the features that enable traditional driving and vehicle operation, thus rendering manual driving behavior as unnecessary for all users, irrespective of visual status. Existing state laws are therefore problematic by effectively precluding people without a driver's license from reaping the benefits of driverless technology, while also contributing to the sentiment among BVI people that policy discriminates against their interest. Federal policy interventions, as we review in the following, can serve as a useful mechanism for solving this problem by elevating minimal standards related to accessibility.

4.3   Federal Policy

Federal efforts to support and incentivize FAV development are ongoing. 2017's **Safely Ensuring Lives Future Deployment and Research in Vehicle Evolution (SELF DRIVE)** Act sought to establish the Highly Automated Vehicle Advisory Council within the NHTSA to, among other efforts, advance "…mobility access for the disabled community with respect to the deployment of automated driving systems to ensure awareness of the needs of the disability community as these vehicles are being designed for distribution in commerce" [Latta 2017]. Unfortunately, although the SELF DRIVE Act passed unanimously in the 115th Congress's House of Representatives, it stalled in the Senate. On September 23rd, 2020 the SELF DRIVE Act was reintroduced in the 116th Congress as H.R.8350 [Latta 2020]. Notably, the revised bill retains language for promoting mobility access, while also adding language with regard to discriminatory state laws: "A State may not issue a motor vehicle operator's license for the operation or use of a dedicated highly automated vehicle in a manner that discriminates on the basis of disability (as defined in section 3 of the Americans with

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Disabilities Act of 1990)". Although this bill would do much to ameliorate concerns surrounding existing state laws that effectively prevent BVI people from operating an FAV, to date, the bill has only recently been introduced in the House and its prospects of passing are low according to its sponsors given current congressional gridlock [Miller 2020]. Lacking congressional agreement, the executive branch has tasked itself in recent years with providing guidance for the development of FAVs through the DOT and the NHTSA. Most relevant to the current discussion includes the NHTSA's **Vehicle Performance Guidance for Automated Vehicles (VPGAV)** and the DOT's series of *Automated Vehicles* reports.

The VPGAV was first issued in September of 2016 as part of the Obama administration's Federal Automated Vehicles Policy [DOT 2016]. The VPGAV included an enforceable 15-point assessment specifically intended for use with FAVs, with failure to comply resulting in potential recall for both in-development and consumer-ready vehicles. The assessment included several relevant points for promoting accessibility: a "human machine interface to fully accommodate people with disabilities (e.g., through visual, auditory, and haptic displays)," an "accessible, clear, meaningful data privacy and security notice/agreement," and "measures to maintain the accuracy of personal data and permit vehicle operators and owners to review and correct such information when it is collected in a way that directly or reasonably links the data to a specific vehicle or person" [DOT 2016]. Unfortunately, as stated previously, the VPGAV was replaced in 2017 by the new administration's *Automated Vehicles 2.0* guidance [DOT 2017], which eliminated VPGAV's enforceable assessment in favor of voluntary guidance. This new guidance failed to include incentives or requirements for accessible **Human Machine Interfaces (HMIs)** or related technology for increasing mobility among people with disabilities.

The legacy of *Automated Vehicles 2.0* has continued in each annual iteration of the DOT's *Automated Vehicles* reports by prioritizing a laissez-faire approach to FAV development where standards for supporting access among people with disabilities remained completely voluntary. Some efforts, however, should be applauded. 2018's *Automated Vehicles 3.0* established "…expanding access to safe and independent mobility for people with disabilities" as one of the DOT's Automation Principles and also established incentives to support accessibility research through the Accessible Transportation Technologies Research Initiative [DOT 2018]. Further efforts to incentivize accessibility research in 2020's *Automated Vehicles 4.0* have been substantial through its commitment to $40 Million for a Complete Trip Deployment Solicitation, $5 million in cash prizes for the Inclusive Design Challenge, and a notice of Funding Opportunity for the Federal Transit Administration's FY 2020 Mobility for All Pilot Program [DOT 2020a]. While we would be remiss not to recognize the importance of these research incentives for accessibility, we argue that without the "teeth" of a clear piece of legislation or enforceable regulation, these incentives from the executive branch (i.e., from the DOT) will be outweighed by state laws that preclude people with visual impairments from operating FAVs. To buck this trend, the following section offers a road ahead by recommending adaptations to existing language in the ADA and by reinstating enforceable standards informed by the emerging corpus of BVI FAV research.

5 POLICY AND DESIGN RECOMMENDATIONS

5.1 Eliminate Discriminatory State Laws

The position of our research group is that for the social and economic/workforce benefits of FAV transportation to be fully realized, the mobility afforded by FAV systems should be guaranteed to those who cannot drive and consequently do not hold driver's licenses, including many people with visual impairments. Our first recommendation calls for BVI stakeholders to advocate for passing the provision in the SELF DRIVE Act that eliminates states' ability to issue FAV laws that

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discriminate on the basis of disability. Passing this law would respond effectively to Brinkley et al.'s [2020] finding that the vast majority of BVI respondents were concerned about discriminatory laws that would limit people with visual impairments from operating self-driving vehicles. A proactive solution that emerged in this research was the concept of an FAV operator's license, as opposed to a driver's license, which would eliminate processes that discriminate based on disability (e.g., traditional driving tests and vision tests), while retaining age requirements. The operator's license would be available to those who are unable to pass traditional driver's tests but would still like to be able to use FAVs. We argue that a federal law that not only supersedes discriminatory state laws, but also establishes this new conceptualization of an operator's license would do much to assuage BVI people's concerns, while also providing a sensical path for state FAV licensure processes separate from the traditional driver's license, which is no longer necessary with FAVs.

5.2   Extend ADA Driver Requirements to FAV AI Requirements

Our next set of recommendations concern enforceable policy regulations. Unfortunately, accessibility must often be mandated to ensure the needs and safety of all users, as was the case with many transportation requirements enacted in the ADA. ADA transportation rules detailed in Part 37 require that all transit provide adequate information in accessible formats; for BVI people, ADA compliance includes braille alternatives, large print formats, and/or electronic screen reading equipment and related software. ADA compliance also requires operator training to ensure that the operator is knowledgeable about providing adequate information for people with disabilities, including stop announcements and destination and route information [ADA §37.1 – 37.215 1990]. While ADA requirements serve as a useful guide for future FAV policy, the act needs to be updated for the 21st century, as FAVs will employ a new suite of technologies not considered in ADA guidelines as they are presently composed (e.g., touchscreen interfaces and AI drivers). These technological advances, combined with predictions that FAVs are expected to operate both as privately owned passenger vehicles and as a rideshare service [Narayanan et al. 2020], cast uncertainly as to whether the ADA, as it is currently constructed, will apply seamlessly to FAVs. The ongoing legal battle between disability advocates and rideshare services provides discouraging insight, having initially resulted in split decisions favoring Uber and Lyft's arguments that, as private peer-to-peer technology providers, they are not subject to ADA liability, instead offering their own disability policies [Columbia University 2020].

    Much like Brewer and Ellison's [2020] research with rideshare drivers revealed the utility of ridesharing as a proxy for FAVs, we can use ridesharing as a proxy to demonstrate the need for expanded FAV accessibility policy. In order for FAV services to avoid the legal gray area surrounding ridesharing accessibility, a pragmatic policy approach is to update, adapt, and extend existing language in the ADA to FAVs. Given that FAVs inherently lack a human operator, the information provisions and training that is currently required by the ADA of bus, shuttle, and taxi drivers can be translated into requirements for 'training' the AI at the wheel of autonomous vehicles. For example, in line with Brinkley et al.'s [2020] finding that BVI people desire features for verifying correct arrival destinations, AIs of FAVs should be programmed to grant passengers this information, in multiple formats. The ADA offers language in this regard, as transit operators are already required to provide orientation information to passengers upon arrival (such as signs and announcements to relay that "the destination is…" or "…doors will open on the right side"). ADA requirements should also be updated to include responsiveness to self-disclosed information concerning a person's disability. Much like the ADA requires bus and taxi drivers to receive and provide information in a respectful, courteous way, FAVs should be required to be responsive to self-disclosed disability information and handle this information appropriately. For example, FAV services could respond to a user disability profile by prioritizing vehicles with sufficient cargo

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space (e.g., an SUV) for passengers whose profile indicates a service dog. This provision would be in line with Brewer and Ellison's [2020] discussion regarding the importance of self-disclosure of disability in FAV apps and would do much to provide a responsive and accessible user experience for BVI people.

5.3   Revise and Reinstate the VPGAV

When considering interaction modalities for accessible FAVs, the VPGAV provides a useful starting point in its call for an HMI to fully accommodate people with disabilities (e.g., through visual, auditory, and haptic displays). However, in the years since the VPGAV's inaction (and subsequent replacement), FAV research with BVI people has revealed several specific points that should be included in an enforceable update. First, a readily available FAV integration with users' existing smartphones would enable BVI people to rely on the native accessibility features they are already accustomed to, especially considering that touchscreen-based smart device usage among the visually impaired population has increased dramatically over the last decade, from 12% in 2009 to 88% in 2017 [WebAim 2017]. Results from Brinkley et al.'s [2020] study support that FAV smartphone-based integrations should enable both dictation and touchscreen-based interaction modalities. Indeed, the multimodal nature of smartphones can be leveraged to open new doors for research and access in FAVs. For instance, touchscreens designed to appropriately utilize vibro-audio feedback have been demonstrated to be highly effective in rendering previously inaccessible visual content for spatial navigation information that would be relevant to FAV travel (e.g., route mapping) [Giudice et al. 2020]. Using haptic feedback in this way would align well with Brewer and Kameswaran's [2018] suggestion that tactile solutions may be preferred for understanding, reflecting on, and changing plans in dynamic driving environments. The inclusion of smartphone-based integration is also supported by Brewer et al.'s [2019] discussion of app-based passenger profiles that include disability information. Policy supporting smartphone-based integrations in FAVs would therefore promote BVI users in selectively disclosing their disability to receive additional supports from the vehicle, while also enhancing usability through multimodal interactions that have relevance throughout the complete trip. When taken as a whole, the small but growing body of BVI research in relation to FAVs has revealed that each stage of the trip (i.e., route planning, locating a vehicle, entering, operating, exiting, and arriving at the destination) all present needs that should be considered in policy to promote accessible vehicle design. By guiding the design of FAVs to include multimodal tools for route planning, vehicle location, entry/exit process, and information access/control during the trip, a new regulatory framework for the future of FAVs would do much to assuage BVI stakeholder concerns in the near-term, while promoting usability for all during widespread implementation.

Ultimately, in order to promote a future that includes fair, accountable, and transparent mobility for all transportation populations, FAV stakeholders would be wise to prioritize policy that obliges diverse AI interaction modalities that are accessible to all, instead of adopting one-size-fits all approaches. Multimodal interfaces that leverage haptic vibration and audio in combination with visual displays will not only promote inclusion, but also convenience for all users across the complete trip. One way to achieve this outcome is by prioritizing inclusive and universal design in native FAV interfaces, whereby features such as hearing assistance, screen readers utilizing text-to-speech, full haptic vibration support, and visual enhancements (e.g., magnification, reverse polarity or contrast, enlarged buttons) are included as available utilities during every interaction. By legislating these requirements through the SELF DRIVE Act, the ADA, and the VPGAV, and by prioritizing universal design principles, FAVs and related AIs will be poised to reach their full potential by providing access to people with visual impairments, as well as people across the spectrum of ability — sensory, motor, cognitive, or otherwise.

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6 DISCUSSION

Fully autonomous vehicles represent an enormous potential to mitigate existing travel barriers experienced by many people with disabilities. By situating our findings in the current political landscape, we argue in the following discussion that the time is now for researchers, designers, and BVI stakeholders to advocate for substantive policy reform. We also expand on this theme to discuss the advantages of smartphone-based HMI integrations, as well as the ways in which legal challenges to ride-hailing services offer insight into important updates to the ADA. We conclude the discussion by contrasting our recommendations with concerning trends related to consumer trust and acceptance of FAVs at large.

6.1 Legal Necessity

The current status of the SELF DRIVE Act (as discussed in Section 4.3), coupled with state laws emphasizing licensure requirements (as discussed in Section 4.2), suggest that new policy is necessary to satisfy concerns among BVI people related to discriminatory state laws (i.e., those that require driver's licenses and/or the ability for manual takeover) [Brinkley et al. 2020], and those related to distrust in FAV policy makers [Bennett et al. 2020]. As congressional gridlock continues to entrust state legislatures as the de facto governing body for FAV development and testing, a new presidential administration represents a chance to usher in executive branch reforms and priorities for accessible autonomous transportation. We argue that although bottom-up advocacy by BVI researchers and advocacy groups have done much to illuminate the needs of BVI people in FAVs, the unfortunate reality is that these insights have not been prioritized through the voluntary guidance emphasized in Automated Vehicles 2.0-4.0. While on-going efforts by the DOT to fund research for accessible FAV development is a step in the right direction, these efforts are undoubtedly less impactful in terms of public perception than enforceable mandates for accessible FAV design, as would have been the result of implementation of regulatory tools included in 2016's VPGAV. In other words, should the laissez-faire regulatory approach from the federal government continue, it is likely that so too will the status quo with regard to BVI skepticism and related distrust in FAVs working for those without vision. This skepticism and distrust not only presents a concerning scenario in which BVI people are less likely to adopt FAV technology when it becomes available to consumers, it also suggests the very real possibility that these concerns are grounded in a fundamental truth: that FAV technology is in fact *not* being designed with the needs of BVI people in mind, despite the many life-changing benefits that this technology promises for this demographic. While Waymo's presentation of an accessible smartphone-based app assisting BVI people throughout the complete journey at 2020's Sight Tech Global [*Accessibility from the Wheels Up* 2020] suggested an alternative, resulting in cautious optimism, future research is needed to determine if the majority of major auto manufacturers are heeding insights revealed by ongoing BVI FAV research efforts.

6.2 Smartphone-based App Integrations

Our findings through a deep-dive into the BVI FAV user research and current policy landscape suggest that smartphone-based app integrations, such as Waymo's example, should be included in a revised version of the VPGAVs requirements for accessible FAV HMIs. This approach would not only enable the audio and haptic interaction capabilities that existing research has already revealed are ideal for completing various tasks related to autonomous mobility [Brewer et al. 2019; Brewer & Kameswaran 2018; Brinkley et al. 2020], but would also fit well into the critical need for broadening applications of information access technologies at large. We argue that a holistic, integrative approach that cuts across disciplines is necessary to solve accessibility challenges in areas of emerging and disruptive technology, such as FAV development. By leveraging existing

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development efforts to apply evidence-based outcomes from research related to accessible input/output devices, designers would be equipped to quickly respond to the accessibility needs in FAVs without the need to completely reinvent the wheel.

Of particular interest are the opportunities afforded by touchscreen-based smart devices, which employ a host of multisensory features in their native user interface. In addition to auditory and enhanced visual interactions, a growing body of research has shown that the embedded vibration motors and haptic engines used to provide alerts, solicit attention, and enhance the visual experience in these commercial devices can also serve as a primary channel of haptic interaction. This newest class of information-access technology, called a **vibro-audio interface (VAI)** [Giudice et al. 2012], is particularly adroit at conveying spatial information, such as graphical content and non-textual information, which is inaccessible to current screen readers but highly relevant to the graphical user interfaces employed in FAV applications. Research has demonstrated the efficacy of using touchscreens with the VAI for accessing many types of content, including (1) recognizing different polygons [Giudice et al. 2012], as might be extended to icon recognition during FAV operation, (2) for learning maps [Giudice et al. 2020], as could be used to indicate FAVs driving routes, and (3) to indicate movement direction [Grussenmeyer et al. 2016], as may be used to indicate actions about the vehicle's immediate path of travel. Importantly, a significant body of research assessing the best psychophysical and usability parameters has already been conducted with BVI users using the vibro-audio interface with different touchscreens. This work has led to a clear set of perceptually-motivated and empirically-validated design guidelines [Palani et al. 2020; Gorlewicz et al. 2020], which are readily extendable to use with FAVs, whether it be through a dedicated smartphone app or via the vehicle's touchscreen-based control center. In addition to providing guidance on maximizing the multisensory usability of touchscreens, this work also provides guidelines for schematizing traditionally visually-based graphical content for non-visual access using the VAI. This research provides an important resource for OEMs and third-party developers interested in increasing FAV accessibility and enhancing BVI control and spatial understanding during FAV transportation. Given that the user research has clearly revealed that many BVI people desire touchscreens as a backup form of interaction in FAVs, but were skeptical given experiences with inaccessible touchscreens [Brinkley et al. 2020], and guidance that tactile information should be used to augment understanding and control in dynamic driving environments [Brewer & Kameswaran 2018], the emerging research employing haptic interactions using commercially-available vibration actuators in conjunction with existing touchscreens provide an obvious and empirically-validated solution that could result in the implementation of low-cost, transformative accessibility features in FAVs.

The near ubiquitous penetration of smartphone technology in the BVI market means that including policy requirements for accessible FAV integrations with existing mobile devices would also reduce the learning curve, cost, and OEM hardware adaptations associated with making FAVs fully BVI accessible. Furthermore, smartphone-based app integrations would do much to enable users to self-disclose their disability and enable FAV AI understanding of the accessibility features that users already use, as discussed in Brewer and colleague's research [Brewer et al. 2019]. By enabling human-AI information exchange in this way, FAVs AIs would be better equipped to respond effectively to user ability information, as we suggest a reimagined ADA should require.

6.3 Inadequacy of Ride-hailing as a Legal Proxy

Just as research utilizing ride-hailing serves as a useful proxy for understanding the ways in which BVI people will experience FAVs, lessons learned from legal challenges to these services can inform improvements to FAV policy. Our review of the literature revealed that drivers of ride-hailing services may still have the opportunity to discriminate against people with disabilities

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[Brewer et al. 2019], despite earlier settlements such as that awarded to the National Federation of the Blind's members in a class-action lawsuit against Uber in 2016 [*National Federation of the Blind of California, et al. v. Uber Technologies, Inc., et al.* 2016]. Our research group has personal experience with this unfortunate reality, as a rideshare trip to the local airport by the corresponding author of this paper was denied because of his guide dog, resulting in a missed flight. Coupled with evidence of the inapplicability of the ADA to ride-hailing services [Columbia University 2020], a new regulatory framework that updates the ADA to extend requirements to FAV AIs would guarantee BVI people (and their guide dogs) access to transformative mobility.

6.4 The Paradox of FAV Information Access

The proliferation of smart devices in the last decade has resulted in increased usage and acceptance of technologies that rely on access to sensitive user information. From Fitbits to Apple Health to in-home AI-based assistants such as Amazon's Alexa, it is tempting to assume that people are becoming increasingly comfortable with disclosing their information, disability, accessibility, or otherwise, to the technology of the future. However, this trend has been complicated by an increased emphasis on data privacy, both as a result of new technology requiring more sensitive human data, and privacy violations at the hands of social media conglomerates and governmental organizations. As designers intend to increase user satisfaction and trust by making AI-enabled technology more personalized and responsive to humans, there is a paradox in that these information-rich approaches can actually decrease trust and comfort with technology through the information collection processes.

In the context of autonomous transportation, we refer to this phenomenon as the paradox of FAV human information access, where users might distrust information sharing yet continue seeking technology that works best with user specific information. This paradox is critical to consider in any conversation involving increasing AI awareness of human data as a means to improve the user experience. Given the policy recommendations that we advocate in this paper to furnish FAV AIs with access to users' smartphones and self-disclosed disability information, we would be remiss not to mention that the AAA Foundation reports that over 70% of people in the U.S. distrust self-driving cars, even when considering the benefits to safety and efficiency the technology represents [AAA Foundation 2019]. Therefore, we acknowledge that, in tandem with our proposed policy and design recommendations, further investigation of the ways in which FAV AIs collect, monitor, and utilize user information is necessary should autonomous driving technology prove palatable, not only for transportation-limited populations but for widespread consumer acceptance. An important consideration is the degree to which users understand, have access to, and control over the data they share with their vehicle. We predict that by increasing user control over FAV data usage, through a combination of policy and technology design that promotes transparent and accessible formats, the human trust problem currently plaguing FAVs will gradually give way to cautious optimism that promotes the technology's further implementation as an everyday mode of transportation. By so doing, FAVs will be enabled to yield their full potential towards mediating the adverse circumstances experienced by many individuals who currently face transportation limitations, while drastically improving these individuals' mobility, independence, and quality of life.

7 CONCLUSION

This paper reveals the ways in which FAV research with people who are blind and visually impaired, representing a large and growing demographic of our society, should inform policy for the road beyond 2020. Results demonstrate that although people with visual impairments are by in large excited for the mobility and independence afforded by FAVs, additional advocacy is

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necessary to ensure that federal and state policy encourages accessible FAV development. A meaningful contribution of this work is elucidating the areas in which the research to policy pipeline in the FAV domain should be strengthened to include smartphone-based accessibility integrations and new multimodal tools for navigation across the complete journey of driving.

7.1 Limitations

The primary limitation of this work derives from the fast-moving FAV research and policy landscape. The user research and policies reviewed here only pertain to those available prior to January 1st, 2021. It is important to note that given the intense research, development, and political interest in FAVs, stakeholders must stay apprised of rapid changes in this domain in order to most effectively advance new policy and legislation.

7.2 Future Work

Future work motivated by the results of this paper could include both user research and policy development. Further examination of the ways in which smartphone-based accessibility solutions can integrate with FAV technology and infrastructure is necessary to understand how existing accessibility tools can support FAV travel among BVI people. New multimodal techniques to support information access and dynamic spatial understanding in FAVs is also of interest. Emerging research from DOT supported projects, such as the Inclusive Design Challenge, presents a significant opportunity to consider how these research efforts and others relating to underserved transportation communities can inform proactive and transformative policy.

APPENDIX

A ACRONYMS

Acronym	Term
BVI	Blind and Visually Impaired
FAVs	Fully Autonomous Vehicles
AI	Artificial Intelligence
AVs	Autonomous Vehicles
OEM	Original Equipment Manufacturers
MaaS	Mobility-as-a-Service
DOT	Department of Transportation
NHTSA	National Highway Transportation Safety Administration
VPGAV	Vehicle Performance Guidance for Automated Vehicles
ADA	Americans with Disabilities Act
SELF DRIVE	Safely Ensuring Lives Future Deployment and Research in Vehicle Evolution
HMI	Human Machine Interface
VAI	Vibro-audio Interface

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CHAPTER 3: The Autonomous Vehicle Assistant (AVA): Emerging Technology Design Supporting Blind and Visually Impaired Travelers in Autonomous Transportation

Contribution statement: The following paper has been submitted for publication in *The International Journal of Human – Computer* Studies and is currently under revision. My contribution on this multiyear project included much of the initial ideation and writing, which funded the project in Stage I of the USDOT's Inclusive Design Challenge with a $300,000 prize. During AVA's iterative development, I led the initial survey with (n=90) *ITN*America drivers and conducted all data analysis and reporting. My contributions also included assisting in data collection for the series of interviews with (n=12) BVI users, while also leading data analysis and reporting of these data. For the fourth study involving the prototype evaluation, I led data collection for rider profile accessibility, obstacle avoidance, and vehicle localization. As first author on the paper, I oversaw and contributed the vast majority of text leading to submission. Finally, I co-authored the written component based on this work leading to our team's Stage II prize in the challenge for an additional $300,000.

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.

Keywords: Autonomous vehicles, People with visual impairment, Accessibility

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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 the winning second-round finalist team 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 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 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 & 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 that 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 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 among this demographic.

1.1 Complete Trip Accessibility in FAVs for BVI Users

The Complete Trip initiative by 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 using survey, interview, and focus group methodologies, few projects have sought to design solutions for the trip itself (Dicianno et al., 2021). Interview and focus group-based 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 & Ellison, 2020; Brewer & 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 & Kameswaran, 2019; Kameswaran et al., 2018). The extant survey research has largely examined 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, Daily, et al., 2019; 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 limited examples of human-machine interfaces for BVI users like the audio and speech-input based ATLAS project (Brinkley, Posadas, et al., 2019). 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 presents 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 on social isolation and increased rates of depression in 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 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 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 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 ITN*America* 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. Figure 1 summarizes these data.
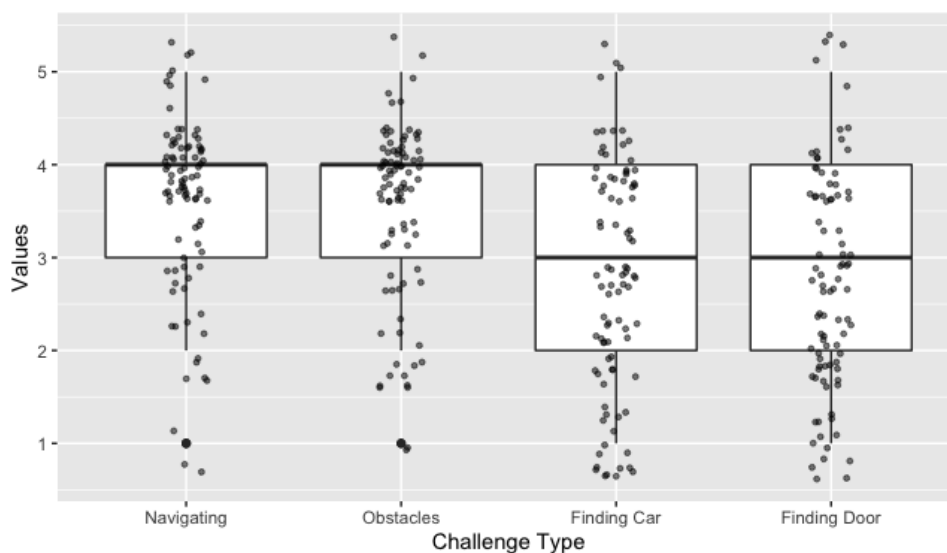

Figure 1. Likert scores for each challenge type question in survey with (n=90) transportation service drivers

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 strong 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 semi-structured with both prepared questions and follow-up questions from the researchers. Questions centered on participants' day-to-day experience with transportation, what challenges they faced, and how they imagined FAVs could best address these challenges. We used transcriptions of the recordings (with informed consent from participants) to summarize 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).

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 degrees 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.

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 & 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. It takes the image frames from the camera as inputs, and the output is a set of bounding boxes that enclose the objects in the image frames, along with class labels and confidence scores for each box. 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. Figure 2 (left) depicts the ride-hailing screen from an early AVA prototype.
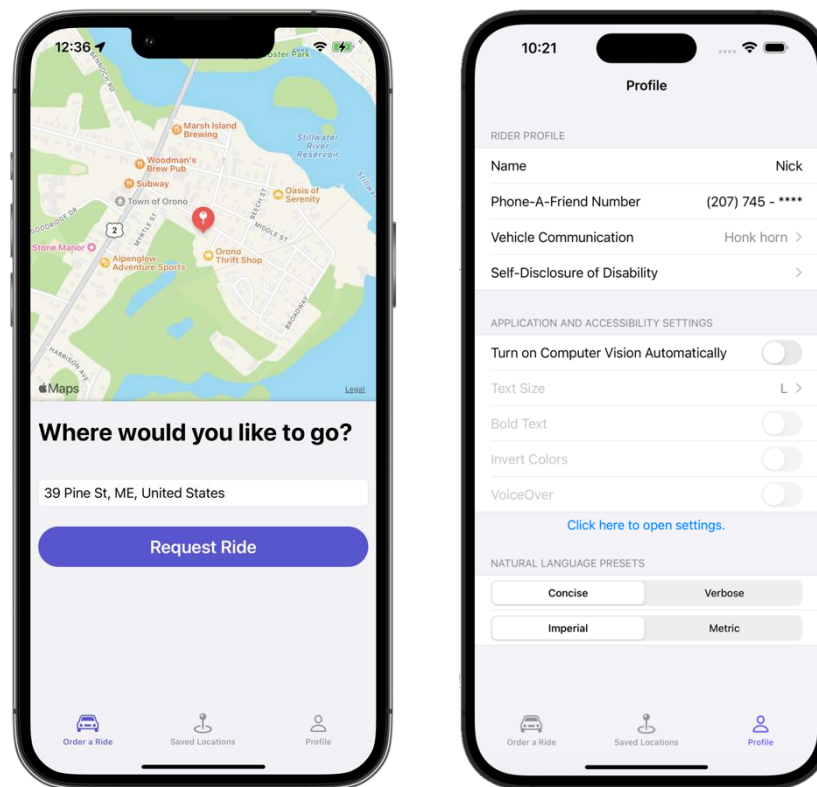

Figure 2 (left): A view from the AVA ride hailing screen. Figure 2 (right): A view from the AVA rider profile screen.

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

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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, 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), and 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, 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. Figure 3 provides a high-level overview of the user interface elements and sensor fusion used to support navigation assistance.
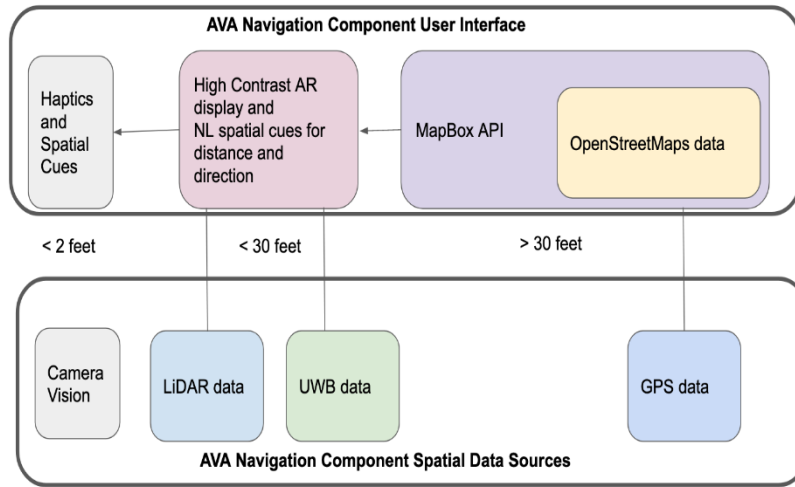

Figure 3. High-level architecture of the AVA navigation component

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 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 8.5m and vertical accuracy between 6 and 12.5m (Massad & Dalyot, 2018; Zandbergen & 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 10m, distance measurements accurate to within 0.1m accuracy, and angular direction measurements accurate to 5º, 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 (2-3GHz) 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 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 the other (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 & 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 the 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 30-40º 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 Figure 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 & 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 & 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.
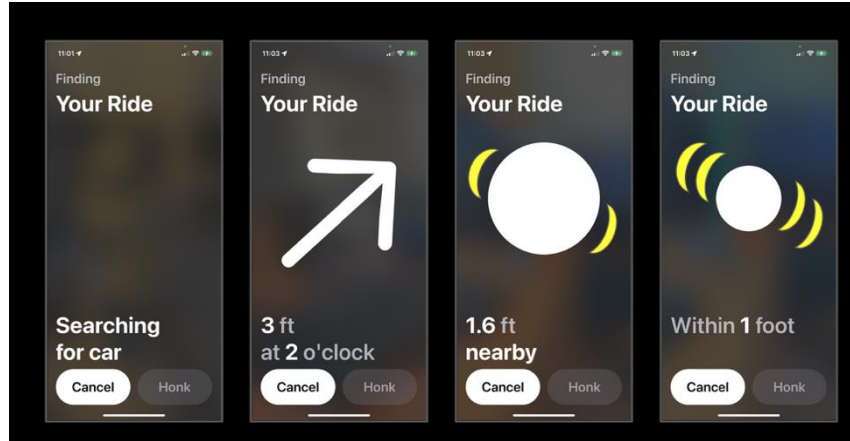
Figure 4. AVA navigation component interface interactions at near distance to door handle localization

4.1.3 Obstacle Detection and Avoidance

Our initial survey and user interviews (summarized in Sections 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 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).

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 in real time along with their distance from the user. The high-contrast bounding boxes (depicted below in Figure 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 review). 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, Figure 5 also depicts two buttons in the Obstacle Avoidance module: "Phone" and "Honk."

Figure 5. AVA's Obstacle Avoidance module

The phone button is an important error-handling feature that allows users to call a pre-defined friend in case there is an emergency, that is registered via the "phone-a-friend" field in the rider profile (Figure 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 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 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 and 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. Participants

started inside the building, put on a blindfold and were led out of the building by a researcher to avoid seeing the vehicle stimuli. Once outside, each participant was led to the starting position with the vehicle parked at 20 feet before hearing a pre-navigation summary (discussed in 4.1.2) of where the vehicle was parked in relation to their position. Participants started at the same position and direction for both the GPS and the UWB positions. In each condition, 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 Navigation Study Results

In the 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 UWB sensor in an average of 48.8 seconds (range 33-75 seconds). This is in comparison to 17 seconds (range 16-18 seconds) for a baseline time for a non-blindfolded walk to the vehicle from the same starting position. This non-blindfolded time 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 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.

In the GPS trials, all 10 participants failed to complete the task of navigating to the door handle of the vehicle (0% task completion). Even with the strongest GPS signal, this finding shows that GPS alone was not sufficient for any of the participants to successfully navigate 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 seconds (range 38-78 seconds). This difference in the navigation task completion results between the UWB and the GPS sensors provides 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.

The post-experiment survey responses suggest participants were overall satisfied with the functionality and features of the app. Participants provided open response feedback on what they considered to be the most helpful features in the AVA app. They 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 to the phone when the handle was within 1 meter of the participant.

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

Participants were also asked to provide open response feedback on what they considered to be the most confusing or difficult features in the AVA app. Relevant responses included mentioning that the speed at which directions were given was difficult to process, 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.

- 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, 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 1m to the target door handle. The quantitative trial results and the qualitative survey results of the blindfolded sighted participants (n=10) provided strong evidence that our sensor fusion approach to layered multisensory spatial information in the AVA app by combining UWB and GPS signals 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 5.2), our team undertook a prototype evaluation of AVA 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). 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 they could use AVA to identify the branches overhead along the path. While not part of the task itself, the enthusiasm that was evident during this process was encouraging of the 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 (i.e., 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 this project include a novel technology solution to 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 a prototype evaluation with BVI participants (n=6). Extensions of these efforts, namely to include more user groups, user training, and form factor (as reviewed in the following), will be critical for future research in

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, including obstacle avoidance, accurate vehicle identification, and localization of vehicle entry. While the existing BVI literature had identified some of these issues in current rideshares (i.e., locating a ride and navigating after the ride) (Brewer & 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 UWB/GPS approach imbued 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 & Kameswaran, 2018; Fink et al., 2021), which we designed and tested here with one of the first known prototypes. Results from our prototype evaluation indicated enthusiasm for extending the 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. 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 adoption, transportation technology like AVA must be implemented in parallel with new techniques for user training. As such, 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. 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 many 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 capability on current smartphones. That is, in order to maximize technical efficacy, immediate benefit, and adoption likelihood, continuing to develop software solutions like 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.

8 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.

9 ACKNOWLEDGEMENTS

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CHAPTER 4: Vibro-audio Maps for the Future of Accessible Ridesharing

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Vibro-audio Maps for the Future of Accessible Ridesharing

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Abstract
For millions of people who are blind and visually impaired worldwide, ridesharing provides an important means of independence and mobility. However, a common challenge relates to finding the vehicle when it arrives to an unanticipated location. Although the current solution of coordinating with the driver for assistance is serviceable in the near term, new solutions are necessary when a human is no longer available in future automated and completely driverless vehicles. As such, this paper presents and evaluates an innovative smartphone-based ridesharing map system using haptic vibration and audio cues with (n=12) blind and low vision users. User study results comparing the vibro-audio maps (VAMs) with current nonvisual audio user interfaces in ridesharing apps suggest that VAMs promote superior spatial confidence and reasoning. Participants also rated the VAMs as desirable to use with reasonable ease of use, demonstrating the practical utility of VAMs to address both current and future pre-journey challenges for people with visual impairment.

Keywords: Accessibility; Ridesharing; Haptic Interfaces; Blind and Visually Impaired Users

1 Introduction

Rideshare vehicles rarely arrive precisely when and where users expect. Congestion, construction, and roadway pattern all contribute to slight, but nevertheless cumbersome, alterations in pickup location and arrival time. Combined with state-by-state and city-by-city policies that determine where and how rides can arrive, rideshare users rely heavily on features within their smartphone-based interface of choice to anticipate and navigate to their summoned ride, particularly in unfamiliar locations. To assist in finding the vehicle, ridesharing apps (e.g., Uber or Lyft) provide extensive pre-journey information related to ride arrival time, route of travel, and location in real time. This information is typically conveyed visually via a map that displays the vehicle's route to the pickup location and a dynamically-updated indicator representing the vehicle along the route. Real-time tracking solutions like this have long demonstrated positive impacts on user satisfaction and system understanding in transit systems among sighted users (Pholprasit et al., 2013), but what if the user cannot access that map due to a visual disability?

There are an estimated 338.4 million people experiencing moderate to severe visual impairment worldwide, 7.3 million in the United States alone, (Bourne et al., 2021) and this demographic utilizes ridesharing services at significantly higher rates (2-3x) than other groups of people with transportation limiting disabilities (Eisenberg et al., 2022). Despite the comparatively high rates of use, understanding the arrival behavior of rideshare vehicles is a real problem among BVI rideshare users, with specific concerns related to when the vehicle will arrive, where it will arrive, and if it will arrive at all (Brewer & Kameswaran, 2019; Fink et al., 2021; Kameswaran et al., 2018). Unfortunately, the onboard tracking solutions provided by rideshare apps that address these problems among sighted users are largely inaccessible to BVI people. When waiting for a ride, BVI users are typically only provided the estimated time of arrival (e.g., 4pm or 5-minutes away) and sometimes the distance (1000 feet away), which introduce significant challenges for users when the pick-up destination changes or the vehicle is delayed. Whereas sighted users can use the map provided by the application to quickly perceive and interpret where the vehicle is, why it might be delayed, and if the pick-up destination might change, BVI users are left only with the vague and error prone arrival estimations through audio updates available in the user interface. Lacking onboard information from the app, users must coordinate with the human rideshare driver by calling or texting to assist in meetup, which can introduce serious challenges. For instance, one of the authors of this paper who is himself congenitally blind and a frequent rideshare user has experienced drivers failing to respond, thereby rendering the ride unusable and often incurring additional costs, wasted time, and increased stress and frustration. This problem will likely only get worse, given predictions that fully autonomous vehicles will prioritize rideshared service models with a human driver no longer in the loop (Narayanan et al., 2020). As such, we argue that the future of autonomous transportation demands new approaches to accessible pre-journey information beyond the driver-dependent status quo.

To address the differential information access problem in current ridesharing apps, we leverage an emerging research area exploring nonvisual spatial applications via the use of multisensory maps based on combined haptic, auditory, and kinesthetic information, rendered on touchscreen-based smart devices, called vibro-audio maps (VAMs). This body of work has demonstrated the powerful real-world utility of VAMs for promoting cognitive map development and related spatial behaviors for both BVI users and sighted users in nonvisual situations (Giudice, Guenther, Jensen, et al., 2020; Palani et al., 2022). However, the extant

research, which largely relies on fixed, static maps, has yet to explore how real-time location data can augment spatial understanding and user experience. By contrast, our prototype solution utilizes existing psychophysical design guidelines for tactual perception on touchscreens (Gorlewicz et al., 2020; H. P. Palani et al., 2020) to develop a real-time vibro-audio ridesharing solution rendered on a smartphone. The study presented here evaluates the solution compared to a control condition using the audio-only approach currently available in commercial-grade ridesharing applications.

2 Related Work

2.1 Ridesharing literature with BVI travelers

Understanding the needs of BVI passengers in rideshares is a pivotal first step in implementing technology to improve the user experience among this demographic. Previous work has sought to evaluate the experience of BVI ridesharing users and to postulate needs for future autonomous transportation systems. Findings have emphasized the valuable contributions to independence for this demographic that ridesharing can facilitate as users become less reliant on friends and family (Brewer & Kameswaran, 2019; Kameswaran et al., 2018). However, results from interview-based work also suggest that BVI users are concerned with the accessibility of ridesharing systems for tasks such as ordering a ride, entering and exiting the vehicle, as well as accessing environmental descriptions throughout the trip (Brewer & Ellison, 2020). Drivers of current rideshare vehicles do much to overcome these accessibility challenges and improve the user experience by assisting with vehicle entry and exit behaviors, providing social and emotional support, and building trust through multiple trips with passengers (Brewer et al., 2019). This body of work highlights that although rideshares provide a beneficial form of transportation to BVI travelers, there are underlying challenges currently being addressed by human-dependent interactions with the driver. As such, we argue there is significant opportunity to further increase the benefits of rideshares for BVI passengers by enabling users to independently utilize these services like their sighted peers. Though a growing corpus of work has investigated how to enable accessible nonvisual information in the vehicle (Brinkley et al., 2019; Fink, Abou Allaban, et al., 2023; Fink, Dimitrov, et al., 2023), far less is known about how to improve information access in the important pre-journey phase of the trip. We argue that heightened focus on accessible pre-journey information like the vehicle's arrival (i.e., through real-time nonvisual map access) will likely support better understanding of the vehicle's behavior with downstream benefits in terms of efficient localization, safe navigation, and successful vehicle entry tasks.

2.2 Nonvisual touchscreen-based access and vibro-audio maps

Strategies for conveying spatial information for BVI users have traditionally relied upon the use of physical tactile maps, which consist of raised elements and braille labels to convey spatial properties (Edman, 1992; Rowell & Ongar, 2003). While tactile maps have long demonstrated significant utility in developing accurate cognitive maps for BVI users that support novel spatial learning and in-situ navigation (Blades et al., 1999; Espinosa et al., 1998; Golledge, 1993; Ungar et al., 1997), disadvantages of this conventional approach include the static (non-real-time) and unimodal nature of the representations, compared to dynamic, multisensory map renderings as are used here. Traditional tactile maps also rely on fabrication processes that are both labor and cost intensive (Giudice, Guenther, Jensen, et al., 2020). To address these limitations, modern digital interactive maps leverage several technologies on commercially available devices to provide highly customizable rendering techniques (O'Modhrain et al., 2015). This new class of

accessible mapping has resulted in positive user performance on dedicated accessibility devices like pin-arrays (Zeng & Weber, 2010, 2016), force-feedback devices (O'Modhrain et al., 2015), as well as on touchscreen-based smart devices (Giudice, Guenther, Jensen, et al., 2020; Grussenmeyer et al., 2016; Palani et al., 2022; Poppinga et al., 2011). Commercial touchscreen mobile devices have built-in vibration motors that enable vibrotactile output as a user's finger contacts an onscreen element. Combining these vibrotactile outputs with auditory cues have given rise to multimodal vibro-audio maps (VAMs), which have demonstrated similar or better performance when compared to traditional tactile maps (Giudice, Guenther, Kaplan, et al., 2020; Palani et al., 2022). We argue, therefore, that the integration of VAMs within ridesharing apps has practical appeal for providing nonvisual access to pre-journey information like ride arrival time, route of travel, and location in real time, as well as increasing overall spatial awareness with respect to the user's current location. As such, the following study employs a mobile app rendering based on our experimental vibro-audio ridesharing map, which provides participants dynamic pre-journey spatial information that can be tracked in real time in comparison with the current features available in commercial ridesharing applications.

3 Methods

3.2 Participants

Twelve BVI participants participated in this research, representing a wide range of visual impairment, onset, and etiology (specific demographic characteristics are available in Table 1). Participants were recruited with help from the Carroll Center for the Blind, a large nonprofit serving the blind and low vision community in Newton, Massachusetts, and were compensated $100 for their participation. No participants self-reported any known tactile sensitivity loss. This research was approved by the University of Maine's IRB.

Table 1. Participant demographic information including extent and etiology of vision loss

Age	Sex	Cause of Vision Loss	Extent of Vision Loss
21	F	Septo-optic dysplasia	Some light and color perception
25	M	Retinopathy of prematurity	Totally blind
31	F	Lebers congenital amaurosis	Legally blind
32	M	Retinopathy of prematurity	Legally blind
32	F	Retinitis pigmentosa	Some light perception
43	M	Diabetes	Some usable vision
45	F	Hereditary	Legally blind
53	M	Cause unknown	Some light perception
54	M	Optic nerve damage	4% field of view in one eye
49	M	Lebers congenital amaurosis	Some light and object perception
62	M	Cone dystrophy	Legally blind
50	F	Stargardt disease	Some peripheral vision

3.1 Vibro-audio Ridesharing Maps

The vibro-audio ridesharing maps (VAMs) used in this research were developed using Swift and presented via an iPhone application using the phone's onboard vibratory motors and speakers. Vibrotactile parameters, summarized in Table 2, were derived from psychophysical guidelines

on vibro-audio interfaces established and validated from our group's previous work (Gorlewicz et al., 2020; Palani et al., 2020, 2022) and prototyping prior to the experiment. The maps are represented as 2x2 grids, where grid lines represent roads and vertices represent intersections. The ridesharing vehicle is indicated by a vibrating point, which moves along the grid lines at a fixed speed from a starting vertex to an end vertex (i.e., the arrival location). As a multisensory interface, audio cues supplement each vibration as the user's finger touches the map elements.

Table 2. Summary of audio and vibration cues in maps

Audio Cue	Description	Pattern	Intensity	Duration	Interval
"Route"	Route the vehicle will take	Constant	100%	1s	1Hz
"Grid"	Non-route road	Constant	50%	1s	1Hz
"Corner X"	Numerated vertices on vehicle route	Pulse	100%	.05s	20Hz
"Start"	Vehicle starting point	Pulse	100%	.25s	20Hz
"End of Route"	Intended vehicle end location	Pulse	100%	.25s	20Hz
"Car"	Vehicle's current location along route	Pulse	100%	.1s	10Hz
Error tone	No on-screen element	NA	NA	NA	NA

"Route" can be heard when the user touches the grid route that the vehicle is taking, "Grid" when the user touches the road that is not part of the vehicle route, "Corner X" at vertices that are part of the vehicle route (where X is the vertex number in the order that it appears), "Start" at the vehicle starting point, "End of route" at the user's location, "Car" at the vehicle's location along the route, and an error tone (the same used in Apple's VoiceOver) when the user is not touching a relevant part of the grid. Vibration patterns also allow the user to differentiate between various aspects of the map. The grid lines and vehicle routes are both constant vibrations, however the vehicle route vibrates at a perceptually salient higher intensity than the non-route grid lines. The intersections and end vertices, as well as the vehicle dot all have pulsing vibrations, where the vibration is fastest at the intersection, slowest at the start and end point, and has a medium speed at the vehicle location. Finally, double tapping anywhere on the map will provide an audio ETA update.

An example route on the vibrotactile map is shown in Figure 1. The green dot indicates the start point, the red dot indicates the end point, the blue dot indicates the vehicle location, and the gray dot indicates an intersection along the route. The route is highlighted in blue, with the rest of the grid being black.
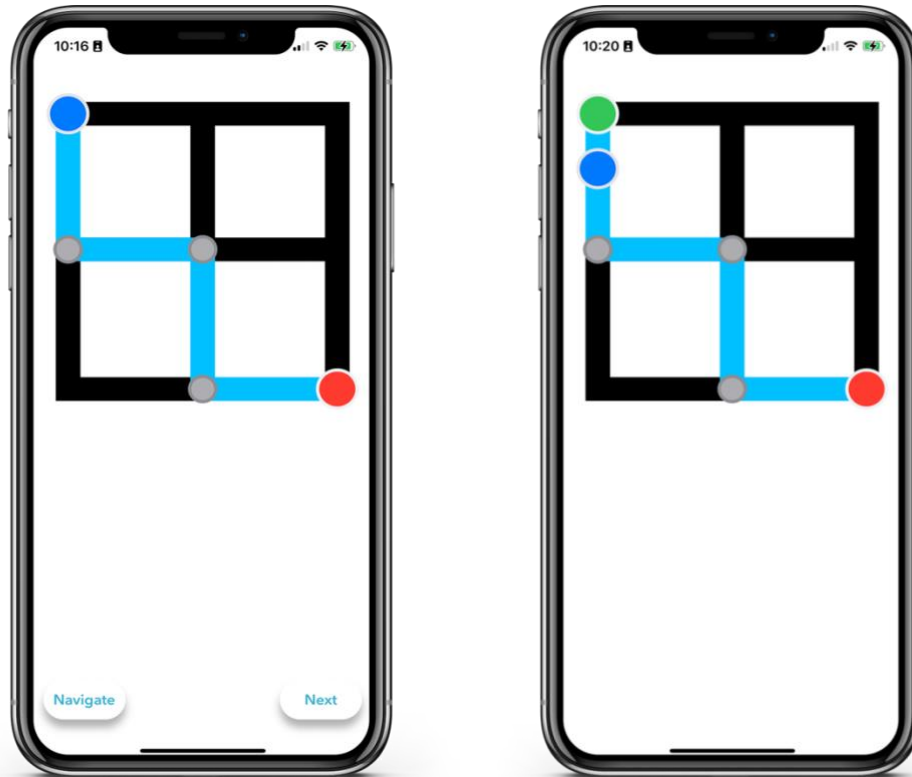
Figure 1. VAMs with the vehicle indicator at the start location (left) and moving (right).

3.3 Procedure
Employing a within-subject design, the study included three phases: practice, experimental, and post-experimental survey. In the practice phase, the experimenter showed participants the start of the route, the vehicle indicator, and the vehicle arrival location. Each of the map parameters were also described (e.g., the start of the route is represented by a pulsing vibration and the audio cue "start"). Then participants were tasked with exploring the VAM and identifying to the researcher each of these map elements. Participants were shown how to use the double tap feature, which told them the remaining time and distance for the vehicle to reach the pick-up location. At the end of practice, participants were asked a series of questions to ensure that they understood the interface and how to use it. These questions included: 1) Which had a stronger vibration intensity, the grid or the vehicle route? 2) Where did the car start its route? 3) Where did the car end its route? And 4) How far was the route in total? Participants were also asked to identify to the researcher all the audio cues available on the map. If the participant incorrectly answered any question, they were given up to two minutes to feel the map again before being asked the same set of questions. All participants correctly answered the questions on the first attempt.

In the experimental phase, participants experienced two conditions, counterbalanced between participants: 1) The experimental vibro-audio map and 2) An audio-only condition that reflected the information currently available to BVI users in ridesharing apps. This audio information included ETA updates (e.g., car is two minutes away) and distance information (e.g., car is two miles away). Since the VAMs provided this information through the double tap feature, the conditions can be understood as additive (i.e., the VAM contained all of the

information from the control condition, while adding the vibratory map parameters). The goal of this approach was to ensure that the only difference between conditions were the experimental vibro-audio elements and that these VAMs were compared against the currently available nonvisual information in ridesharing apps.

Each condition included three trials where participants were tasked with imagining that they had ordered a rideshared vehicle to pick them up. Participants were told that each ride should take two minutes to arrive, but it could be delayed, and it could arrive to a different arrival location. The three trials included one ride that arrived in the correct amount of time (two minutes) to the correct location, one ride that was delayed by thirty seconds (by stopping at an intersection), and one ride that was rerouted "down the block" to an unanticipated pick-up point (the closest corner adjacent to the route). These trials were selected to match real-world challenges that BVI users face when using rideshare services and were derived from the existing literature, as reviewed in Section 2. Each trial used a different vehicle route, matched for complexity with random ordering between participants. Participants were tasked with monitoring each ride as it arrived using a think-aloud method (Jaspers et al., 2004) to gain insight into the user's task-interaction and satisfaction with the interface.

Participants were tasked with consistently stating their thoughts throughout the wait time, with special attention paid toward perception of the vehicle's behavior. The experimenter was present to remind participants of their task whenever they fell silent and all participant responses were recorded and transcribed. To guide this process and gauge basic understanding of the map, participants were asked throughout the wait time to make estimates and/or assumptions about the vehicle's trip and to let the experimenter know (1) When the vehicle was halfway along the route (2) If they thought the vehicle will be or might be delayed, and (3) If they thought the vehicle was changing routes or pick-up location. Depending on condition (vibro-audio map vs. audio-only) this information was inferred by monitoring the movement of the vehicle indicator on the map combined with audio or the audio ETA/distance updates. Of interest in this experiment was the extent to which the VAMs promoted effective spatial understanding and inferencing for users. As such, transcripts were coded using a broad coding scheme, where phrases that related to directly perceivable information from the interface (e.g., "the car is one mile away") were coded as *direct information* and responses that involved spatial inferencing (e.g., "the car is turning left") or supposition from the participant (e.g., "it's probably stopped at a red light") were coded as *inferred information*.

Directly following each ride, participants were asked a series of Likert-style survey questions (1-5, strongly disagree to strongly agree) that our team generated based on results from the existing accessibility and ridesharing literature, including estimated arrival time (Ranjbar et al., 2022), pick-up locations (Brewer and Kameswaran, 2019), and vehicle behavior (Kameswaran et al., 2018). The questions were as follows:

1. After the vehicle arrived, I would be confident in locating and traveling to its location
2. While waiting for my ride, I was confident that it would arrive at the estimated time
3. The provided information was sufficient to understand the vehicle's behavior

At the end of the experiment, participants were directed to a short post-test asking for input on the interface. Two Likert-style questions gauged perceived ease of use of VAMs as well as use-likelihood and two open-ended questions solicited user feedback and suggestions for improvement.

4 Results

Results comparing the VAMs with the audio-only interface showed initial support for the VAMs as an accessible ridesharing solution across question type (confidence in traveling to arrival location, confidence in the arrival time, and understanding vehicle behavior). The following summarizes findings for each of these performance metrics.
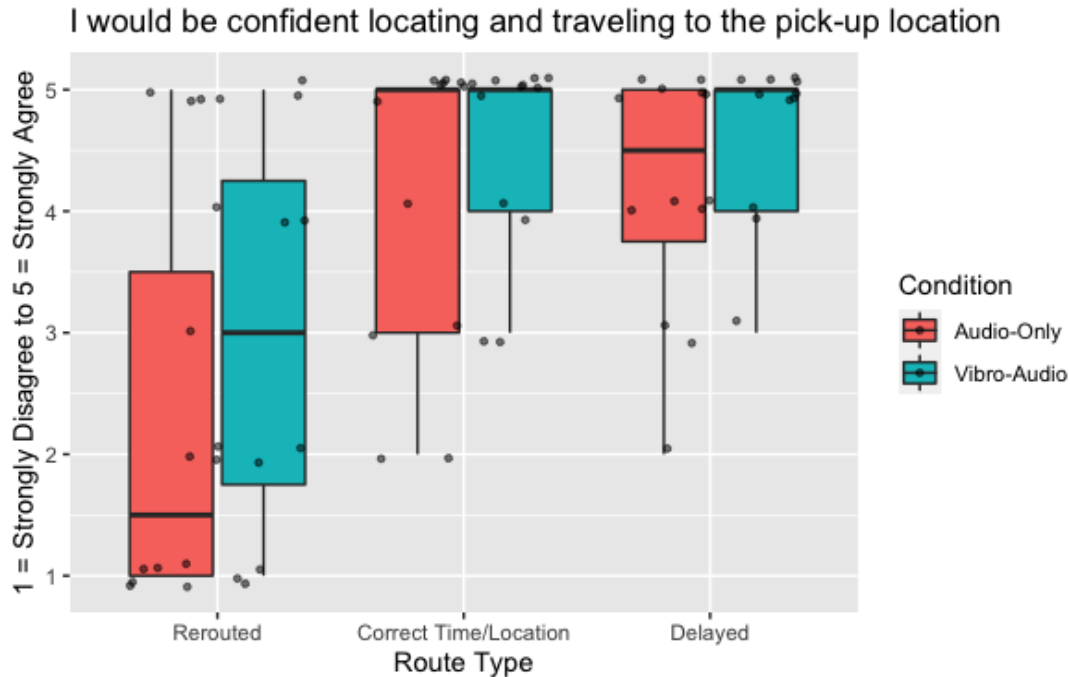

Figure 2. Boxplot showing participant confidence with vibro-audio and audio-only interfaces regarding arrival location.

On the pick-up location question (Figure 2), participants rated overall higher confidence in the vibro-audio map (VAM) condition ($M = 4.03$, $SD = 1.32$) than the audio-only condition ($M = 3.53$, $SD = 1.58$) across trials. A non-parametric within-subject Wilcoxon signed-rank test demonstrated that this difference was statistically significant ($p = .021$). Table 3 displays this combined comparison as well as the per-trial comparisons.

Table 3. Wilcoxon Signed-Rank tests for arrival location between VAM and Audio-Only

Measure 1	Measure 2	W	z	p
Combined: VAM	- Combined: Audio-only	78.500	2.306	0.021*
Rerouted: VAM	- Rerouted: Audio-only	21.500	1.268	0.233
Delayed: VAM	- Delayed: Audio-only	6.000	1.604	0.174
Correct: VAM	- Correct: Audio-only	6.000	1.604	0.174

We interpret the finding from the combined comparison as support that VAMs hold the potential to assist BVI passengers in understanding the vehicle's arrival location and to assist in passenger-vehicle meetup. Although the per-trial comparisons were not individually significant, the mean confidence scores were numerically greater for the VAMs across trial: Rerouted VAM ($M = 3.00$, $SD = 1.65$) vs. audio-only ($M = 2.33$, $SD = 1.72$), Delayed VAM ($M = 4.58$, $SD = .67$) vs. audio-only ($M = 4.17$, $SD = 1.03$), and Correct Time/Location VAM ($M = 4.50$, $SD = .80$) vs. audio-only ($M = 4.08$, $SD = 1.24$). We interpret these numerically higher results as supportive evidence that across types of vehicle behavior and routes (whether it is delayed, rerouted, or performing as expected) VAMs can assist users as well, if not better, than the current nonvisual information available in ridesharing apps.

On the arrival-time question (Figure 3), participants again rated overall higher confidence in the VAM condition ($M = 3.83$, $SD = 1.44$) than the audio-only condition ($M = 3.69$, $SD = 1.41$).
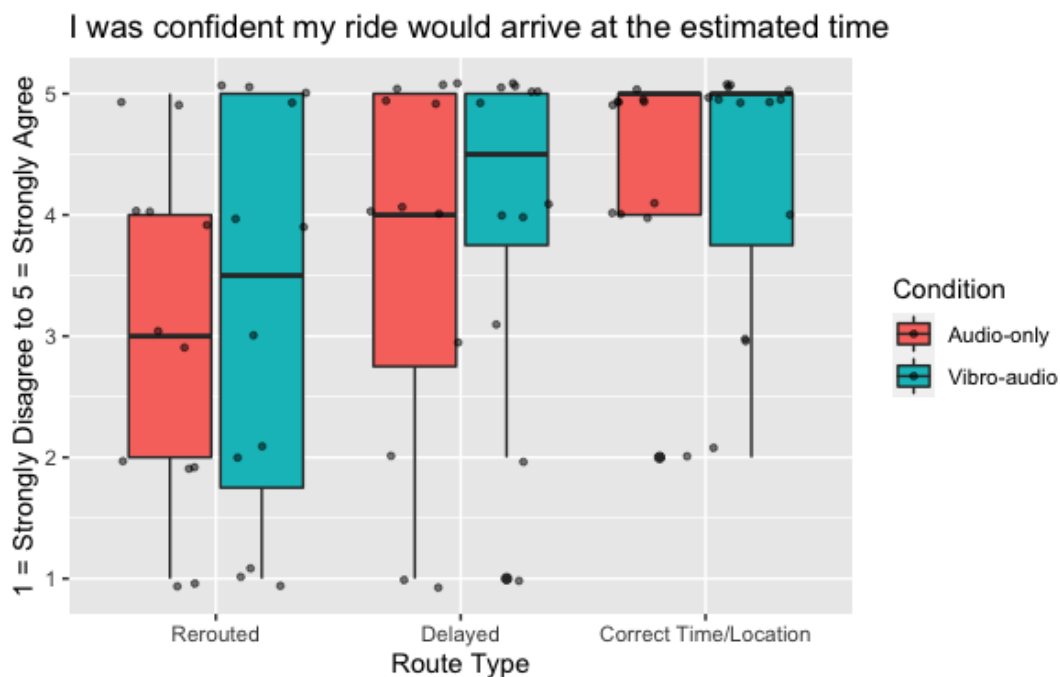

Figure 3. Boxplot showing participant confidence with vibro-audio and audio-only interfaces regarding arrival time.

Although this difference was not statistically significant ($p = .773$), as demonstrated by a non-parametric Wilcoxon signed-rank, in either the overall comparison or the per-trial comparisons (Table 4), the per-trial comparisons revealed slightly higher scores for the VAM in all but the Correct Time/Location trials, where the audio-only condition was rated marginally higher ($M = 4.42$, $SD = .90$ vs. $M = 4.33$, $SD = 1.07$). It is worth noting that in the delayed trials, the time estimates that participants received were updated in real time, so we interpret higher confidence as a positive result.

Table 4. Wilcoxon Signed-Rank tests for Estimated Time across each trial for both conditions

Measure 1	Measure 2	W	z	p
Combined: VAM	- Combined: Audio-only	65.500	0.312	0.773
Rerouted: VAM	- Rerouted: Audio-only	20.000	0.280	0.829
Delayed: VAM	- Delayed: Audio-only	4.500	0.802	0.586
Correct: VAM	- Correct: Audio-only	4.000	-0.365	0.850

On the vehicle behavior question (Figure 4), participants rated the VAMs marginally higher (*M* = 3.86, *SD* = 1.25) than the audio-only condition (*M* = 3.83, *SD* = 1.25) overall.
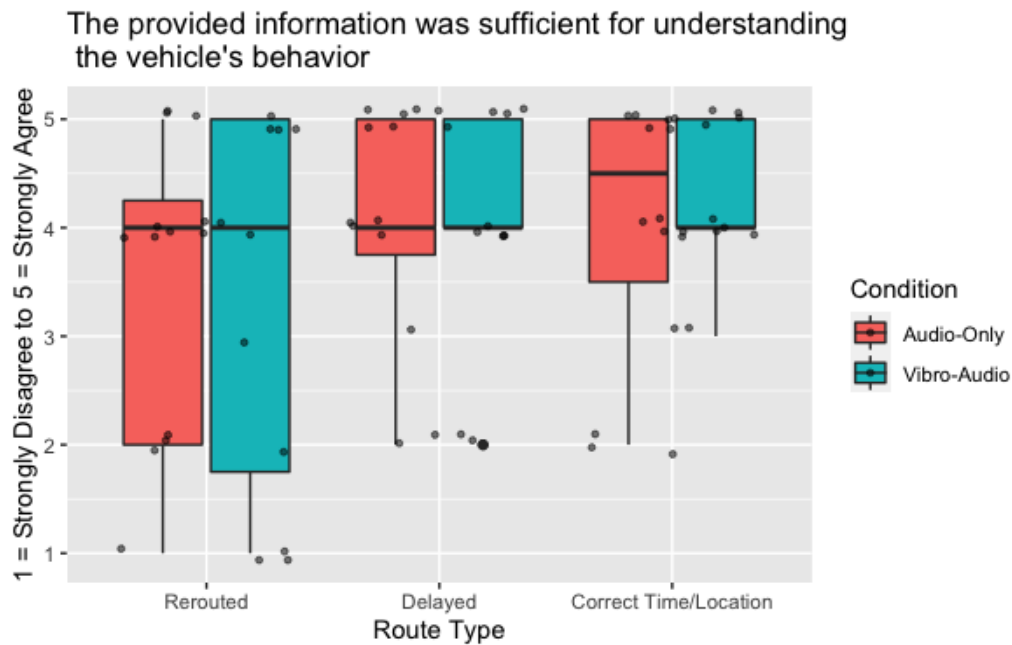

Figure 4. Boxplot showing participant agreement that the vibro-audio and audio-only maps provided sufficient information

A series of Wilcoxon-signed rank tests (Table 5) demonstrated that none of the differences were statistically significant and that the VAM was rated higher in all but the rerouted condition. Given the high degree of agreement among participants (all trials received a median score of 4, "agree," or above), we find that participants had generally enough information to interpret the vehicle's behavior in both conditions.

Table 5. Wilcoxon Signed-Rank tests for Sufficient Information for both conditions

Measure 1	Measure 2	W	z	p
Combined: VAM	- Combined: Audio-only	124.500	0.313	0.761
Rerouted: VAM	- Rerouted: Audio-only	8.500	-0.419	0.751
Delayed: VAM	- Delayed: Audio-only	20.000	0.280	0.829
Correct: VAM	- Correct: Audio-only	17.500	0.592	0.588

From the think-aloud tasks, participants were effective in identifying the halfway point of the route during both conditions. Of the 72 trials, only six (three VAM and three audio) did not identify the halfway point on the route. The time differential between when the participant stated the vehicle was halfway and the true location was analyzed for the remaining 66 trials using a within-subject t-test between trials of the same type (e.g., VAM delayed and audio-only delayed). Results (2-4s mean time differential between audio-only and VAM) indicated no statistically significant difference between the VAM and the audio-only conditions on this task ($p = .218$). Similar results were born out in the reroute and delay think-aloud tasks. For instance, in the reroute identification task, only four VAM and four audio-only trials missed that the car had rerouted ($p = .157$ for time differential comparisons), with only two audio trials and one VAM trial missing the delay ($p = .674$ for time differential comparisons). These data support that both interfaces were effective for identifying basic vehicle behavior and are consistent with the self-reported Likert data showing that participants had sufficient information to understand what was happening on the maps, as reported in Figure 4 above.

Qualitative data analysis from the think-aloud transcripts provided a more nuanced perspective on the utility of the VAMs. Results centered on the extent to which participants used basic *direct* from the interface (e.g., "the car is one mile away") vs. using the provided information to *infer* behavior about the vehicle (e.g., "it's stopped at a red light") while waiting for it to arrive. This analysis (examples provided in Table 6) demonstrated that the VAMs promoted more inferencing about the vehicle's location, behavior, and what might be happening throughout its trip than the audio-only condition.

Table 6. Representative examples of participant think-aloud response for both conditions

Vibro-audio Condition	Audio Only Condition
P2: "The car is done with three turns"	P1: "The car is one and a half minutes away"
P4: "Car is stopped at the corner"	P3: "It's one mile away"
P5: "Stopped at a light. Turned coming towards me"	P6: "It's travelling along"
P7: "It's going to a different pickup location"	P8: "It's still driving"
P8: "Car is in traffic. Car has sped up and is moving"	P9: "I think it's heading to me"
P10: "Still moving the way it's supposed to"	P12: "Getting closer and time is going down"
P11: "Turned south instead of north at the corner"	

Frequency of the direct vs. inferred information transcript codes were counted from the transcripts for each type of route (correct time/location, rerouted, and delayed). Results (Table 7) again indicate that across trials, VAMs promoted more inferred spatial information about the trip than the audio only condition.

Table 7. Frequency of think-aloud codes by route type and condition

	Vibro-audio (VAM) Condition			Audio Only Condition		
Route type (trial)	Correct	Rerouted	Delayed	Correct	Rerouted	Delayed
Direct Information	20	17	23	57	59	69
Inferred Information	78	85	88	15	24	27

Overall, the VAM condition resulted in 251 inferred responses and 60 direct information responses, compared to just 66 inferred responses and 185 direct information responses in the audio-only condition. We interpret this result as strong support that VAMs enable users to understand the route taken and the vehicle's behavior more than what is currently available for nonvisual access in ridesharing apps.

The post-test questions assessing desirability and ease of use of VAMs indicated high likelihood of use among participants. Importantly, results (Figure 5) demonstrated that all but two participants (10/12, 83.33%) agreed or strongly agreed with wanting to use the VAMs. When considering how easy they were to use, a majority (8/12, 66.67%) indicated that they were easy to use or very easy to use.
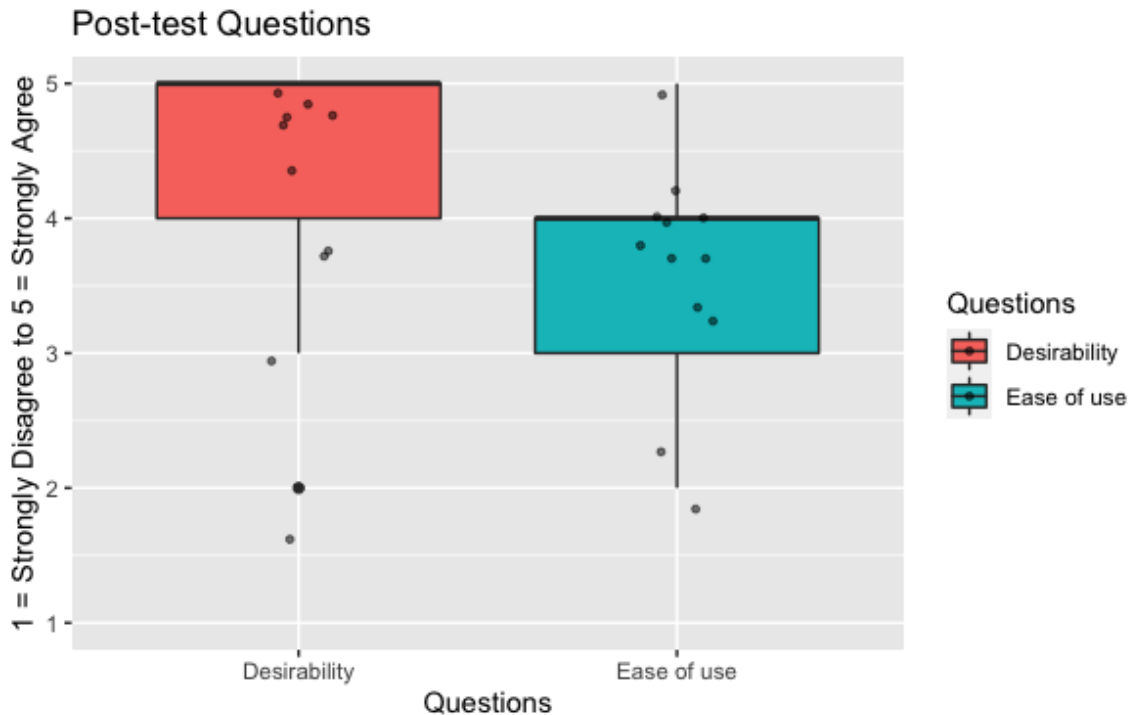

Figure 5. Boxplot for post-test questions regarding desirability and ease of use of VAMs

Long-answer post-test questions focused on improvement for the VAMs and gave a chance for participants to share their thoughts more generally. Common notes of improvement included

adding street names to the audio cues associated with the VAM interface and to automatically trigger audio for certain vehicle behaviors (e.g., when the vehicle was turning or it was changing its route). Though participants noted that they were able to follow the vehicle, these automatic audio updates could make tracking easier. Several participants noted that they thought the VAMs would also get easier to use with time and that they just were not very familiar with vibration and maps. This comment was not a surprise to us given our group's previous work with VAMs and motivated the practice phase used in our procedure here. Participants also mentioned that customization of the interface in terms of audio speed and vibration intensity would likely improve usability.

5 Discussion

User study results with (n=12) blind and visually impaired (BVI) participants demonstrated that ridesharing maps augmented with vibro-audio cues significantly improve confidence in locating a vehicle's arrival location. This finding suggests that accessible vibro-audio maps (VAMs) hold the potential to solve the critical user-vehicle meetup challenge for BVI travelers in the future of automated vehicles. Beyond the practical appeal of this solution, VAMs also facilitated substantially more spatial inferencing and discussion about the vehicle's behavior than audio-only nonvisual user interfaces, suggesting that VAMs promote improved information access and global understanding of maps more generally. The following discussion couches these findings in conversation with the literature and posits future work for implementation in current rideshare services and future autonomous systems.

5.1 Spatial Reasoning for Situational Awareness

The primary positive results from this research included improved user confidence in locating a vehicle's arrival location and enhanced spatial inferencing and logic provided by participants during the wait time over current audio-only user interfaces. Both results speak to greater user understanding of the vehicle's location, behavior, and driving situation, which all connect to the broader goal of promoting nonvisual situational awareness. Enhanced situational awareness has emerged time and time again as a critical desire among BVI travelers, especially in future autonomous vehicles (Brewer & Ellison, 2020; Brinkley, 2021; Brinkley et al., 2020). We contend, therefore, that VAMs hold the potential to compliment a growing research area aimed at improving situational awareness for BVI users (Fink, Abou Allaban, et al., 2023; Fink, Dimitrov, et al., 2023), both during pre-journey tasks like waiting for a ride to arrive, as well as during vehicle travel. Though this study explored the former, future work should investigate the ways in which accessible maps combining multisensory cues can promote situational awareness and actionable spatial reasoning and behavior during in-vehicle navigation. The novel real-time user interface elements that allow for this dynamic spatial tracking should also be further explored, as discussed in the following.

5.2 Multisensory Real-time Tracking without Vision

This work presents, to our knowledge, the first vibro-audio user interface that enables nonvisual tracking of dynamic objects. Although a growing body of research has used vibro-audio interfaces for graphical access and education (Giudice et al., 2012; Klatzky et al., 2014; Doore et al., 2023, Tennison et al., in press) and mapping (Giudice, Guenther, Jensen, et al., 2020; Palani et al., 2016; Palani et al., 2022; Palani & Giudice, 2017), these solutions have relied solely on

static user interface elements. By contrast, results presented here demonstrate that users can track a vibration-based element moving across other vibratory elements like lines and vertices. Beyond the real-time vehicular mapping applications of this technology, as studied here, dynamic tracking of on-screen elements has extensive implications for future accessible user interfaces, such as within data visualizations (e.g., for animated time-series bar charts), wayfinding applications (e.g., for vibratory real-time compasses), multimedia applications (e.g., for tracking progress bars on videos and songs) and accessible games for entertainment. Future work should build on the proof-of-concept demonstrated here (using a moving vibro-audio circular object at a fixed speed) to investigate and identify the ideal perceptual parameters for other dynamic shapes, sizes, and movement speeds for these applications.

6 Conclusion

This paper presents a novel vibro-audio mapping (VAM) solution enabling real-time nonvisual vehicle tracking for blind and visually impaired (BVI) ridesharing users. A user study with (n=12) BVI participants compared the VAM user interface with the nonvisual audio information provided in current ridesharing apps. Results indicate superior confidence in navigating to the vehicle's arrival location using VAMs, complimented by more detailed understanding of the vehicle's en route behavior. These results have broad implications for near-term mobility and independence in current rideshares, while also paving the way for future accessible use in autonomous vehicles.

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CHAPTER 5: Give Us Something to Chauffeur it: Exploring User Needs in Traditional and Fully Autonomous Ridesharing for People who are Blind or Visually Impaired

Contribution statement: The following paper has been submitted for publication in *Transportation Research Part F: Traffic Psychology and Behaviour* and is currently in revision. My contribution on this project, which included a survey to (n=187) BVI ridesharing users, consisted of the design of the survey and interpretation of the data. As first author on the paper, I also led the written component up to and including submission.

Give Us Something to Chauffeur it: Exploring User Needs in Traditional and Fully Autonomous Ridesharing for People who are Blind or Visually Impaired

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ABSTRACT

As self-driving technology advances, there is enormous potential to optimize fully autonomous vehicles (FAVs) for use by people who are blind and visually impaired (BVI). Today, BVI users often rely on ridesharing services for daily travel, which present both challenges and opportunities for researchers interested in the accessible design of FAVs. The parallels between current BVI travel experiences in rideshares and predictions that FAV services will adopt rideshared models presents an enticing opportunity to use ridesharing as a proxy for understanding BVI needs in future FAV transportation. However, a key challenge is identifying the extent to which FAVs should be designed to provide the same assistance that human drivers currently provide for BVI travelers in rideshares. To address this issue, ridesharing users with visual impairment (n=187) completed a survey instrument designed to assess and compare desires for interactions, information, and assistance between human operated and fully autonomous rideshare vehicles, as well as the modality of information delivery (auditory and/or haptic). Results indicate strong support for access to environmental information (e.g., spatial information about the destination) and contextual information (e.g., progress along the route) across the trip with automated vehicles via natural language interactions. Although results suggest significantly less desire for social interaction with the AI "at the wheel" of FAVs when compared to human drivers, findings indicate that participants desire some social collaboration and human-in-the-loop control during autonomous driving. By empirically comparing human and autonomous ridesharing and exploring both the information needs and modality preferences across information category, the results provide much-needed guidance for future design of humanlike, anthropomorphized, FAV AIs with important implications for social autonomous agents more generally. Results also speak to the ways in which inclusive and accessible user interfaces should support user needs across the range of vision loss in future transportation networks.

Keywords: Autonomous vehicles, People with visual impairment, Ridesharing

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1 INTRODUCTION

Growing efforts to realize the full potential of fully autonomous vehicles (FAVs) have resulted in emerging research examining strategies to support people who are blind and visually impaired (BVI) in this new class of transportation technology. From survey and focus-group based designs (Brinkley et al., 2020), to approaches that involve imagining and designing interfaces for FAVs (Brewer & Kameswaran, 2018; Huff et al., 2020), researchers have deployed a myriad of methodological tools for understanding how BVI people should be supported in a technology that is, as of

yet, not widely available. One important strategy has built on predictions that FAVs will operate much like ridesharing services operate today (Narayanan et al., 2020). This approach utilizes experiences with current human-driven ridesharing services (e.g., Uber or Lyft) as a proxy for understanding BVI needs in future AI-driven FAV transportation (Brewer & Ellison, 2020).

Beyond the primary task of driving, the extant literature suggests that human rideshare drivers often assume social roles to support BVI travelers. For instance, drivers engage in *emotional labor* by sharing information regarding their personal life or by simply listening to the passenger express their thoughts in order to provide comfort (Brewer et al., 2019). Drivers also serve to enhance *trust-building* with passengers through conversational small-talk, which can include discussing their lives or holding positive and friendly conversation to build shared social capital (Brewer & Kameswaran, 2019). By collaborating with BVI passengers when asked for help during the trip, drivers have also been noted to facilitate passenger independence (Kameswaran, Gupta, et al., 2018). These value-added roles assumed by human drivers during BVI ridesharing have coincided with more general research exploring highly human-like social AIs and the associated benefits of AIs assuming social roles, such as increased user trust (Toader et al., 2020) and satisfaction when meeting user expectations (Rapp et al., 2021). In the automotive space, anthropomorphized interfaces in FAVs have begun to gain traction for promoting trust and user acceptance (Niu et al., 2018; Ruijten et al., 2018; Waytz et al., 2014). Indeed, designers have sought to capitalize on these positive outcomes, which has manifested in onboard AI assistants like Volkswagen's Sedric (Biermann, 2022) and Toyota's Yui, "more pal than interface" (Coulter, 2019).

Taken together, this body of work would seem to suggest the importance of highly social human-like AIs 'at the wheel' of autonomous vehicles, both for the general public, and specifically for BVI people who may particularly benefit from social interaction with human rideshare drivers. However, the available research offers little guidance as to the prioritization of social parameters when transitioning from human rideshare drivers to FAV AIs, nor does it provide best practices for design along this translational path. While it is likely true that people with visual impairments desire FAVs capable of providing *some* of the social interactions they value in human rideshares, it would be foolhardy to assume that FAVs should attempt to convey *every* aspect of human-like interaction. Indeed, many of the valuable services provided by rideshare drivers and identified by BVI people in previous research do not include social aspects, instead pertaining to the context of the trip (i.e., route progress, entry and exit information, and environmental information) (Brinkley, 2021; Brinkley et al., 2017). To disambiguate this relationship, and to provide guidance to FAV designers, the present study compares the perceived value of both social and contextual/environmental information when provided by a human rideshare driver versus an AI driver. By doing so, results from the survey instrument designed to support the study not only identify a host of parameters that should be prioritized in FAV development, but also offer valuable theoretical insight into the use of rideshare models as proxies for FAV futures.

1.1 Related Research with BVI Users and FAVs

A growing body of work has begun to examine the perception of FAVs among BVI people and the needs of this demographic in the future of transportation. For instance, Bennett, Vijaygopal and Kottasz's (2020) survey study of 211 BVI respondents in the UK assessed attitudes towards Level 5 (fully autonomous) vehicles, with their findings suggesting that independence, safety, and affordability were significant factors for perceived future use (Bennett et al., 2020). Results also suggested concerns and skepticism among BVI people about being adequately considered, a central theme that also arose in related research (Brinkley et al., 2020; Fink et al., 2021). Specifically related to ridesharing, in Brewer and Ellison's (2020) interview study of 16 BVI rideshare users, findings suggest that common expectations for drivers include assistance in finding and entering the vehicle, ending the ride at an accessible location with assistance in exiting the vehicle, and desired communication including environmental descriptions and general conversation. Participants also described placing trust in their drivers to safely transport them to their destination, which increased with drivers whom they had previously driven with. Some concerns were raised with regard to difficulty in rideshare accessibility, such as ordering and locating a ride, as well as navigation after arriving at a destination (Brewer & Ellison, 2020; Brewer & Kameswaran, 2019). These results suggest that BVI rideshare users believe being able to interact with a driver is not only useful, but also important for safety and confidence. Interacting

with the driver is understandably important for accurately receiving information about the route and the surrounding environment, raising concerns about whether FAVs will be designed to provide the same level of assistance. Although it is clear interactions with the driver are valuable in determining rideshare passengers' expectations in human rideshares, an empirical investigation of these interactions is necessary to determine effective transition to FAV ridesharing. By so doing, findings would help form the foundation for future research agendas supported by inclusive design guidelines for FAV development and successful Human-AI interactions with this new form of transportation. Related research from the perspective of rideshare drivers also elucidates the importance of this effort, as described in the next section.

1.2 Related Research with Ridesharing Drivers

Prior research has explored the perspective of rideshare drivers with BVI passengers, revealing methods of interaction with these passengers and the important role that the driver plays in assisting people without vision. For instance, Brewer et al.'s (2019) interview study with 18 ridesharing drivers investigated ways in which drivers assist BVI passengers beyond the primary task of driving (Brewer et al., 2019). The authors found drivers engage in labor that falls within one of three domains: physical, emotional, and relational. Physical labor involved helping the passenger enter and exit the vehicle, as well as assisting them in reaching their destination. Although not explicitly discussed, drivers indicated they engaged in emotional labor through conversations about their personal lives and lending an ear for passengers to speak what is on their mind. The authors also found drivers who drove the same passenger on multiple occasions engaged in relational labor by building interpersonal connections with them, which was viewed positively by both parties. This finding regarding the importance of social interaction between driver and passenger in ridesharing was also supported in a related study with 13 rideshare drivers, where drivers discussed engaging in conversation as a means of emotional support as well as to build rapport (Kameswaran, Cameron, et al., 2018). Participants found that they benefited from these interactions as they became more knowledgeable with regard to culture and social conflicts, such as learning about the Black Lives Matter movement or about different types of food and music. Indeed, the benefits of social interaction with drivers of ridesharing services may well extend across user ability and age – a recent study with 169 older adult rideshare users found that passengers tend to appreciate friendly conversations with their drivers and are even inclined to build friendships throughout their trips (Bayne et al., 2021). Taken together, these findings suggest that physical, social, and informational engagement between rideshare drivers and passengers are an important aspect of the ridesharing experience. As such, further exploration is necessary to shed light on the extent to which these interactions should be conveyed as transportation systems transition from human drivers to AI-driven FAVs, as we seek to do here.

2 MOTIVATION AND CONTRIBUTIONS OF THE PRESENT STUDY

To better conceptualize the similarities and differences between human and autonomous rideshares, and to identify a host of features that would support BVI people in FAVs, a survey study was designed and completed by (n=187) adults in the United States, with the selection criteria of (1) having some form of self-reported visual impairment and (2) having ridesharing experience. Of interest was determining the relative importance of features along two categorical domains, each derived from the existing BVI ridesharing research: (1) social interaction (e.g., small talk, social support, and collaborating on tasks) and (2) contextual/environment information (e.g., turn-by-turn directions, route-progress, and environmental information). By comparing responses from these two categories, and between assessments when using human operated (traditional) vs. AI operated (FAV) rideshares, we aimed to assess the ways in which the desire for information and services provided by a driver may change depending on the driving agent: human or AI. Aggregate results demonstrating a preference or distaste for a set of these features in the FAV compared to the human rideshare would be of important theoretical value in clarifying the use of ridesharing as a surrogate for BVI desires in future FAVs. Furthermore, by identifying a host of features to be prioritized in FAV interface development, results from the survey could be used as guidelines that contribute to the accessible design of future FAVs, as well as the high-fidelity simulators increasingly being used in user-driven FAV research. We contend that

to realize the benefits of these efforts, results must include a set of accessible design guidelines to promote inclusive, usable, and trustworthy systems for both ongoing research and real-world deployment.

Of critical interest here is also the modality in which these features are presented. That is, in addition to knowing what types of information and interactions are important to BVI people in FAV transportation, effective information transfer and positive user experiences rely on *how* that information is presented. We feel this is an important variable to study, as all too often, an accessible, nonvisual user interface simply means that it uses speech and natural language (NL), which has become the de facto solution for providing information access to BVI users. Despite their significant benefit, the use of other modalities in inclusive user interface (UI) design, such as haptics, spatialized audio, and multisensory interactions are rarely considered or studied. Although interfaces relying solely on NL are effective, they are slower and require more cognitive load than more perceptual UIs (haptics, spatialized audio), especially when conveying spatial information that would be relevant to autonomous vehicle travel like inter-object relations and maps (Giudice, 2018). Therefore, a secondary goal of this research is to identify the ways in which multimodal UIs leveraging multisensory cues can support the types of information and interactions BVI people most desire in FAVs. This effort is important because the often-utilized approach to UI development in current semi-autonomous and emerging fully autonomous vehicles involves a visuocentric control center via a touchscreen that is inaccessible to BVI people (see (Palani et al., 2020, 2022) for a review of the limited examples of accessible touchscreen design). As such, for UIs and interaction styles to support BVI people in FAVs, there needs to be new multisensory or nonvisual approaches to support control and operation. Results are predicted to support the growing body of work emphasizing multimodal interfaces in FAVs for people with sensory impairments (Brinkley, 2021; Brinkley et al., 2019; Fink et al., 2021) while also providing much needed guidance in the inclusive FAV design space by providing per feature recommendations for multimodal interaction.

3 METHODOLOGY

The survey instrument used in this work was developed and deployed remotely by Qualtrics (Qualtrics, Provo, UT) to 205 people reporting moderate to severe vision loss. 18 of these responses were eliminated due to the participants not having any ridesharing experience, leaving 187 responses that were analyzed. Participants took on average 5.5 minutes to complete the survey. The survey situated questions in both a human rideshare scenario, where participants were tasked with imagining riding with a human driver, and in an FAV scenario, where participants were tasked with imagining riding with an autonomous AI driver. Items on the survey covered specific types of contextual/environmental information (e.g., landmarks of interest along the trip vs. turn-by-turn directions) and aspects of social interaction with the AI (e.g., social support vs. small-talk), each derived from the related literature with BVI users, FAVs, and ridesharing. Participants began the survey with 13 demographic questions detailing factors such as the type and extent of their visual impairment and their frequency of rideshare usage. Then, participants undertook the inventory items related to social aspects in both the FAV and human scenarios. These questions were designed using a 7-point Likert scale, where 1: Strongly Disagree and 7: Strongly agree represented the response range. Question items were derived from results in the BVI FAV research reviewed in Section 1 and the full inventory can be found in Appendix A-1. For each inventory item in the FAV scenario, participants were also asked to identify the ways in which the information or interaction should be presented (i.e., through an auditory interface, a tactile/haptic interface, or combinations thereof). These 'modality' questions were presented through multiple choice options. This research was approved by the University of Maine's Institutional Review Board.

3.1 Sample

Participant ages ranged from 18 to 82 (M = 40.12, SD = 15.84), with 78.72% of the sample being female. The survey was conducted in the United States, with 66.84% of the sample reported living in an urban area and the rest living in a rural area. All participants reported some type of visual impairment, affecting 80.85% of participants in both eyes. The most common reported visual impairments included astigmatism (27.27%), nearsightedness (19.25%), and neuropathy or diabetic neuropathy (8.02%). Overall, 83.96% of participants reported having low vision and 9.63%

reported being legally blind. All but one participant used glasses or contacts and two participants used a white cane. Forty percent of participants reported using an accessibility feature while taking the survey, with the most common features including Google talkback (14.44%), Apple voiceover (10.70%), and magnification (9.09%). Sixty-five percent of participants reported that their vision has changed within the past 5 years, while the rest reported consistent vision during this time period. All participants reported prior ridesharing experience, with the most common usage frequencies being yearly (41.12%), monthly (34.22%), and weekly (12.30%).

3.2 Research questions

The study was guided by the following research questions:

RQ1. What social factors are most important in human and FAV rideshares for BVI users?
RQ2. Is there a difference in importance for social factors between human rideshares and FAV rideshares?
RQ3. What environmental factors are perceived to be most important during FAV rideshares?
RQ4. Among the desired social and contextual/environmental information, what presentation modalities do BVI passengers prefer in FAV rideshares (i.e., haptic/vibratory, auditory based, combinations of both)?

In the following section, results are reported in relation to each research question.

4 RESULTS

When considering the importance for social interaction with the human driver in traditional rideshares and the AI driver in FAV rideshares (RQ1), we analyzed participant responses for each scenario in terms of items derived from the related research: emotional/psychological support, collaboration and giving input, building trust through interaction, and engaging in small talk. Given that our sample included a wide range of vision loss, we chose to analyze and report both the entire sample (n=187) and participants who specifically identified as legally blind (n=17). Figure 1 displays responses for these two groups in the human ridesharing scenario.
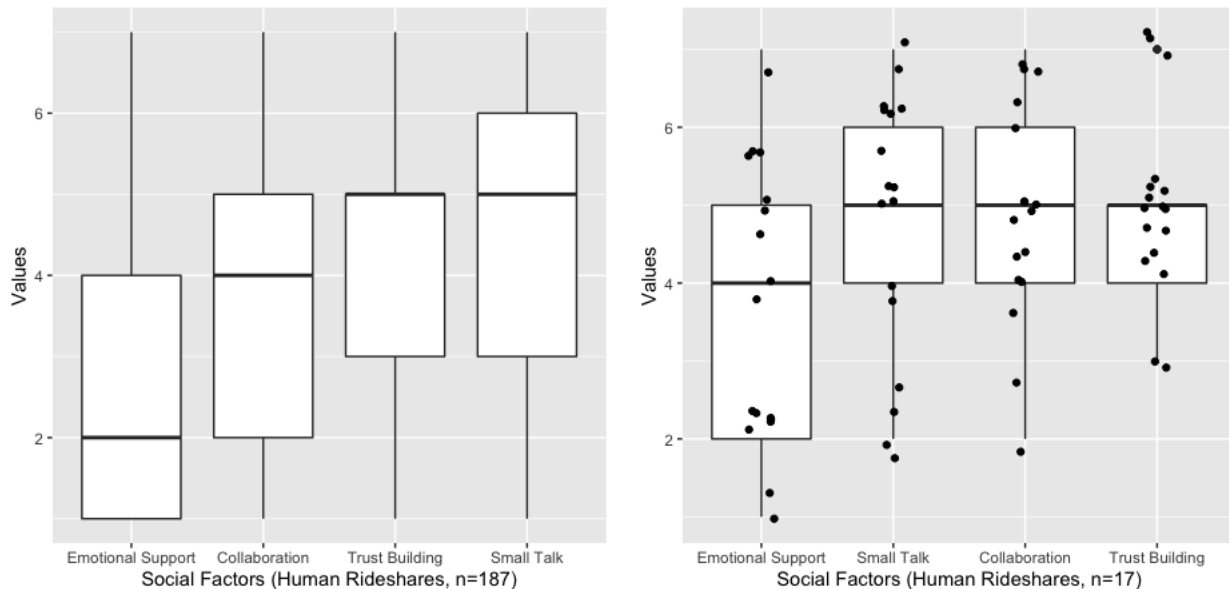

Figure 1. Social factor importance with rideshare drivers for all participants (left) and legally blind participants (right)

Descriptively, the values suggest that for the larger group, small talk with human rideshare drivers is the most important to people with vision loss, with 60.96% of participants generally agreeing (rating 5 or above on the Likert scale question) that they would like to engage in small talk. This finding was followed by trust building with the driver

(51.87% generally agreeing), collaborating with the driver (41.71% generally agreeing), and finally receiving emotional support from the driver (22.99% generally agreeing). For legally blind participants, building trust (70.59%) was rated as most important, followed by small talk (64.71%), collaboration (58.82%), and emotional support (41.18%). It is interesting to note the substantial increase in agreement across social category for the legally blind participants compared to the full sample. Potential explanations for this phenomena are discussed in Section 5.

To determine if the difference in perceived importance between each social aspect/factor are statistically significant in the full sample, we performed a Friedman's test recognizing the non-parametric nature of these Likert data. The type of social interaction demonstrated a significant effect on participant Likert scores $\chi^2(3) = 111.835, p < .001$. Post-hoc comparisons demonstrated that small talk was rated as significantly more desirable than collaboration and emotional support ($p's < .001$), as were trust building and collaboration from emotional support ($p's < .001$).

We undertook the same process of analysis for social interaction with the AI "driver" of FAVs. Figure 2 displays responses for all participants in the FAV scenario, as well as responses for those identifying as legally blind.
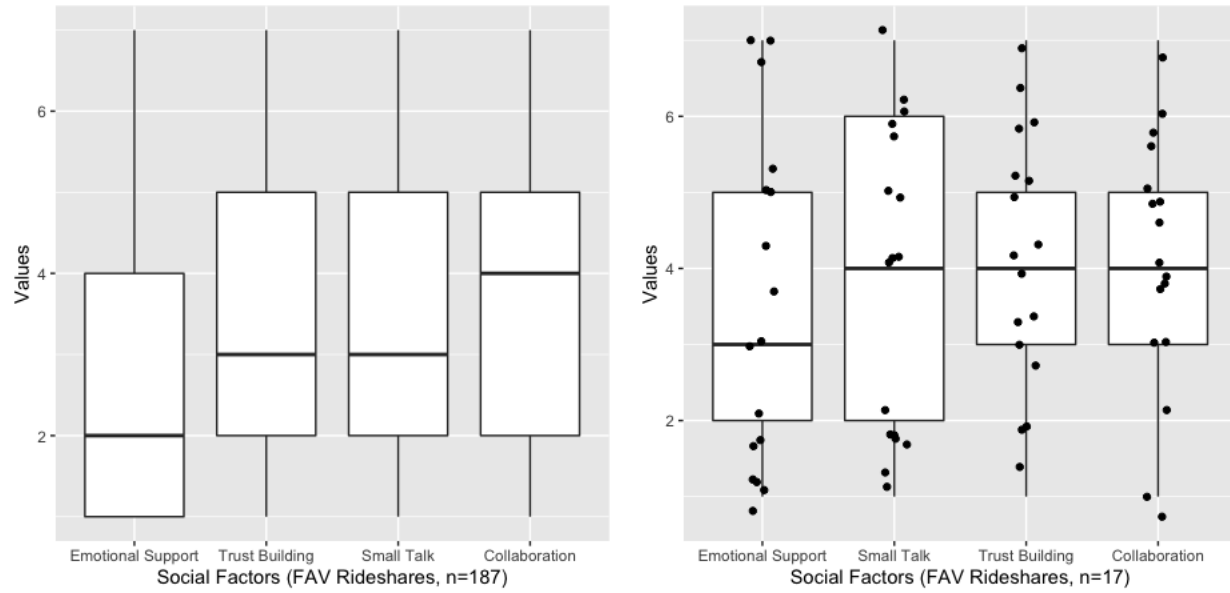

Figure 2. Social factor importance with FAV rideshares for all participants (left) and legally blind participants (right)

In the FAV scenario, the values for the full group suggest that collaboration with the AI driver is most desirable with 42.45% of participants generally agreeing and 39.57% generally disagreeing (with 18.18% neither agreeing nor disagreeing). This was followed by small talk (33.16%), trust building (31.55%), and emotional support (12.83%). Among legally blind participants, collaboration was also rated as most important (47.06%), followed by building trust (41.18%), small talk (41.18%), and emotional support (35.29%). Again, just as in the human driver scenario, agreement scores across category were substantially greater for participants who identify as legally blind. The Friedman's test in this case again revealed that the type of social interaction significantly impacted participant Likert scores $\chi^2(3) = 80.473, p < .001$, with post-hoc comparisons demonstrating that collaboration, small talk, and trust building were all significantly different and rated as more important than emotional support (all $p's < .001$).

Whereas in RQ1 we were interested in the perceived importance *within* human or FAV driven rideshares, in RQ2, we sought to compare the importance of social factors *between* FAVs and human rideshares. To do so, we first conducted a paired t-test that compared the mean social importance score for each participant between the FAV and human scenario. This test suggests that there is greater preference for social interactions in human rideshares (M = 3.828, SD = 1.200) compared to FAV rideshares (M = 3.224, SD = 1.377), which was statistically significant ($p < .001$). We then conducted a within-subject analysis at the per question level using the non-parametric Wilcoxon test. Results of this test are summarized in Table 1.

Table 1. Wilcoxon Signed-rank Test

Measure 1	Measure 2	W	z	p
Small Talk (Human)	- Small Talk (FAV)	6739.5	6.438	< .001
Emotional Support (Human)	- Emotional Support (FAV)	2651.0	3.361	< .001
Trust Building (Human)	- Trust Building (FAV)	5293.0	5.699	< .001
Collaboration (Human)	- Collaboration (FAV)	3098.5	0.829	0.400

Results indicate significant difference along all question types (p's < .001), except for collaboration with the driver (p = .400). Taken together, these results suggest that although there is less desire for social interaction with autonomous drivers than with human drivers overall, BVI passengers still hope to collaborate with the AI driver and give input during the trip to the same extent as with human drivers.

For RQ3, we sought to assess the importance of different *environment factors* in FAVs among BVI users. Figure 3 displays all participant responses along the environmental information inventory items of interest and derived from the literature, as well as those for participants identifying as legally blind. These items included entry and exit assistance, information about pedestrians, information about the surrounding environment around the vehicle, receiving turn-by-turn directions, information about accessing the destination, receiving a route overview prior to driving, information about changes in vehicle behavior, and information about progress along the route.
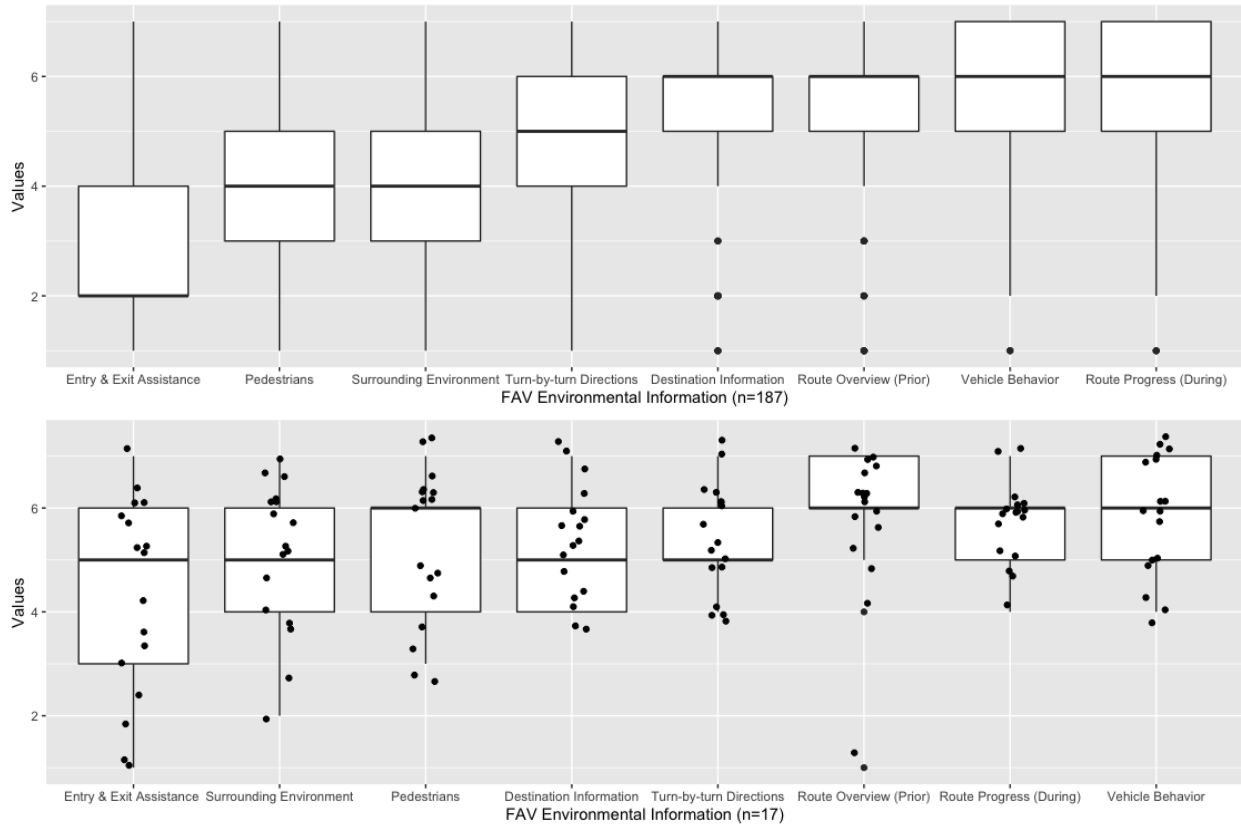

Figure 3. Environmental information importance for all participants (top) and legally blind participants (bottom)

In the FAV scenario, route progress was rated as most desirable with 89.3% of all participants generally agreeing and 5.35% generally disagreeing (with 5.35% neither agreeing nor disagreeing). This was followed by vehicle behavior (81.3%), route overview prior to the trip (80.22%), destination information (76.47%), turn-by-turn directions

(62.02%), surrounding environment information (48.67%), pedestrian information (43.32%), and entry and exit assistance (22.47%). For the subsample of participants identifying as legally blind, route progress information was rated as most important with 94.12% generally agreeing, followed by route overview prior to the trip (88.24%), vehicle behavior (82.35%), turn-by-turn directions (76.45%), destination information (70.59%), pedestrian information (70.59%), surrounding environment information (70.59%), and entry and exit assistance (52.94%).

The Friedman's test revealed that the type of environmental interaction significantly impacted participant Likert scores $\chi^2(7) = 457.735$, $p < .001$. Post-hoc comparisons showed that route progress (during), vehicle behavior, route overview (prior), and destination information were all significantly different and rated as more important than turn-by-turn directions, surrounding environment, pedestrians, and entry & exit assistance (all $p's < .001$).

For RQ4, we aimed to evaluate which modalities of information presentation BVI users would prefer in an FAV (haptic, natural language, or both). The percentage of each response was evaluated for each individual question. It was found that across all questions, participants preferred natural language only (64.71%–73.97%), followed by both natural language and haptic (21.76%–26.55%), and haptic only (4.11%–12.35%). This was true for all participants as well as the subsample of participants who identified as legally blind.

5 DISCUSSION

Results from this research highlight the distinct differences that people with visual impairment desire between current human-operated rideshare vehicles and future AI-operated autonomous vehicles. Notably, though results suggest that BVI users want less social interaction in FAVs as a whole, collaborative engagement with the AI "driver" was desired to the same extent as with human drivers. Results also suggest that designers should be aware of the range of vision loss experienced by BVI people, as people who are legally blind reported substantially more desire for interaction in both the human-operated and FAV scenario, particularly related to building trust. Furthermore, findings demonstrate strong support for users desiring a battery of environmental/contextual information throughout travel with autonomous vehicles, an important corroboration of research indicating the need for increased situational awareness. The following offers insight on each of these findings in relation to the future design of accessible FAVs.

5.1 Ridesharing as a Proxy for the Fully Autonomous Future

Results from this study indicate that researchers and designers should exercise caution when applying knowledge from the human-operated ridesharing domain to the design of accessible FAVs. Although ridesharing is a frequently mentioned pathway for studying autonomous transit (Brewer & Ellison, 2020; Brewer & Kameswaran, 2019; Fink et al., 2021; Kameswaran, Gupta, et al., 2018), it is logical that the needs and expectations of users in these two modes of travel do not translate 1:1. At a high level, our results suggest that people with visual impairment want much less social interaction in FAVs than they do with rideshare drivers, an important finding when contrasted with growing research lauding the benefits of anthropomorphic and conversational UIs in automated vehicles (Li & Suh, 2021; Niu et al., 2018; Ruijten et al., 2018; Verberne et al., 2015; Waytz et al., 2014). However, there is a critical caveat here: our results showed that the majority of participants wish to engage in collaboration with FAVs and give input on decisions to the same extent as with human drivers. We interpret this finding as an indication that even in fully autonomous vehicles, there is a desire to be "in-the-loop" of vehicle control and exercise some agency over the trip itself. Indeed, support for agency and control in automated vehicles has been found in related qualitative research with BVI travelers (Brewer & Kameswaran, 2018). We postulate that this desire for collaboration and input in the automated driving process likely manifests more for specific driving actions over others. For instance, people might want to give input on the vehicle's speed more so than its following distance. Logic would suggest that there could be alignment between the types of information people desire during a trip and the types of vehicle control on which they wish to give input. Considering our results from the environmental/contextual questions, which showed preference for information on the route and changes in vehicle behavior, route-based control (e.g., altering the route, adding a stop, or choosing the "scenic" route versus the fastest route) and vehicle behavior that may change frequently (e.g., speed) may be specific types of control that BVI people desire in FAVs. More research is needed to uncover how

human-vehicle collaboration should be prioritized across driving action and how user interfaces should be designed to support multisensory access to information that enables this control. That is, designers should carefully consider how to include all people in control-based decision making in automated vehicles by developing vehicle interfaces – anthropomorphic or otherwise – that are inclusive rather than exclusionary of people with sensory impairments.

5.2 Designing for Trust Across the Range of Vision Loss

People with visual impairment are often studied as a homogenous group, when in actuality, the range of etiology, onset, and extent result in disparate needs and lived experiences. This phenomenon was borne out in our data, where the seventeen legally blind participants noted substantially greater desires for interaction with both human drivers and FAVs than the larger group of visually impaired participants. Although the unequal sample sizes made a statistical comparison inappropriate, of note here is that differential scores were particularly the case for the question concerning interactions that build trust. Legally blind participants noted building trust as important at substantially higher rates than the full group of BVI participants: roughly 10% more in the FAV condition and 20% more in the human condition respectively. We postulate that the increased desire for interaction and trust-building conversation among legally blind participants in rideshares could be the result of desiring more access to information from the perspective of the "sighted" agent (human or AI) compared to their peers with more usable vision. In other words, since monitoring the surrounding environment, the vehicle's progress on a route, the proximity of the vehicle's location to a known location at pick-up or drop-off, and related distal tasks is difficult using nonvisual sensing, we postulate that legally blind passengers with limited functional vision will report greater reliance on information access from the rideshare driver to obtain this knowledge. While the current data provide tentative support for the notion that there will be an increase in trust requirements and information-exchange demands as a function of decreasing visual status of the passenger, more research is needed to empirically study this prediction. Furthermore, we contend more research is needed to investigate the ways in which desires for interaction and trust manifest across the spectrum of disability, visual or otherwise. This effort would inform the pursuit of user trust at large, which has emerged as a critical factor in the autonomous vehicle literature, where only 14% of drivers note that they would trust riding in an FAV (Edmonds, 2021). We argue in support of the existing research discussing the myriad benefits of multisensory access in FAVs (Brewer & Kameswaran, 2018; Brinkley et al., 2019; Fink et al., 2021), and predict that as information about the trip is presented meaningfully through accessible interfaces, so too will trust increase.

5.3 Environmental Information for Situational Awareness

Our results offer what we believe to be the first per-feature comparison of nonvisual environmental information to be conveyed in automated vehicles, which offers insight as to what information should be prioritized in inclusive FAV UIs. Turn-by-turn directions, destination information, information related to the route (both a pre-journey overview and enroute progress), and information regarding changes in vehicle behavior were the most highly rated by participants. Combined with our results regarding the modality for presentation, namely a priority across information type for natural language, these results can be used to guide the development of new nonvisual interfaces that increase spatial knowledge about the trip (e.g., accessible mapping) and audio interfaces that increase situational awareness in relation to the vehicle's decision-making. It is worth noting, however, the relatively low indicated preferences for haptic UIs should not be taken out of context, as these results are likely the outcome of participants lacking experience with navigational interfaces that rely on haptics. That is, people tend to be much more familiar with natural language navigational supports, thus impacting their reported preference. Regardless of the presentation modality, the need for increased situational awareness via these accessible, multisensory interfaces has often been cited in the BVI FAV literature (Brewer & Ellison, 2020; Brinkley, 2021; Brinkley et al., 2020) and our results empirically corroborate much of these findings at a more granular and tractable level. Surprisingly, however, given the attention paid to entry, exit, and last meter assistance in these previous studies, as well as in the recent U.S. DOT Inclusive Design Challenge Projects (Inclusive Design Challenge, 2020), our participants rated entry and exit processes fairly low compared to the other information types. This was less the case for the legally blind participants versus the larger group with some level of visual impairment, which suggests that preference for this type of information may increase as a function of

visual loss and further supports our argument that researchers and designers must consider the range of vision loss and type of disability in general when designing for accessibility.

6 CONCLUSION

People who are blind and visually impaired (BVI) stand to greatly benefit from automated vehicles if they are designed to convey relevant information about the trip, accessibly and appropriately. Our survey-based results with (n=187) BVI users revealed the need to exercise caution when translating current ridesharing models to fully autonomous vehicles, particularly related to conversational and social AIs. Furthermore, we analyzed environmental information relevant to FAV travel, with results demonstrating the importance of route-based and vehicle behavioral information for promoting situational awareness. Findings enable future research programs to prioritize both the information type (i.e., vehicle behavior, route-based information, and information about the destination) and presentation modality (i.e., natural language) for near-term exploration. Results from this research can be used to increase the accessible design of current simulator platforms and future FAV services that promote inclusive transportation.

7 ACKNOWLEGEMENTS

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Appendices

Appendix A-1. Survey questions

Q1. What device are you taking this survey on?

- Phone
- Computer

Q2. Do you utilize any of the following accessibility features? Please select all that apply.
- JAWS/NVDA screen reader
- Apple voiceover
- Google talk back
- Magnification
- High contrast
- Other (please specify)
- None

Q3. What is your age?

Q4. What gender do you identify as?
- Male
- Female
- Non-Binary/Other
- Prefer not to say

Q5. How would you describe the area that you live in, urban or rural?
- Urban
- Rural

Q6. Do you have a history of any diagnosed visual impairments?
- Yes
- No

Q7. Have you used a rideshare service (e.g., Uber, Lyft) before?
- Yes
- No

Q8. Briefly detail the name and cause of visual impairment (e.g., Leber's congenital amaurosis, present at birth; Diabetic neuropathy, present from age 10).

Q9. To which eye(s) does the visual impairment apply?
- Both
- Left
- Right

Q10. What is your visual status? Please select all that apply.
- Low vision
- Legally blind with no remaining vision
- Legally blind but use speech access
- Legally blind but use magnification
- Other (please specify)

Q11. Has your vision changed over the past 5 years?
- Yes
- No

Q12. Do you utilize any of the following accommodations for the visual impairment? Please select all that apply.
- Glasses/Contacts
- White cane
- Guide dog
- Other (please specify)
- None

Q13. How often do you utilize rideshare services? Please select one option.
- Daily

- Weekly
- Monthly
- Yearly
- Never

Imagine yourself in a rideshare scenario (e.g., Uber or Lyft) with a human driver. Please answer the following questions on a Likert scale from 1-7 (Strongly disagree to Strongly agree).

Q14. I want to engage in small talk with a human driver in rideshare scenarios (e.g., weather, local news, sports)
Q15. I want to rely on human drivers for emotional/psychological support when ridesharing (e.g., talk openly about emotional feelings, discuss personal details)
Q16. I want the human driver to build trust with me through social interactions that are friendly and conversational
Q17. I want to collaborate with the human driver by giving input into their decision making on tasks related to the ride (e.g., choosing highway vs. main road, parking on side of road vs. driveway)

Imagine yourself in a rideshare scenario (e.g., Uber or Lyft) with an autonomous vehicle driver. The difference in this scenario is that there is no human driver, but instead an AI-robot driver. Please answer the following questions on a Likert scale from 1-7 (Strongly disagree to Strongly agree).

Q18. I will want to engage in small talk with an AI driver in rideshare scenarios (e.g., weather, local news, sports)
Q19. I will want to rely on AI drivers for emotional/psychological support when ridesharing (e.g., talk openly about emotional feelings, discuss personal details)
Q20. I will want the AI driver to build trust with me through social interactions that are friendly and conversational
Q21. I will want to collaborate with the AI driver by giving input into their decision making on tasks related to the ride (e.g., choosing highway vs. main road, parking on side of road vs. driveway)

Imagine yourself in a rideshare scenario (e.g., Uber or Lyft) with an autonomous vehicle driver. In this scenario there is no human driver, but instead an AI-robot driver. Please answer the questions on the next pages on a Likert scale from 1-7 (Strongly disagree to Strongly agree). After several of the questions, you will be asked to imagine what type of interaction method you would prefer (natural language, haptic, or both). In these questions, "natural language" can be understood as an audio-based interaction using words and language with which you are familiar, and "haptic" can be understood as an active, touch based, process using vibration on a screen or a dedicated device.

Q22. I will want a route overview prior to the trip
   Q22.1. For a route overview prior to the trip, which modality would you prefer the information to be presented?
Q23. I will want turn-by-turn descriptions of the route throughout the trip
   Q23.1. For turn-by-turn descriptions of the route throughout the trip, which modality would you prefer the information to be presented?
Q24. I will want a description of the surrounding environment throughout the trip (e.g., restaurants, tourist attractions)
   Q24.1. For a description of the surrounding environment throughout the trip, which modality would you prefer the information to be presented?
Q25. I will want information about where the vehicle is in relation to pedestrians on the road (e.g., people at a crosswalk, cyclists on the road)
   Q25.1. For information about where the vehicle is in relation to pedestrians on the road, which modality would you prefer the information to be presented?
Q26. I will want information about sudden changes in the vehicle's behavior (e.g., swerving, sharply braking, rapid acceleration)

Q26.1. For information about sudden changes in the vehicle's behavior, which modality would you prefer the information to be presented?

Q27. I will want information about where the vehicle is on the route in relation to my final destination (e.g., distance from destination, time until arrival)

Q27.1. For information about where the vehicle is on the route in relation to your final destination, which modality would you prefer the information to be presented?

Q28. I will want information about the vehicle in relation to the access point of my final destination (e.g., the door to a building)

Q28.1. For information about the vehicle in relation to the access point of your final destination, which modality would you prefer the information to be presented?

Q29. I will want assistance with entering and exiting the vehicle

Q29.1. For assistance with entering and exiting the vehicle, which modality would you prefer the information to be presented?

CHAPTER 6: Expanded Situational Awareness Without Vision: A Novel Haptic Interface for Use in Fully Autonomous Vehicles

Contribution Statement: The following paper was published in *Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction (HRI '23)*. My role on the project included the design, collection, and analysis of all data in the initial user study with (n=14) participants. As first author on the paper, I also led the written component and revision up to and including publication. I presented the results of this effort at HRI '23 in Stockholm, Sweden on March 14th, 2023.

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Expanded Situational Awareness Without Vision: A Novel Haptic Interface for Use in Fully Autonomous Vehicles

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ABSTRACT

This work presents a novel ultrasonic haptic interface to improve nonvisual perception and situational awareness in applications such as fully autonomous vehicles. User study results (n=14) suggest comparable performance with the dynamic ultrasonic stimuli versus a control using static embossed stimuli. The utility of the ultrasonic interface is demonstrated with a prototype autonomous small-scale robot vehicle using intersection abstractions. These efforts support the application of ultrasonic haptics for improving nonvisual information access in autonomous transportation with strong implications for people who are blind and visually impaired, accessibility, and human-in-the-loop decision making.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; *Empirical studies in HCI*; *Gestural input*.

KEYWORDS

Ultrasonic haptic interface, Fully autonomous vehicles, Gestural control, Blind-visually impaired users, Grid-based navigation

1 INTRODUCTION

New transportation options harnessing highly automated technology afford a significant opportunity for people experiencing transportation-limiting disabilities, including the estimated 49 million people reporting blindness and the 252 million people with moderate to severe visual impairment worldwide [8, 26]. Research suggests people who are blind and visually impaired (BVI) are cautiously optimistic about fully autonomous vehicles (FAVs), but are also concerned that their needs are not being adequately considered in the design of FAV interfaces [5, 12]. Indeed, in order to realize the benefits to independence and mobility that FAVs will provide for BVI travelers, human-machine interfaces must be designed for access without vision. This is true not only for in-vehicle infotainment control, but also for control over critical aspects of the trip itself, such as inputting a route or initiating the vehicle to pull over during an emergency.

In order to engage in successful interaction with FAVs, recent user research with BVI people has indicated that users need increased information access to enable situational awareness (i.e., information about the surrounding vehicle environment) and to convey route knowledge [9, 11, 12]. This body of work has also suggested that haptic (active touch) and tactile interactions would do much to provide this essential information in an accessible and inclusive manner [10, 16]. However, current vehicle development emphasizing touchscreen-based interaction is fundamentally inaccessible to BVI people because no meaningful tactile information is presented back to the user with conventional implementation of these user interfaces (see [27, 28] for the limited examples of multisensory touchscreen-based access). Consider that one of the authors of this paper, who is himself congenitally blind, recently rode in a current model highly automated vehicle and could not interact with the interface to change the radio station, let alone engage in a more important task like altering the route to nearby points of interest. As such, the current study was motivated by gaining deeper understanding of the important role that interfaces incorporating tactile feedback can play in helping BVI people to

comprehend and interact with their surroundings and to initiate these critical navigation tasks in accessible FAVs.

To address nonvisual access problems in FAVs, we present and evaluate a novel ultrasonic haptic device to increase situational awareness and route knowledge via mid-air tactile representations of the roadway. Our approach involved significant pilot testing with three experts in BVI navigation and experimental results with (n=14) blindfolded-sighted users. While the broad impacts of this work speak to the importance of accessible interfaces for BVI users, there is a dearth of research exploring nonvisual learning and access among sighted participants. Given the brain's natural ability to use and synthesize multisensory information, multimodal UIs are relevant to all people during eyes-free situations and situations of reduced visibility (e.g., at night), supporting the approach used here as both practical and needed. Results provide compelling evidence for nonvisual haptic performance, which we validate with an initial proof-of-concept autonomous small-scale robot car (1/10th the size of a traditional vehicle), demonstrating how haptic roadway representations could be used to initiate non-visually dependent human-in-the-loop control during driving events.

The paper is organized as follows: Section 2 provides an overview of nonvisual access and situational awareness, Section 3 explains in detail the haptic device and intersection abstraction, Section 4 outlines the methodology of the user study evaluating the performance of ultrasonic haptics, Section 5 presents the results of the user study, Section 6 provides a proof-of-concept for the utilization of ultrasonic haptic control in automotive scenarios, and finally Section 7 summarizes future research directions.

2 BACKGROUND

2.1 Sensory Substitution

Although visual impairment results in the loss of a major sensory stimulus with a large bandwidth for receiving information, vision is not the only sensory modality that humans use. Indeed, much of the same stimuli is salient to all of our senses and has been theorized as being encoded and represented in a similar (functionally equivalent) manner across modality in the brain [14, 22, 24]. To clarify, the human brain fuses sensory information about our surroundings from multiple input modalities (i.e., visual, auditory, haptic, and olfactory senses). A growing body of evidence suggests it represents this multisensory information in an amodal (sensory independent) "spatial" representation in memory that supports equivalent spatial behaviors, irrespective of the encoding modality [21]. The ability for visual and nonvisual information to develop into a common spatial representation of the environment helps explain why sighted and BVI individuals can perform spatial tasks, often at a similar level of performance, based on different sensory inputs (see [17] for review).

This understanding of how different sensory information is represented in the brain helps to explain the success of sensory substitution devices (SSDs), which are used to substitute information encoded from one sensory modality to be presented through another, e.g., visual input from a camera being translated and presented through an auditory or tactile interface. SSDs have been developed and tested since the '60s, starting with the pioneering work of Paul Bach-y-Rita who used camera inputs to project tactile information about objects and their directions onto the user's back [3], later updated to deliver to a tongue display, which has much higher tactile resolution [4].

Spatial information, understood and studied here as relating to space around the person with egocentric interpretation, has also been shown to be processed in the same region for visual and tactile inputs with both blind and sighted people in a brain area specialized for spatial processing, called the Parahippocampal Place Area, suggesting that spatial computation is performed independently of sensory input or visual status [36]. The brain's ability to "substitute" sensory information and demonstrate cross-modal plasticity is even possible during short-term visual deprivation. For instance, in a human study where participants were blindfolded for 5 consecutive days, fMRI results showed that the visual cortex was activated during tactile stimulation of the fingers [29]. The authors interpreted this as showing the "metamodal" nature of the brain, where it utilizes different cortical regions based on common stimulus computation rather than sensory-specific input, which suggests that the brain operates similar to a "Mixture of Experts" architecture [20].

Taken together, these findings suggest that regions of the brain that perform similar computation (e.g., spatial information) can process this information equivalently, independent of the sensory input. Also, that in the presence of vision loss (even short-term) the brain can learn to functionally adapt, accurately substituting vision with like information from the other available nonvisual sensory modalities. The combined theoretical and empirical evidence is a strong motivation for the current work in the domain of nonvisual accessibility in autonomous driving as we believe that the use of new sensory substitution devices, harnessing the brain's ability to use common spatial regions and recruit traditionally "visual" areas for nonvisual (haptic) processing will open new doors for multisensory user interactions and human-machine interfaces. We posit that the ability to use the newest type of dynamic ultrasonic haptic interfaces, as we evaluate here, will lead to the formation of accurate spatial representations that can be used to support new nonvisual interactions for use during autonomous vehicle travel compatible for both BVI and sighted individuals.

2.2 BVI Spatial Awareness in FAVs

The precise and rapid 3D perception and distance information afforded by vision is slower, less accurate, and more error prone when conveyed by nonvisual sensing [21]. However, as described earlier, spatial information is accurately encoded from other nonvisual senses and when the information is reliably available and consistently used, these key spatial cues can be fully specified, especially through the use of touch, which shares many of the same spatial properties and perceptual characteristics as vision (for review, see [17]. BVI individuals rely more on other senses, such as haptic and auditory feedback, to form a spatial image, a three dimensional understanding of the world around them [22]. Auditory stimuli provides an omnidirectional and distal stream of information which makes it useful as an "alerting" sense, however, it lacks precision when compared to visual localization [19]. Auditory output is also not always ideal for users in noisy environments or in shared spaces where privacy is desired [17, 18]. Haptic and tactile

feedback presents the advantage of conveying salient spatial information irrespective of the environment and has strong support from the FAV user research with BVI people for promoting spatial awareness [10, 16, 31].

It should be noted that increased spatial awareness during autonomous travel is a critical unmet need that user studies with BVI people have consistently indicated. For instance, in Brinkley's (2021) persona design sessions with 13 BVI people, participants described the need for information to support situational awareness (e.g., the location of other vehicles) and en route information in relation to their final destination [11]. Likewise, in Brinkley and colleague's (2020) survey and focus group study, BVI participants frequently discussed the vehicle needing to be able to provide spatial information in relation to their vehicle in real time "...to mirror the type of information that a sighted operator would have" [12]. In pursuit of this goal, other BVI user research concerning autonomous vehicles has suggested that haptic and tactile interactions may be well suited for providing situational and spatial awareness during vehicle travel [10, 16]. Indeed, a recent study with (n=5) BVI participants demonstrated that vibration-based devices placed on the wrist, hands, chest, and back could improve information during a trip with a simulated FAV. In fact, participants noted wanting more vibrotactile information about the route, landmarks, and ongoing events (e.g., traffic jams, stops at intersections) [31].

The related research offers strong support for heightened focus on how we can augment or encode non-visual stimuli, such as touch and sound, to support BVI individuals in spatial knowledge acquisition, representation, and behavior in FAVs. It stands to reason that our approach here of augmenting haptic stimuli through meaningful abstractions of real-world elements can enable both BVI and non-BVI individuals to better localize, navigate, and understand the trip when riding with FAVs.

3 APPROACH

Our approach in this work is inspired by (and compared against) what is considered the gold standard for non-visual tactile exploration: embossed hard copy maps that convey spatial information through raised dots on paper (similar to Braille). Embossed tactile representations of this kind have been used for years, with the efficacy of tactile maps being demonstrated in the literature for supporting accurate cognitive map development and improved spatial learning and navigation both before travel and during in situ usage by both blind children and adults [6, 7, 34, 35]. Applied to the driving context, we posit that haptic feedback presented in mid-air through a novel ultrasonic array can be used to accurately and efficiently present complex driving environments (i.e., intersections of multiple roads and angles). The advantage of this approach, should it prove worthwhile, is that these ultrasonic intersections can be updated dynamically and in real time allowing for en route information access as opposed to the static and time-intensive process of producing embossed paper representations. Intersection representations provide a strong test environment for this work given their complexity and relevance both to the driving context and situational awareness in the previously discussed FAV research with BVI people. This approach also adds to the growing body of

literature concerning ultrasonic haptic and multimodal control for vehicular and autonomous systems more generally [13, 32].

3.1 Hypotheses

The following hypotheses guided this work. Both rely on roadway identification via clock face positions as this technique for conveying directionality and spatial location is common in BVI navigation training and communication so provide a practical means from which accuracy can be measured [33].

(1) Without the use of vision, individuals can use the haptic feedback from an ultrasonic array to efficiently and accurately identify clock face positions, which can be used as an abstraction for describing road intersections.

(2) Without the use of vision, individuals can perform similarly when identifying clock face positions using mid-air ultrasonic haptic feedback mechanisms compared to physical tactile feedback.

3.2 Ultrahaptics

Figure 1: Ultrahaptic device attached to the cradle

The UltraHaptics (UH) is a device comprised of an array of ultrasonic transducers that can be used to generate haptic shapes in mid-air. We use the UH to generate abstractions of roadway intersections using standing waves of ultrasonic sound. To do so, the UH makes use of a combined sequence of discrete focal points that create pulsing haptic sensations and time-point-streaming that emits continuous streams of sensation over time. Our series of pilot tests revealed that hovering the hand over the device for extended periods became tiring, so a cradle was designed where the user could rest their wrist during use. The cradle and UH are depicted in Figure 1.

3.2.1 Intersection Abstraction Representations. Multiple iterations of intersection representations were considered for the implementation of the intersection abstraction. Our first attempt involved generating a 3D model of an intersection. However, the UH was
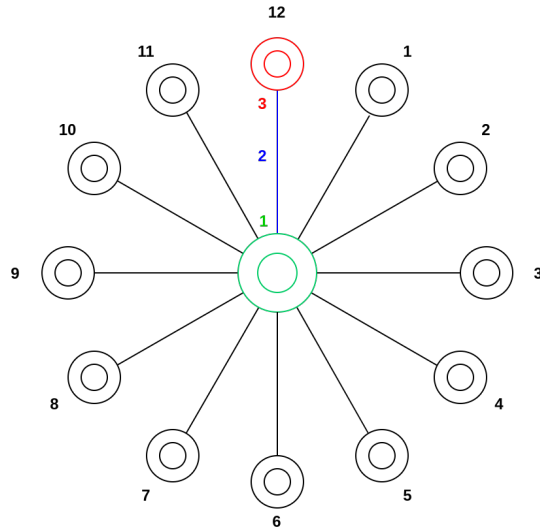
Figure 2: An example of all the possible clock face positions with our proposed approach colored and numbered. The center circles in green represent the two pulses in the 1st step of the sequence, the blue line the 2nd step, and the circles at the end of the line the two pulses in the 3rd step.

unable to represent disconnected shapes, which was necessary for our representation.

We then represented the intersection by drawing sequences of shapes using the UH. The first sequence we tried involved drawing a circle on the palm of a user's hand, and then drawing a line towards the center of the circle and back for each clock face position. For example, if we wanted to represent the 3 o'clock position, we would draw a circle and when the focal point reached the 90 degree angle, draw a line towards the center and back out to the circle's circumference. When we pilot tested this sequence with three navigation experts, including one of the authors who is himself congenitally blind, we found that it was too complicated for users to reliably recognize any of the clock face positions. We also tried drawing the line out of the circle and back towards the circumference, as well as experimenting with different circle radii, line lengths, and drawing speeds, but they were all too complicated to accurately and consistently identify.

The sequence we ultimately found most promising through qualitative prototyping was much simpler than the original approaches. The UH pulses n-times in the center of a user's palms to indicate the number of roads. Then, it draws a line from the center towards the direction of the first road. Finally, it pulses two times at the end of the line, indicating that the road is finished being drawn. This process repeats clockwise across all roads in the intersection.

A visual representation of both the clock face positions and the sequence can be seen in Figure 2. Each clock face position was drawn clockwise starting from the 12 o'clock position. The timing and speed of the sequence played an important role in ensuring the ultrasonic representation was perceptually salient and functionally intelligible. We summarize the timings and frequency used for each step and drawing in Table 1.

Table 1: Summary of parameters used for drawing the ultrasonic haptic sequence

Description (Sequence)	Parameter
Double Pulse (1, 3)	3.33 Hz
Intermission (1-2)	500 ms
Line Points (2)	10 points
Line Frequency (2)	5 Hz
Intermission (2-3)	500 ms

4 METHODOLOGY

A three-stage user study (n=14) was conducted to compare individuals' abilities to identify intersection patterns using the dynamic, ultrasonic haptic interface versus the gold standard, embossed hard copy interface. In the following sections, we describe the experimental protocol and results.

4.1 Participants

14 blindfolded-sighted people (13 right-handed) participated in this experiment (9 male and 5 female), age range 20 to 32 years old ($\mu = 23.75$, $\sigma = 3.82$). Participants were recruited from an established subject pool and volunteered their time in the 60 minute study. Only one participant reported having some (minor) loss of tactile sensitivity on their hand, and none of the participants had previously used an ultrasonic haptic device. IRB approval was obtained prior to running the experiment.

4.2 Experimental Protocol

The study was performed in an office environment where there were no external disturbances and only the participant and the experiment moderator were present. The moderator guided subjects through the stages of the protocol and provided them with detailed instructions on how to perform each task as described below. The moderator recorded subject responses and time to first response for all tasks in a spreadsheet. The moderator also prepared the UH device and embossed hard copy stimuli between each task.

The first stage of the experiment was a simple criterion task asking participants to identify positions on an image of a clock face. The test was used to familiarize participants with clock face directions, while also filtering out any candidates who were not capable of identifying these directions. All study participants successfully completed this simple criterion task on their first attempt.

The second and third stages were the experimental tests of interest comparing the embossed and ultrasonic stimuli, whose order was alternated for each participant to mitigate potential learning biases and order effects between modes. In both stages, blindfolded-sighted participants were used, as is frequently done in the early stages of assistive technology design [17]. After donning the blindfold, participants were asked to identify the number of roads being represented and the clock face positions that were represented in each mode, and their responses were recorded and timed via a stopwatch. Each condition had 12 different clock face position patterns, randomized for each participant. Conditions also followed the same embossed and ultrasonic stimuli sequence pairs. For example, if the order was the 4th, 10th, 1st, etc. pair, then the same embossed and
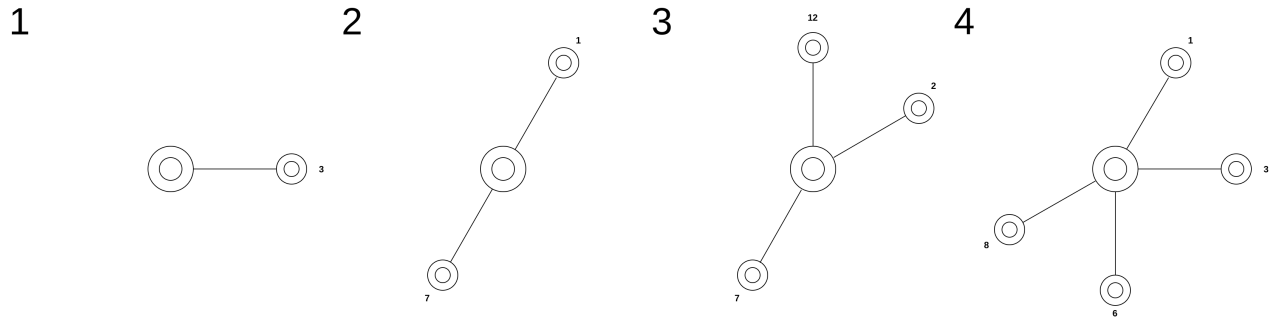
Figure 3: 4 examples of the clock face sequences used to represent intersections in the study. From left to right, pattern 1 is 3 o'clock, pattern 2 is 1 and 7 o'clock, pattern 3 is 12, 2, and 7 o'clock, and pattern 4 is 1, 3, 6 and 8 o'clock.
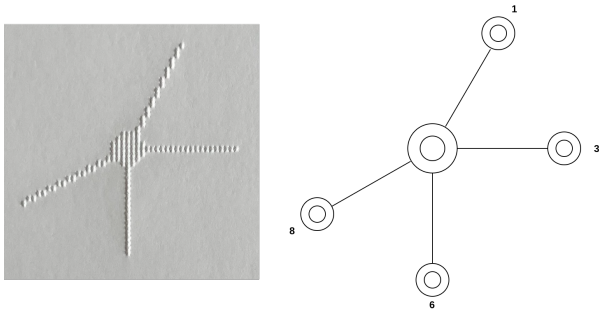

Figure 4: Example of an embossed clock face pattern (left) and the corresponding ultrasonic sequence (right) representing 1, 3, 6, and 8 o'clock.

ultrasonic patterns for that pair were used during their respective condition. Figure 3 includes examples of clock face sequences and Figure 4 shows an example of a clock face pattern on embossed paper and a representational drawing of its ultrasonic counterpart.

For the embossed stimuli, we prepared 12 sheets of hard copy paper using a Tiger Emprint embosser from Viewplus Technologies, which is the gold standard for rendering traditional static tactile stimuli. Participants were instructed to feel the embossed positions and then to verbally communicate how many roads there were and the clock face positions they believed were being represented. The experiment moderator would then repeat back the number of roads and positions to confirm the response.

For the ultrasonic stimuli, participants were asked to place their hand on an arm rest designed to position the hand at a specific height from the Ultrahaptics' sensors and distance from the center. The optimal height, 18 cm, was assessed from bench testing where the resulting sensations on the palm and fingers felt most focused. Like the embossed stimuli, 12 patterns were drawn on the participant's hand, in the manner described in Section 3.2.1, and participants were tasked with verbally communicating the number of roads and clock face positions being presented.

After experimental completion, participants were given an exit survey with questions about performance over time, whether they thought ultrasonic haptics was a useful replacement for embossed stimuli, ease of use, and suggestions for improvement.

5 RESULTS

The following provides results for participant accuracy (identifying the number of roads and their clock face position) and efficiency (response time). Clock face position accuracy was scored in two ways: absolute error (e.g., answering four o'clock when the road was at three o'clock was scored as "1") and error with a dead-band of +/- 1 clock face steps (i.e., error was only counted beyond one clock face position from the correct position). We included this second metric as a practical attempt at assessing the real-world applicability of the interface, as the angular separation of roads at intersections is often greater than the 30° separation of clock face positions.
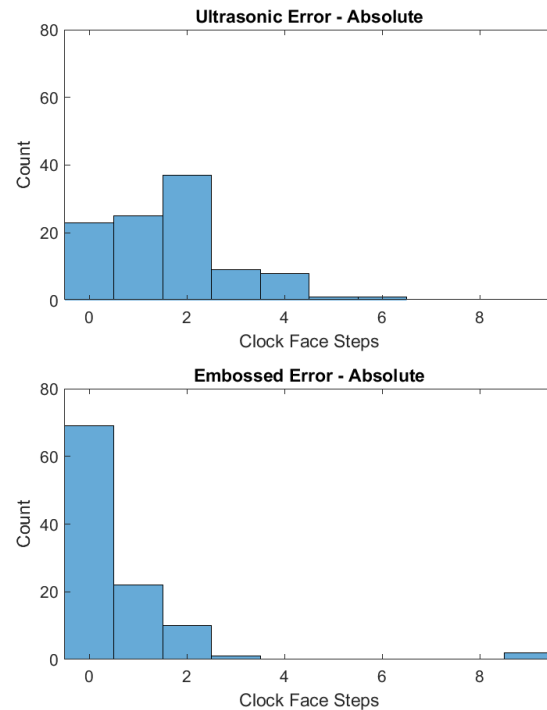

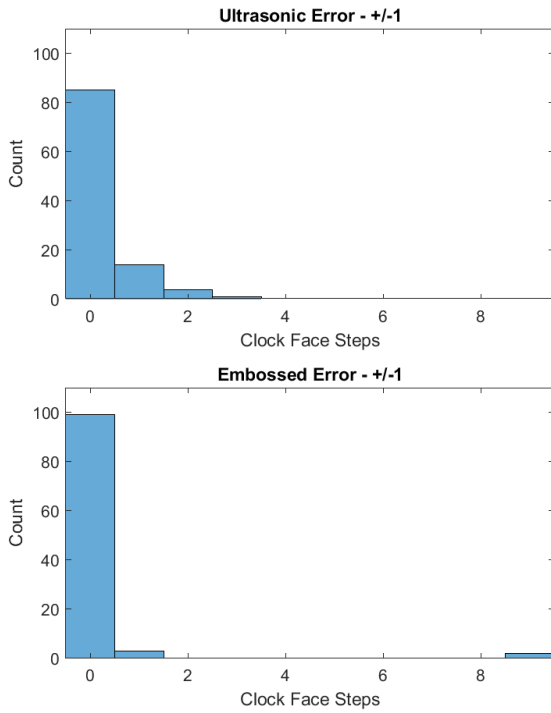**Figure 5: Histograms with absolute error in clock face steps.**

Figure 6: Histograms showing the error in clock face steps with a dead-band of plus-minus one step.

Figure 7: Histogram showing the time to complete the task.

Figure 8: Boxplot showing the time to complete the task.

All fourteen participants were able to accurately identify the number of roads in the ultrasonic haptic condition. Two of the fourteen participants responded incorrectly in the embossed condition during four-way intersections by answering three roads instead of four roads. To account for this inaccuracy when scoring clock face positions, we scored a missed road as an error of 9 (opposed to 12) given that these participants eliminated three of the potential roads in their answers.

Figure 5 and Figure 6 display histograms of the total counts for each scored error (measured in clock face steps) using the absolute and +/-1 accuracy for both conditions respectively. Figure 7 shows the time it took participants to identify the first ray of each pattern. Qualitatively, the histogram shows that the time it takes for participants to answer was longer for the ultrasonic stimuli. However, the boxplots (Figure 8) show the median time increases are minimal, with no outliers representing variance that is orders of magnitude different between the ultrasonic and embossed stimuli.

Analyzing these results in relation to the experimental hypotheses, which sought to test the efficiency and accuracy of the haptic condition in relation to the embossed condition, demonstrated initial support for the haptic interface for real-world usage. Importantly, in the +/-1 dead band comparison, results from a paired t-test (p=.781) suggest that there is no statistically significant difference between the conditions at this accuracy level with a small effect size (d=.04), which supports functional similarity between the conditions. Although there was statistical difference and relatively large effect sizes with absolute error (p<.001, d=.77) and time (p<.001,

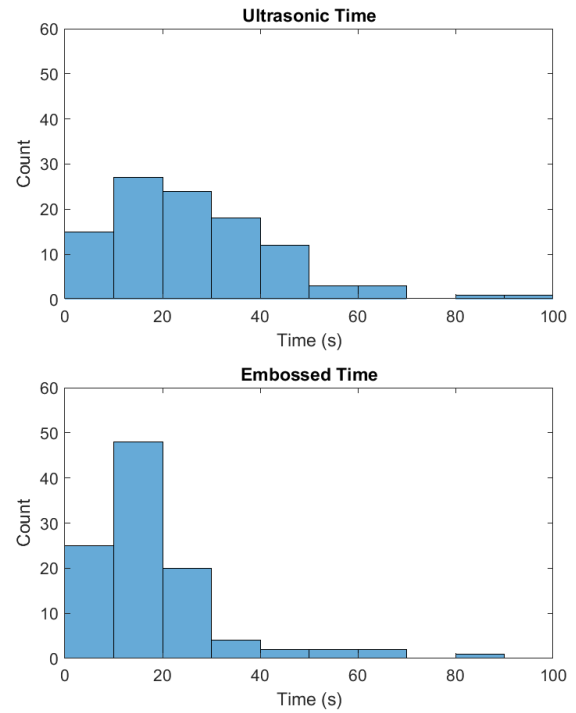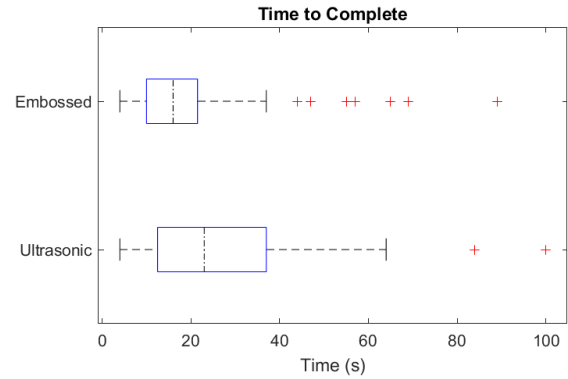d=.51), the qualitative analysis of the post-test answers indicate that these differences may not be relevant for real-world application, especially considering that time in-between intersections is regularly 60+ seconds.

For instance, 9 out of 14 participants (64%) reported that they felt that the ultrasonic device could be a replacement for physical tactile feedback and 10 out of 14 (71%) reported they felt like they performed better over time using the haptic condition. The majority of participants (64%) also mentioned in long answer questions that the haptic interface could easily be improved by increasing the intensity of the vibrations or by providing a frame of reference for

where vibrations would occur. In support of these findings, one participant mentioned:

> "I could see this being used to display maps or places a user should turn. It seems like with some tweaks it could really aid in navigation."

The following provides results for the ease of use and perceived performance questions that were also included in the exit survey.

QUESTION 1 (Q1). *On a scale of 1-5, 1 being very difficult and 5 being very easy, how easy was it to identify the positions with the ultrasonic stimuli?*

$$\mu = 2.14 \text{ and } \sigma = 0.663$$

QUESTION 2 (Q2). *On a scale of 1-5, 1 being very bad and 5 being very well, how well do you think you performed in identifying the positions with the ultrasonic stimuli?*

$$\mu = 2.43 \text{ and } \sigma = 0.756$$

QUESTION 3 (Q3). *On a scale of 1-5, 1 being very difficult and 5 being very easy, how easy was it to identify the positions with the embossed stimuli?*

$$\mu = 3.79 \text{ and } \sigma = 0.893$$

QUESTION 4 (Q4). *On a scale of 1-5, 1 being very bad and 5 being very well, how well do you think you performed in identifying the positions with the embossed stimuli?*

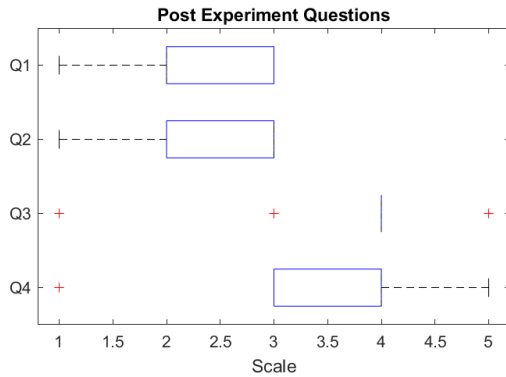$$\mu = 3.64 \text{ and } \sigma = 0.929$$

Figure 9: Boxplot showing the results for the post-experiments questions.

Figure 9 presents participants answers to Q1 through Q4 as boxplots. Participants found the embossed paper easier than the haptic device (Q1 and Q3) and this difference was statistically significant as demonstrated by a pairwise Wilcoxon signed-rank test (p<.001). Participants were also clearly more confident in their answers using the embossed paper (Q2 vs. Q4), which was also statistically significant (p<.001). Interestingly, participants felt they did not do well with the ultrasonic device despite the contrary empirical results above showing that they were performing at an acceptable level. This may be the result of a training effect due to lack of familiarity with the device and haptic stimuli in general. It is promising to see

that a significant number felt they performed better on the tasks over time, indicating that more training may help bridge the confidence gap. This will likely also improve the time it took to complete the task, narrowing the discrepancy with the embossed stimuli. In addition, a significant number indicated they see the potential of this type of ultrasonic device as a more flexible replacement to physical tactile feedback.

Taken holistically, we interpret these results as indicating that the ultrasonic interface shows promise to increase situational and spatial awareness in FAVs, with some room for improvement. Although they were not as precise or confident as the embossed paper, people were remarkably good at using the device, reliably understanding roads to within 1 hour (30°) of ground truth.

6 SCALE VEHICLE PROOF-OF-CONCEPT

To demonstrate the applicability of the ultrasonic interface in a realistic environment, we followed the initial experiment with a small scale vehicle proof-of-concept using similar intersection representations to the first experiment. In this scenario, we used an F1Tenth vehicle, an open-source small-scale autonomous cyber-physical platform, used for affordable, rapid, low-risk autonomous vehicle experimentation [25]. The vehicle drove from intersection to intersection, while the user felt each intersection and could alter the route by selecting directional commands through gestures. Gestural input was used due to its non-visually dependent nature and the native hand-tracking support with the UH device. Due to local COVID restrictions, no experiments with the ultrasonic device and human subjects were performed on this test track, and this initial proof-of-concept was demonstrated by one of the sighted authors on this paper.

6.1 Methods

Non-visual control with the F1/10 was enabled with an optical hand tracking module via Leap Motion sensor and gestural recognition. To do so, we leverage the Leap's 3D hand landmarks tracking to train a deep-neural net (DNN) focused on hand gestures. Our DNN architecture is a bidirectional LSTM, with a ReLU activation and a fully connected layer at the end. This architecture has been reported to have reasonable performance for gesture recognition in previous research [1, 2, 23]. We used the DHG-14 dataset [15] as part of a hyperparameter sweep to find parameters for the model, which we then overfit with our own gestures for use with the F1/10 vehicle. We used three gestures with the index finger to indicate which direction the car should take: turn left, turn right, and go straight (vertical motion along y-axis).

Our software stack, summarized in Figure 10, is composed of 4 modules that communicate with each other using the Robot OS (ROS) [30] library: (1) Coordinator, (2) F1Tenth Controller, (3) Motion Capture (MoCap) Node and (4) UH Controller.

The Coordinator handles the processing and transforming of information from the all components as well as displaying any necessary information to the end user. The F1Tenth Controller handles communicating high level commands between the Coordinator and the vehicle's motors. It also serves as a multiplexer between the Coordinator's commands, a safety controller, and a teleoperation controller. The MoCap node is responsible for communicating with
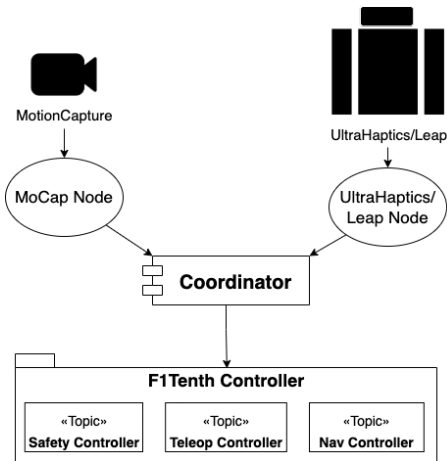
Figure 10: Summary of the software stack.

the motion capture system and publishing the car's 6D pose along the outdoor track. The UH Controller executes the haptic sequence representing the intersection sent from the Coordinator on the UH device. It also communicates with the Leap sensor attached to the UH and streams predicted gestures from our gesture recognition model. The predicted gestures are sent to the Coordinator when it requires user input on which direction the car should take.

6.2 Proof-of-Concept Evaluation

Figure 11: A view of the grid, scale car, and motion cameras.

To evaluate the interoperability of ultrasonic feedback with FAVs, we set up a grid-based track with the F1 Tenth vehicle. See Figure 11 for an overview of the setup. The vehicle stopped at every intersection, successfully informed the driver (one of the authors of this paper) of the intersection layout, and queried the driver of which direction to take. Given that we set the speed of the vehicle and distance between intersections to roughly match suburban scenarios, we were particularly interested in if the user had sufficient time to interpret the upcoming intersection.

Results demonstrated that the prototype implementation was successfully able to convey the intersections and enable timely intervention by the operator when determining the grid navigation path.

We interpret this result as initial support for the viability of ultrasonic haptic and gestural control in highly automated vehicles when visual interpretation is impossible or undesirable. More broadly, when combined with gestural input, ultrasonic haptic interfaces may very well hold the potential to increase non-visual situational awareness in a range of shared control scenarios, particularly where touch-free interaction is desirable (e.g., future rideshared FAVs and robotic workplace control panels). Future work in this regard is explored in the following.

7 FUTURE WORK

Future work should explore the ways in which ultrasonic haptic interactions can be leveraged to promote accessibility for all users, as well as within a range of touch-free HRI applications. The results of our initial user study and proof-of-concept demonstration indicate that the use of an ultrasonic input device shows real promise, but there are also clear areas where improvements need to be made before viable consumer use.

Feedback from participants in the initial user study suggested ways to improve accuracy with the haptic device, by either adding an indication of 12 o'clock or by improving alignment of the pattern on the user's hand. Improved hand tracking could also enable a more salient and focused sensation on the hand, which is currently a limitation of our implementation. Results showed that users were sufficiently accurate with the device to select directions reliably, but were not confident in their performance. Ultimately, improving user's confidence of what they are feeling will be critical to future work focused on extending our prototype implementation to real-world use-cases. Indeed, moving beyond proof-of-concepts to "in the wild" testing of non-visual sensing in vehicle scenarios is necessary to ensure the practical utility of this novel interface. We contend that integration of directional, immersive spatialized audio that reaffirms what users are feeling could significantly improve performance and practical use by fusing multimodal spatial information to create a more accurate cognitive map for actionable behavior.

8 CONCLUSION

Ultrasonic haptic interfaces hold potential to improve situational awareness with broad implications for non-visual interactions with autonomous systems. User study results (n=14) demonstrated comparable performance to a standard benchmark when exposed to intersection abstractions. A proof-of-concept with a scale autonomous vehicle suggest that, when combined with gestural interaction, haptic information can be used to enable non-visually dependent shared control. The impacts of this work include increased accessibility among users who are blind and visually impaired and usability for all users in eyes-free and/or touch-free implementation scenarios.

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CHAPTER 7: Autonomous is Not Enough: Designing Multisensory Mid-Air Gestures for Vehicle

Interactions Among People with Visual Impairments

Contribution Statement: The following paper was published in *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems.* My contribution on this project included the design of the three user studies presented in the paper, as well as all data collection, analysis, and reporting. I led the development of the experimental interface that culminated in this work, which was subsequently filed for a patent, which I also authored in collaboration with Toyota Research Institute. As first author on the paper, I led all aspects of the written submission. Results from the paper are to be presented at 2023 CHI Conference on Human Factors in Computing Systems in Hamburg, Germany on April 26th, 2023.

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Autonomous is Not Enough: Designing Multisensory Mid-Air Gestures for Vehicle Interactions Among People with Visual Impairments

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ABSTRACT

Should fully autonomous vehicles (FAVs) be designed inclusively and accessibly, independence will be transformed for millions of people experiencing transportation-limiting disabilities worldwide. Although FAVs hold promise to improve efficient transportation without intervention, a truly accessible experience must enable user input, for all people, in many driving scenarios (e.g., to alter a route or pull over during an emergency). Therefore, this paper explores desires for control in FAVs among (n=23) people who are blind and visually impaired. Results indicate strong support for control across a battery of driving tasks, as well as the need for multimodal information. These findings inspired the design and evaluation of a novel multisensory interface leveraging mid-air gestures, audio, and haptics. All participants successfully navigated driving scenarios using our gestural-audio interface, reporting high ease-of-use. Contributions include the first inclusively designed gesture set for FAV control and insight regarding supplemental haptic and audio cues.

CCS CONCEPTS

• **Human-centered computing → Accessibility design and evaluation methods**; **Empirical studies in accessibility**; *Haptic devices*; **Gestural input**.

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*Author conducted this work at Toyota Research Institute.

KEYWORDS

Autonomous vehicles, Accessible design, Interfaces for blind or visually impaired individuals, Spatial audio, Gestures, Situational awareness

1 INTRODUCTION

Fully autonomous vehicles (FAVs) hold enormous potential to transform mobility for the roughly 300 million people who are blind and visually impaired (BVI) worldwide [2, 25]. Today, BVI people must rely on others for transportation, either through friends, family, public transportation, or rideshare. FAVs that are designed accessibly will enable independent travel among BVI people, thus resulting in more mobility and personal autonomy. However, for independence and autonomy to be fully maximized, it is argued here that people will desire to be "in the loop" of vehicle control. Whether it is personalizing the vehicle's driving style (e.g., speed or following distance), giving input on where to be dropped off, or even changing the route entirely, it stands to reason that having some sense of control over the trip is part and parcel with increased independence and autonomy. Indeed, the connective tissue between FAV control and independence was illuminated in Brewer and Kameswaren's (2018) focus group study exploring (n=15) BVI people's perceptions of autonomous vehicles. Their findings demonstrated that people desire control across the spectrum of vehicle autonomy and that new mechanisms are needed to enable actionable behavior [4].

It should be noted that although FAV control for BVI people is a promising goal, information access to the surrounding environment

and driving context is a prerequisite. Termed situational awareness, recent research has found that to be inclusive, FAVs must be designed to increase understanding of the vehicle's decision making process [3, 5] as well as to give details about the surrounding environment [5, 6]. Situational awareness is essential to independence because it increases understanding of the driving environment such that actionable behavior and control are possible across the trip (e.g., for route planning). The extant research in this domain has postulated that multisensory interfaces that combine haptic (active touch) and auditory cues in FAVs represent an exemplary approach in pursuit of this goal. For instance, Brewer and Kameswaren (2018) suggest employing tactile interactions (e.g., those that mimicked the use of a white cane) in tandem with audio cues for conveying the driving environment and altering vehicle behavior, and Fink et al. (2021) suggest using vibro-audio maps for conveying route-based information [12]. The rationale for designing BVI interfaces with multimodal input-output processes include supporting distributed cognitive load across the senses and fewer demands on working memory than those that rely on a single modality [26]. However, despite being proposed for use in FAVs, few systems have been developed to convey situational awareness harnessing the benefits of multimodality, instead relying on auditory interaction [7] or vibrotactile output [30] alone.

Mid-air gestural systems are an emerging interaction technology with a number of advantages that motivated this research in terms of multisensory and accessible FAV use among people with visual impairments. First, a key advantage of mid-air gestures is that, unlike traditional touchscreen-based vehicle displays, gestures can be performed in free space without the guiding use of vision [18]. This non-visually dependent nature of gestural systems affords significant opportunity to increase natural and accessible interactions for BVI users over traditional visual-only vehicle displays. There are also significant hygienic advantages of this approach (consider that FAVs may well adopt rideshared service models and that knowing if a shared service is clean is often challenging for BVI users). Furthermore, gestures are location-independent and can be performed at a distance [35], for example throughout a vehicle cabin opposed to confined at a central display, which would afford greater flexibility for seating arrangements in future FAVs. It should be noted that handheld smartphones and dedicated accessibility devices offer some of these same advantages and will likely continue to be popular among the BVI demographic. Indeed, handheld devices are ideal for certain navigation tasks like feeling a map. However, mid-air gestural interaction presents the opportunity to offload tasks that can be performed as a natural extension of body movement, thereby enabling computational resources and interaction on existing devices that support the benefits all people will gain from driverless transportation: more time for socializing, work, and relaxation.

Recognizing these advantages, this paper explores a user-driven interface for increasing situational awareness and control in automated vehicles via mid-air gestural interaction. To do so, we first conducted a needs assessment with (n=23) BVI users to identify the types of vehicle control that are important to this demographic and the situational information necessary to be conveyed (Study 1 in Section 3). A subsequent user study session involving (n=15) participants who also completed the Study 1 survey explored the

design of a mid-air gestural system to promote multisensory control (Section 4). Finally, the resulting experimental interface, which combines ultrasound-based haptic representations of the driving environment, queryable spatialized audio descriptions, and mid-air gestures to mediate between the two, was evaluated with (n=8) BVI participants from the original Study 1 group (separate from the Study 2 group). Results provide compelling evidence for increased BVI situational awareness and control potential in partnership with FAVs and identifies a first-of-its-kind gesture set for FAV control that promotes inclusion (Section 5). This system is designed to serve both BVI people who have previously operated traditional vehicles, as well as people who have never driven before, representing broad and inclusive usability across the spectrum of vision loss.

2 RELATED WORK

The research presented here was informed by the small but growing body of work exploring accessibility in FAVs for BVI users. The following reviews this work, as well as the ways in which mid-air gestural interaction has been used in the driving context and among the BVI demographic more generally.

2.1 FAVs and BVI Individuals

FAVs are predicted to have outsized impacts on underserved transportation populations, including BVI travelers, in terms of increased mobility, workforce participation, and overall quality of life [9]. A number of studies have examined the perceptions of this demographic with regard to automated driving. For instance, Brinkley et al. (2020) conducted a survey with 516 BVI respondents and subsequent focus groups (n=38), with results indicating strong support for FAVs, interest in ownership, but concerns regarding accessible design [6]. Likewise, Bennett, Vijaygopal, and Kottasz (2020) conducted a survey with 211 BVI participants and found favorable attitudes towards automated driving but, again, skepticism with regard to the accessibility of this technology [1]. Related research has also postulated how to make this technology accessible, indicating the need for new policy frameworks [12] and interfaces that enable understanding and control [4, 12]. Perhaps most important to enabling this understanding and control are findings that suggest that BVI users desire increased situational awareness in FAVs [3, 5, 6]. The logic here is that in order to adequately understand the environment such that control actions can be performed safely, users desire more information about the driving situation and context.

Although the available research suggests the importance of new human-machine interfaces (HMIs) to increase access and situational awareness in FAVs, there has been relatively little work exploring accessible FAV user interfaces. A 2021 systematic review of the literature indicates that only two HMIs have been designed or evaluated for fully autonomous use among BVI people, with only one involving a user study [11]. For instance, a text-to-speech and speech-to-text system was developed for use in FAVs with computationally efficient results, but did not involve user testing [33]. The Accessible Technology Leveraged for Autonomous vehicles System (ATLAS) was designed as a speech input and audio output system with extensive feedback from users and tested with 20 participants [7]. Although the ATLAS study results are incredibly encouraging in terms of user trust and usability, the system relies on audio as

the only non-visual modality, which may present disadvantages when audio interaction is undesirable (e.g., in a loud scenario or when a fellow passenger is sleeping), nor does it harness the previously discussed intrinsic benefits of multimodality. Likewise, a 2022 study with (n=5) blind participants investigated vibrotactile feedback delivered using the Ready-Move and Ready-Ride devices on the wrist, hands, chest, and back, providing encouraging results in terms of finding the vehicle, receiving information during the trip, and arriving at the destination, but did not explore modalities beyond haptics [30]. As such, no research to date has evaluated a non-visual interface for FAV use leveraging multiple senses, as we propose to do here mediated by mid-air gestural interaction.

2.2 Mid-Air Gestural Interaction

Mid-air gestures (such as a wave hello or a thumbs up) are location independent movements performed in free space that predominately involve manipulation of the wrist, arm, and hand position [24, 34]. Unlike vehicle touchscreens, which predominantly require the use of vision (see [27, 28] for the limited examples of multi-sensory touchscreen usage), gestures are non-viually dependent. Recognizing this advantage for eyes-on-the-road time, mid-air gestures have begun to gain traction in the automotive domain, with several studies exploring the design and implementation of UI elements on infotainment displays using mid-air gesturing as the primary interaction modality [8, 19, 23, 32]. This body of work demonstrates that driving performance and safety can be improved by complementing gestural interaction with haptic and audio interaction. However, no work to our knowledge has leveraged the non-visual advantage of mid-air gestural systems to improve access to control in automated vehicles for people with visual impairment, as is the focus of this research.

Gestural interaction has, on the other hand, begun to gain traction in the FAV literature for manipulating driving behavior among sighted users. For instance, Qian et al. (2020) conducted a user study in a vehicle simulator to identify a set of static hand-shape gestures (held for 10 seconds) for controlling autonomous vehicles across common driving tasks (i.e., go straight, turn left, turn right, stop, slow down, back up, turn around, and pull over). Users performed gestures in three locations (steering wheel area, shifting area, and free region/open-cabin), and despite executing gestures more efficiently in the shifting area, preferred the free region condition. Questionnaire results supported the use of gestural based navigation in autonomous vehicles, particularly over short distances or as a backup form of interaction if other software failed [29]. Detjen et al. (2020) also found encouraging results of maneuver based vehicle control via gestural interaction during driving tasks similar to Qian et al.'s (2020) stimulus set, albeit with higher task load than speech and touch [10]. Although research investigating vehicle control via gestural systems has yet to include BVI people, gestural interaction has shown promising results when combined with multimodal feedback among this population more generally. For instance, Kim et al. (2016) explored use of a mid-air gesture system by BVI people to navigate a large public video display and found that audio and haptic feedback improved navigation performance compared to one modality alone [21]. Likewise, Gross et al. (2018) found positive navigation performance and low cognitive load among BVI

people using a gestural system combined with audio to navigate web-based menu structure [18]. Taken together, this body of work suggests that the nonvisual advantages of mid-air gestures have the potential to increase access and control in FAVs among BVI people, particularly when combined with supplemental audio and haptic cues.

3 STUDY 1, NEEDS ASSESSMENT SURVEY

3.1 Motivation for User-driven Design

The studies presented in this work followed a principled trajectory where early results informed later design decisions, beginning with a user needs assessment via a survey delivered to BVI individuals (n=23). The needs assessment survey sought to identify the FAV driving tasks over which participants desired control, as well as the situational information that would be necessary for each driving task. Our goal was to use results from this initial phase (i.e., driving task importance and information needs) to inform the driving context and information required in the subsequent interface study (Section 5).

3.2 Methods

The Study 1 survey aimed to assess the types of information and importance of control across a range of common driving tasks. Driving tasks were adapted from Qian et al.'s (2020) stimulus set and were grouped along categories of task to reduce redundancy: *stop/start behavior*, *maneuvering behavior* (e.g., left, right, straight), *speed manipulation* (e.g., speed up, slow down), and *pulling over behavior*. Two other types of driving tasks were added to the stimulus set: *altering the route* and *adjusting the following distance*. *Altering the route* was added because of its relevance to the fully autonomous context of interest to this paper and *following distance manipulation* was added given current capabilities in consumer available driver assistance systems. The study included two types of questions. Five-point Likert scales were used to rate the importance of personal control over each type of driving task from 1 - Not important to 5 - Very important. Open-ended questions were used to identify the situational information users would need or want to issue a specific driving task command (e.g., change the following distance) when riding with FAVs.

3.2.1 Participants. Participants were recruited through a mailing list by the Carroll Center for the Blind, a facility that focuses on serving the blind and low vision community in the greater Boston, Massachusetts area. Participants (n=23), all identifying as blind, represented a broad spectrum of vision loss, onset, etiology (specific visual demographics for each participant can be found in Table 1) and age, ranging from 28-71 (*M* = 50.48, *SD* = 14.25). Of these, 13 identified as former drivers and 10 identified as having never driven before. Participants predominantly identified as white or of European descent (73.91%). 8.72% identified as black or African American and 95.65% reported as not identifying as ethnically Hispanic or Latino/x, while 4.35% of participants did. Four participants chose not to indicate racial or ethnic identify. 30.43% of participants had attained a Bachelor's degree, 26.09% a Master's degree, 21.74% some college but no degree, 4.35% an associate's degree, 4.35% High

Table 1: Vision loss etiology and extent for each participant

Etiology of Blindness	Residual Vision	Study
Retinitis pigmentosa	No usable vision	1 & 2
Unknown	Severe vision loss	1 & 2
Norrie syndrome	No usable vision	1 & 2
Cancer of the retina	No usable vision	1 & 2
Retinopathy of prematurity	No usable vision	1 & 2
Retinitis pigmentosa	Some light and shape perception	1 & 2
Diabetic retinopathy	Central vision with a 10 degree field	1 & 2
Unknown	No usable vision	1 & 2
Retinitis pigmentosa and cataracts	Some light and shape perception	1 & 2
Cortical blindness due to stroke	No usable vision	1 & 2
Congenitally low vision	No usable vision in right eye. 20/250 in left eye	1 & 2
Ushers Syndrome II	No reported vision	1 & 2
Retinopathy of prematurity	No usable vision	1 & 2
Autoimmune retinopathy and posterior sclerosis	No reported vision	1 & 2
Retinopathy of prematurity	20/400 in one eye with limited field	1 & 2
Glaucoma and corneal opacities	Able to recognize large objects at 1 foot or closer	1 & 3
Retinopathy of prematurity and glaucoma	20/7000. Some light and contrast vision. 10 degree field	1 & 3
Leber congenital amaurosis	No usable vision	1 & 3
Unknown	20/300. Steady	1 & 3
High blood pressure in eyes	No usable vision	1 & 3
Cone dystrophy	1 or 2 fingers at approximately 1 foot	1 & 3
Injury	No usable vision	1 & 3
Injury	Usable peripheral vision in both eyes	1 & 3

school or equivalent, and 4.35% a Ph.D. Two participants chose not to report educational attainment.

3.2.2 Procedure. The survey was delivered in-person and proctored by an experimenter who entered participant responses in Qualtrics. Each response was read aloud to participants and verified to be accurate prior to submission. This research was approved by the University of Maine IRB and participants were compensated for their travel and participation time ($100/study hour), in line with the Carroll Center for the Blind's recommendations.

Participants began the survey being asked to "imagine riding in a fully autonomous vehicle that can take you where you need to go safely, efficiently, and legally, without any required intervention on your part." Then participants were asked to think about and tell the experimenter what information they would want or need to decide to control the driving task (e.g., control the speed, either speed up or slow down). After this, participants were asked to rate how important being able to control that driving task would be from 1-Not Important to 5-Very Important. Both the long answer question and importance score were recorded in Qualtrics. This process repeated across the *stop/start*, *maneuvering*, *speed manipulation*, *following distance*, *altering the route*, and *pulling over* driving behaviors.

3.2.3 Hypotheses. The four Hypotheses for Study 1 were organized under two overarching research questions:

RQ1: What **types of vehicle control are important to BVI people** in autonomous vehicles?

The first hypothesis was derived both from the existing literature [3, 5] and informal input our group has received with regard to the importance of route-based control, as these behaviors have most influence on the success of the trip.

> H1: BVI people will have stronger preference for controlling and *altering the route* than other driving tasks (e.g., *following distance*, *vehicle speed*, and *starting/stopping*).

Although we predicted that route-based control would be the most important across participant, it stands to reason that former drivers might value control over the process of driving than those who have never driven before. As such, our second hypothesis stated:

> H2: People who have driven before will demonstrate stronger preference for non-route based control (e.g., *following distance*, *speed*, *turning behavior*, *starting and stopping*) than people who have never driven before.

The second research question pertained to the required information for situational awareness:

RQ2: What **types of driving information are necessary** when considering control in autonomous vehicles? Given that situational awareness includes both the vehicle's operational space and the surrounding environment, we hypothesized that:

> H3: Both behavioral information (what the vehicle is doing and will do next) and environmental information (what is in the driving environment) will be important to BVI people opposed to one category over the other.

Much like our first set of hypotheses, we also predicted that information pertaining to the route would be prioritized, as this is most

relevant to the driving task of efficiently and safely reaching the destination:

> H4: *Route-based information* (e.g., time-to-destination) and *route objects* (e.g., roads/intersections, points of interest (POIs)) will be emphasized more than *non-route information/objects* (e.g., speed, following distance, pedestrians, etc.).

3.3 Results

The results of Study 1 (Figure 1) showed strong support for control across driving action. The mean importance score for each driving task category was greater than 3, with control over *altering the route* and *starting/stopping* equal to 4.9 and 4.7 respectively.
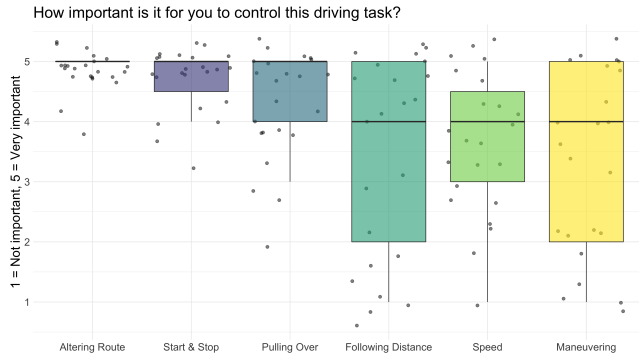

How important is it for you to control this driving task?

Figure 1: The perceived importance of being able to control certain driving tasks

As within-subject, non-parametric factors, we conducted a Friedman's test to analyze statistical significance of this difference. Control Type demonstrated a significant effect on subjective importance scores ($\chi^2(5) = 40.819, p < .001$). As shown in Table 2, post-hoc pairwise comparisons showed that importance is significantly different between *altering the route* and the remaining types of control (all $p < 0.05$), except *starting and stopping behavior* ($p = .417$), and *pulling over* when using Bonferroni and Holm correction ($p = .348$ and $p = .188$).

Table 2: Conover's Post Hoc Comparisons - Control Type

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Altering Route	Start/Stop	0.816	110	109	100.5	0.417	1.000	1.000
	Pulling Over	2.303	110	109	85	0.023	0.348	0.185
	Following Distance	4.318	110	109	64	< .001	< .001	< .001
	Speed	4.174	110	109	65.5	< .001	< .001	< .001
	Maneuvering	4.797	110	109	59	< .001	< .001	< .001
Start/Stop	Pulling Over	1.487	110	100.5	85	0.140	1.000	0.699
	Following Distance	3.502	110	100.5	64	< .001	0.010	0.007
	Speed	3.358	110	100.5	65.5	0.001	0.016	0.011
	Maneuvering	3.982	110	100.5	59	< .001	0.002	0.001
Pulling Over	Following Distance	2.015	110	85	64	0.046	0.695	0.324
	Speed	1.871	110	85	65.5	0.064	0.960	0.384
	Maneuvering	2.495	110	85	59	0.014	0.211	0.127
Following Distance	Speed	0.144	110	64	65.5	0.886	1.000	1.000
	Maneuvering	0.480	110	64	59	0.632	1.000	1.000
Speed	Maneuvering	0.624	110	65	59	0.534	1.000	1.000

Taken together, these results demonstrate support for H1, which predicted that *altering the route* would be rated as more important

than other types of FAV control, understanding that *starting and stopping* the vehicle and *pulling over behavior* are also important relative to other types of vehicle control.

We also analyzed the extent to which prior driving experience impacts rated importance across driving control type. Although, surprisingly, Figure 2 suggests that people who have driven before rate control importance lower than people who have never driven before across the types of control, a mixed-model non-parametric test suggests that this difference is not statistically significant $F(1, 21) = .284, p = .107$. Taken together, this analysis does not find support for H2, which predicted that people who have driven before will demonstrate stronger preference for *non-route based control* than people who have never driven.

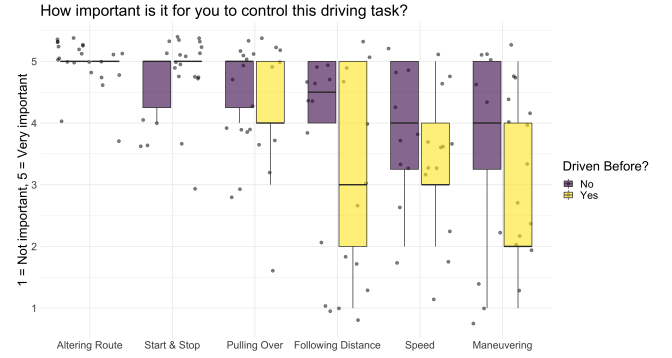How important is it for you to control this driving task?

Figure 2: The perceived importance of being able to control certain driving tasks broken down by whether the participant has prior experience driving or not

The long answer questions illuminated the importance of situational information and awareness across FAV control type. In general, participants imagined wanting a significant amount of information during the trip. For instance, one participant mentioned:

> P16: "I want any relevant information [the FAV] could give me: what caused the [driving] situation to begin with and will it pose a problem if we change."

Participants also mentioned wanting the capability of control over driving tasks, even if they chose not to intervene. Another participant mentioned:

> P13: "I want control, even just for the sense of it. I might not always use it, but if I knew something was going on, like there were emergency cars ahead or a problem ahead, I want to know that I can say, 'let's take a different route, let's turn around.'"

In order to inform the design of the experimental interface and task used in Study 3, we also coded these long answer questions to determine the most frequently mentioned information or scenarios under which participants would want to undertake control of the vehicle. In support of H3, people mentioned wanting to know vehicle behavioral information like its speed or upcoming turn, as well as environmental information such as traffic. Information related to safety or that which would be important during an emergency was mentioned frequently across questions. This included

Table 3: Frequency of Long Answer Codes

Altering Route (56)		Start/Stop (63)		Pulling Over (56)	
POIs	13 (23%)	Safety and emergencies	8 (13%)	Safety and emergencies	19 (34%)
Route	9 (16%)	Route	7 (11%)	Car status	8 (14%)
Intersections and turns	7 (13%)	Obstacles	6 (10%)	Surrounding environment	5 (9%))
Traffic	7 (13%)	Surrounding Environment	5 (8%)	Obstacles	5 (9%)
Current Location	6 (11%)	Entry and exit	5 (8%)	Road status	4 (7%)
Distance	6 (11%)	Current location	5 (8%)	POIs	3 (5%)
Weather	5 (9%)	Traffic	3 (5%)	Weather	3 (5%)

Following Distance (45)		Speed (63)		Maneuvering (37)	
Distance	7 (16%)	Current speed and limit	13 (21%)	Obstacles	12 (32%)
Speed	7 (16%)	Road condition	9 (14%)	Route	10 (27%)
Other vehicle behavior	6 (13%)	Obstacles	8 (13%)	Current location	3 (8%)
Traffic	5 (11%)	Weather	7 (11%)	Traffic	3 (8%)
Weather	5 (11%)	Pedestrians	6 (10%)	Road type	2 (5%)
Obstacles	5 (11%)	Route	5 (8%)	Other vehicles	2 (5%)
Road conditions	5 (11%)	Other vehicles	5 (8%)	POIs	1 (3%)

any sort of malfunction in the vehicle, ways to enter and exit the vehicle safely, where it might be safe to stop the vehicle, and notifications regarding approaching or nearby emergency vehicles. Table 3 summarizes the frequency of codes identified from these long answer questions sorted by control type. The total number of code instances are reported per question type, along with the seven most frequent codes per question (as well as the percentage of codes within that question). Frequency reduced to five instances or fewer beyond this threshold across control type.

Germane to the later interface study, and in subjective support of H4, participants consistently noted wanting more information about POIs, such as nearby businesses, landmarks, or other places to visit. *Route-based information*, including intersections or what roads were nearby, was also mentioned frequently. These results informed the design of the experimental tasks in the subsequent studies.

4 STUDY 2, MID-AIR GESTURAL IDENTIFICATION

4.1 Motivation for Mid-Air Gestures

As discussed in 2.2, the non-visually dependent nature of mid-air gestural interaction and its applicability to the driving context would seem to suggest promise for use in FAVs, particularly among people who are visually impaired. Related research has also identified the need for new multimodal mechanisms to promote accessibility and control in FAVs among this demographic. As such, our goal in this second study session was to first identify a user-driven set of gestures for FAV control as performed by BVI participants (n=15). We also sought to understand what sensory modalities would best support gestural control and to what extent this type of navigation is desirable among BVI people. The resulting set of gestures and multimodal components were used in the subsequent interface test (Section 5).

4.2 Methods

Study 2 involved participants performing gestures for driving actions from the control type categories used in Study 1. Table 4 summarizes these driving actions.

Table 4: Study 2 Actions

(1) Start the Route	(5) Go Straight	(9) Turn Around	(11) Altering Route
(2) Stop the Route	(6) Turn Left	(10) Following Distance	(a) Locate New Route
(3) Speed Up	(7) Turn Right	(a) Closer	(b) Receive More Information
(4) Slow Down	(8) Pull Over	(b) Further Away	(c) Confirm the Route

Given our hypotheses from Study 1 and the supporting results, three subcategories for *altering the route* (locate a new route, receive more information, and confirm the new route) were included to identify gestures that could elicit the situational awareness information necessary to undertake route changing in FAVs.

4.2.1 Participants. The first 15 participants from the Study 1 group participated in Study 2. As such, these participants were also recruited by the Carroll Center for the Blind. These participants again represented a broad spectrum of vision loss, onset, etiology (specific visual demographics can be found in Table 1) and age, ranging from 28-70 (M = 55.53, SD = 13.88). Of these, eight identified as former drivers and seven identified as having never driven before. Participants predominantly identified as white or of European descent without identifying as ethnically Hispanic or Latino/x (86.67%). Two participants chose not to indicate racial or ethnic identify. 26.67% of participants had attained a Bachelor's degree, 26.67% a Master's degree, 20% some college but no degree, 6.67% High school or equivalent, and 6.67% a Ph.D. One participant chose not to report educational attainment.

4.2.2 Procedure. The experimental procedure, as with Study 1, began with participants being told, "Imagine riding in a fully autonomous vehicle that can safely, efficiently, and legally automate the trip." In this scenario, participants were told that gestures could give commands to control the vehicle. The experimenter clarified

that these gestures were performed in mid-air, not on a device like a touchscreen. Participants were deliberately not given an example of what a gesture might look like, as the goal was to elicit whatever felt most intuitive (types of movement, one hand vs. two hand, etc.). After clarifying with participants that they understood their task, the experimenter started the video camera and read the first driving action. Once the participant performed the first action, the experimenter ended the recording and began the next, followed by reading the second driving action. This process repeated until all 14 driving actions were recorded.

The only modification to this procedure involved the three steps for *altering the route*. First, participants were asked to perform a gesture for locating a new route, but not knowing where it was. Then participants were asked to perform a gesture for receiving more information about the new route. And finally, participants were asked to imagine having received that information and to perform a gesture to confirm the new route. Gestures were recorded using a GoPro video camera. Video analysis was undertaken using the GoPro Player video software. Video analysis involved the gestural recordings being scored along four dimensions: movement (yes/no), type of movement (e.g., forward movement of the arm), hand position (e.g., pointed finger or open palm), and repetition (yes/no).

After performing the gestures, participants answered a brief post-test where they were asked what types of information should complement a gestural navigation system: haptic (active touch), audio (e.g., voice), or combinations of audio and haptic. Participants were also asked to what extent they agreed with the statement "I would want a hand gesture navigation system" from strongly disagree to strongly agree. The post-test survey was developed and delivered using Qualtrics.

4.2.3 Hypotheses. Prior to this experiment, we piloted a subset of gestures with 10 sighted users. From the 43 gestural videos we collected in the pilot, it was clear that people were inclined to incorporate movement and directionality in their gestures. This was also in-line with Qian et al.'s (2020) finding that people preferred dynamic opposed to static gestures. As such, our first hypothesis for this study was the following:

> H1: Gestures will prioritize the use of motion and directionality opposed to being statically performed (i.e., held in one position).

In the pilot we also observed that people tended to rely on driving metaphors for their gestures. For example, turning behavior was represented several times by the manipulation of an invisible steering wheel. As such, our second hypothesis was:

> H2: BVI people with prior driving experience will utilize gestures similar to in-vehicle elements (e.g., steering wheel or pedal manipulation) more so than people without prior driving experience.

From the related research reviewed here that suggests the importance of multimodal feedback for BVI people in autonomous vehicles, our third hypothesis was:

> H3: Combinations of audio and haptic cues will be more desirable than audio or haptic alone.

4.3 Results

Of the 210 recorded gestures, 206 included significant hand or arm movement deemed important to the meaning of the gesture during video analysis. Three of the four gestures that were held statically were performed by a single participant, suggesting that some people may prefer motionless gestures. However, the finding that 98% of the gestures involved dynamic hand movement is strongly supportive of H1, which predicted that gestures would include motion and directionality.

Table 5: Most frequently used gestures in Study 2

Driving Action	Movement	Handshape	Repetition	Example
Start	Forward 13 (87%)	Open up 7 (47%)	No 12 (80%)	
Stop	Up 6 (40%)	Open up 10 (67%)	No 15 (100%)	
Speed Up	Rotational 5 (33%)	Finger point 5 (33%)	Yes 10 (67%)	
Slow Down	Down 6 (40%)	Open down 7 (47%)	Yes 9 (60%)	
Go Straight	Forward 14 (93%)	Finger point 6 (40%)	No 14 (93%)	
Turn Left	Left 15 (100%)	Finger point 9 (60%)	No 14 (93%)	
Turn Right	Right 15 (100%)	Finger point 8 (53%)	No 14 (93%)	

Tables 5 and 6 summarize the most frequently used types of movement and handshape for participants' gestures across the driving actions used in this study. Gestures utilized a variety of movement types (e.g., forward, up, directional left/right) and handshapes (e.g., open palm up, pointed finger). All but *following distance further* and *following distance closer* utilized one hand opposed to two. Each gesture reported in the tables is unique (note that *speed up* typically involved a participant's arm being held horizontally across the

Table 6: Most frequently used gestures in Study 2 (contd.)

Driving Action	Movement	Handshape	Repetition	Example
Pull Over	Left or Right 13 (87%)	Open side 5 (33%)	No 11 (73%)	
Turn Around	Rotational 14 (93%)	Finger point 8 (53%)	No 10 (67%)	
Closer	Together 8 (53%)	Finger point 4 (27%)	No 12 (80%)	
Further	Apart 10 (67%)	Finger point 4 (27%)	No 12 (80%)	
Locate	Arc 9 (60%)	Finger point 9 (60%)	No 13 (87%)	
Select/More	Compound 11 (73%)	Open palm 5 (33%)	No 14 (93%)	
Confirm	Left or Right 7 (47%)	Finger point 6 (40%)	No 15 (100%)	

body, whereas *turn around* involved a participant's arm being held vertically, perpendicular to the floor). The tables also provide the extent to which repetition was used in each gesture. Interestingly, *speed up* and *slow down* were the only driving actions for which the majority of participants (67% and 60% respectively) utilized continuous or repetitive gestures. This is logical given that these commands, more so than others, beg the question, "how much?".

Contrary to our expectations, only one participant related gestures to traditional driving controls (i.e., a steering wheel) and this participant did not report prior driving experience. Therefore, results from this gestural task did not support H2.

In addition to performing gestures, participants completed a posttest where they were asked what information modalities should be used in a gestural system. 14 (93%) noted wanting combinations of auditory and haptic information to complement gestural navigation, which supported H3. 11 (73%) indicated that they either agreed or strongly agreed with wanting a hand-gesture navigation system. These results, combined with Study 1 results with regard to the importance of *altering the route*, informed the design of the interface and scenario used in Study 3.

5 STUDY 3, INTERFACE TEST

5.1 Motivation for Gestural-Audio and Interface Test

Given the strong desire for gestural navigation supported by both audio and haptics from Study 2, our resulting interface combines what we refer to here as gestural-audio with haptic feedback. The gestural-audio component utilizes a ring of speakers that users can elicit through gestures to hear spatialized information. This design decision has strong support from the BVI and nonvisual navigation literature, where spatial delivery of auditory information has been shown to increase environmental learning and spatial memory by up to 50 percent [16] and significantly reduce cognitive load compared to using nonspatialized (traditional) auditory descriptions [22]. The haptic component of the interface relies on ultrasonic haptic feedback, which has gained traction in recent years for use in the automotive domain [19, 36]. Haptic exploration, like vision, presents advantages in terms of the relative ease at which information can be conveyed with spatial properties, such as lines, contours, and map elements [13]. As such, the goal of Study 3 was to test the feasibility of this experimental interface using the driving task Study 1 identified as most important: *altering the route*. Of interest was testing if users could receive adequate information from the interface to engage in a route alteration task using the inclusively designed gesture set identified by Study 2. We also sought to compare performance, measured by task completion time, between two conditions: Gestural-audio only and Gestural-audio with haptic feedback, as well as which condition users preferred.

5.2 Methods

The gestural-audio interface (Figure 3) was built using 3" Kicker motorcycle-style speakers mounted on a TrakRacer TR160 racing simulator. The TR160 is designed out of slotted extrusion rails, providing an easy way to mount devices in a modular manner around a vehicle seat. Seven channels of audio are generated through an

Alcorn Mcbride RideAmp-25H Dante amplifier, and fed to the speakers arranged at the clock face positions around the user (9 o'clock, 10 o'clock, 11 o'clock, 12 o'clock, 1 o'clock, 2 o'clock, and 3 o'clock). Clock face positions were chosen throughout this design given the frequency of use in training for navigation among BVI people. The audio files were created using the AI voice generator Voicemaker.

Figure 3: The Gestural-Audio interface used in Study 3

Audio was delivered using SoundPlant, a software package that can map audio files to specific key strokes on a keyboard. The study as a whole utilized a Wizard-of-Oz methodology whereby the experimenter triggered the audio cues as opposed to being triggered via computer vision. Using results from the first two studies, we designed the audio such that it could enable route changing at an intersection. The route changing process, and its related audio was triggered via the following gestures identified from Study 2:

(1) A sweeping gesture, used to locate streets outside the car (see Locate in Table 6)
(2) A selection gesture, used to get more information about what was on a particular street (see Select/More in Table 6)
(3) A confirmation gesture, used to navigate the car in that direction (see Confirm in Table 6).

Using the sweeping/scanning gesture, participants could trigger audio clips based on the direction of their pointed finger. For example, at an intersection of 12 o'clock and 3 o'clock, participants would hear "Right turn, 3 o'clock" from the 90 degree azimuth at 3 o'clock as their finger passed the speaker at 3 o'clock. Using the selection gesture, participants could trigger audio for more information about that road. Using the previous example, participants could perform the selection gesture at the 3 o'clock speaker and hear "Main Street, there's a coffee shop nearby" from that location. Finally, participants could perform the confirmation gesture in the direction of the speaker with the coffee shop and were told by the experimenter that they successfully navigated the car in that direction.

The intersection was also conveyed using haptic representations delivered via a promising haptic modality emerging in related research: mid-air ultrasonic haptics.
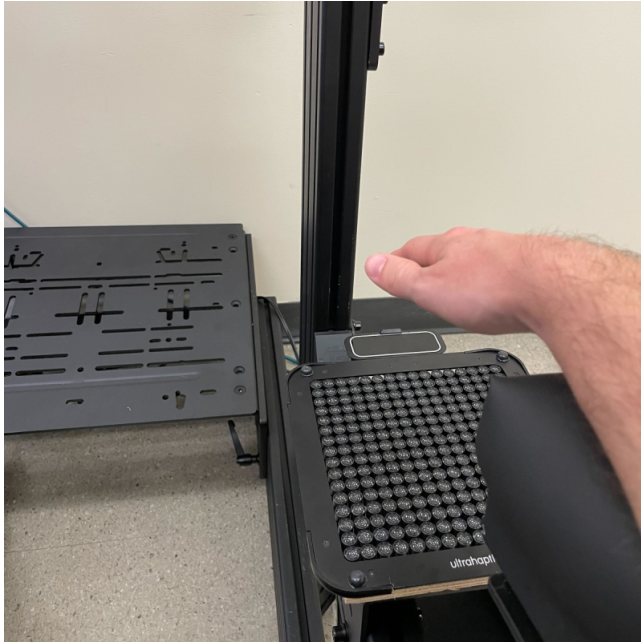

Figure 4: The UltraHaptics mid-air haptic device shown with arm rest and approximate location of the hand during the study.

The UltraHaptics (UH) is a device capable of creating complex, mid-air, haptic sensations using standing waves generated by an array of ultrasonic transducers. We used the UH in our user study as a means of generating haptic sensations to represent abstractions of a street intersection. Pilot testing revealed that hovering the hand over the device for extended periods became tiring, so a rest was designed where the user could rest their forearm during use. The UH is depicted in Figure 4.

Through significant pilot testing with one of the authors on this paper who is congenitally blind, as well as several blindfolded sighted users, we identified a haptic intersection representation that was perceptually salient. When users hover their hand over the device, it utilizes a series of pulses and "drawn" vibrating lines to represent the intersection and roads. First, a user feels pulses in the center of their palm to indicate the number of roads in the intersection. Then, a line is drawn from the palm in the direction of the first road (e.g., towards the thumb of their right hand for a road at 9'oclock). Pulses at the end of the line indicate that the line is done being drawn before the next line is drawn (again from the palm-out). This process repeats until all lines in the intersection are drawn in clockwise fashion and then repeats the sequence. The following summarizes this sequence:

(1) Pulse n-times in the center of the palm indicating the number of roads.
(2) Draw a line from the center towards the direction of the clock face position.

(3) Pulse two times at the end of the line.
(4) Repeat 1-3 until participant responds.

5.2.1 Participants. Eight participants who completed the Study 1 survey participated in Study 3. No participant from the Study 2 group participated in Study 3, as participants were recruited from the same facility in the prior studies for a one hour study (Study 2) or a two hour study (Study 3). Participants again represented a broad spectrum of vision loss, onset, etiology (specific visual demographics can be found in Table 1) and age, ranging from 31-59 (M = 41, SD = 9.78). Of these, five identified as former drivers and three identified as having never driven before. No participants reported any known tactile sensitivity loss. 50% of participants identified as white or of European descent. 25% identified as black or African American and 62.50% reported as not identifying as ethnically Hispanic or Latino/x, while 12.50% of participants did. Two participants chose not to indicate racial or ethnic identify. 37.50% of participants had attained a Bachelor's degree, 25% some college but no degree, 12.50% a Master's degree, and 12.50% an associate's degree. One participant chose not to report educational attainment.

5.2.2 Procedure. The experimental procedure began with participants being asked to imagine riding in a fully autonomous vehicle that could take them where they needed to go safely, efficiently, and legally. Given results from Study 1 in terms of important information for *altering the route* (see Table 3: POIs, intersections and turns) the scenario used in this test involved participants imagining being stopped at an intersection with the goal of changing the route to a nearby coffee shop. Participants were told that they would experience several intersections throughout the study, each with two, three, or four roads extending from their position. They were also told that they would experience the intersections through combinations of gestural-audio and haptic feedback.

Gestural-audio Examples and Practice: First, participants were exposed to two examples of representative intersections using gestural-audio. At the beginning of each intersection presentation, audio played from the speaker mounted at 12 o'clock to indicate that there were two roads, three roads, or four roads. Participants were then told that they could use a series of gestures to receive more information about where the roads were, what was along each, and to direct the vehicle's route. Only one road in each intersection had a coffee shop nearby (the others containing either a flower shop, houses, or a gas station nearby) and participants were instructed that their goal throughout the experiment was to navigate to the street with the coffee shop.

Participants were then instructed how to use the three gestures utilized throughout the experiment (provided in Section 5.2). The experimenter verified that participants understood each gesture and confirmed that each was performed accurately during this example phase.

After completing the examples, participants were exposed to two test intersections to determine that they could independently use the three gestures to interpret the intersection and navigate the vehicle to the coffee shop. All participants successfully completed the two tests without error.

Haptic Examples and Practice: Participants were then exposed to the Ultrahaptic device and told that it was able to project the number of roads and shape of the intersection onto their hand. As in the gestural-audio phase, participants were given two examples of intersections followed by two tests to determine if they could understand the intersection. In these tests, participants were instructed to say aloud how many roads there were (indicated by the pulses at the beginning of the haptic sequence) and their related clock face positions (indicated by the lines drawn from their palms). Six of the eight participants successfully passed these competency tests on their first try. The remaining two were given three tries of repeated examples of the intersections, but were unable to determine the position of the roads. Given that the experimenter verified that the device was working, and that the participants did not report any known tactile sensation loss, the reason for these failures may have been due to the learning curve associated with haptic navigation or the signal intensity from the device. Regardless of the reason, these participants were directed to the post-test and did not complete the remainder of the study.

Experimental Conditions: After the examples, practice, and competency tests with the two modalities, six participants began either the gestural-audio only condition or the gestural-audio and haptic condition. The ordering of these conditions were counterbalanced between participants to avoid any ordering or learning effects.

In both conditions, the participant's goal was to navigate to the coffee shop as quickly as possible while still being accurate. For the gestural-audio only condition, participants heard the number of roads and began scanning using the three gestures learned in the practice phase. In the gestural-audio + haptic condition, participants felt the number of roads and intersection geometry prior to scanning the intersection using the same gestures. The experimenter used a stopwatch to measure the time it took to successfully navigate to the coffee shop. In the haptic condition, the experimenter measured both the total time it took to navigate to the coffee shop and the time spent learning the haptic intersection. The stimulus set for both conditions included 6 intersections: two two-road intersections, two three-road intersections, and two four-road intersections with the ordering of these stimuli randomized between participants and condition to avoid any ordering or learning effects. The position of the coffee shop was different in each condition and was balanced across clock face positions. After completing both conditions, participants completed a brief post-test interview with the experimenter to assess ease of use, preference for interface, and to collect qualitative feedback on improvements to be made. Participants were also asked to assess to what extent they agreed with the statement: "I would want a mid-air gestural navigation system" on a 5-point Likert scale from 1-Strongly Disagree to 5-Strongly agree.

5.2.3 Hypotheses. Given the related research and our results from Study 2 showing preference for combinations of audio and haptic information to support gestural navigation, our hypotheses for Study 3 were the following:

> H1: People will navigate faster in the audio + haptic condition (after experiencing the haptic representation) than in the audio only condition.

We predicted that combining haptics with the audio system would improve performance by providing redundant spatial cues as to the geometry of the intersection.

> H2: People will prefer the gestural audio + haptic condition opposed to the audio only condition

5.3 Results

Importantly, all six participants successfully navigated using the gestural-audio interface. Although the mean navigation time for the gestural-audio + haptic condition (13.16s) was slightly faster than the gestural-audio only condition (14.09s), a paired samples t-test demonstrated that this numeric difference was not statistically significant (p=.48). Additionally, a Bayesian paired samples t-test performed in JASP [20] resulted in a Bayes factor of .226, suggesting moderate evidence in favor of the null hypothesis for H1. The six participants who completed both conditions rated their preferred interface, with four preferring the gestural audio only and two preferring the gestural-audio and haptic interface. This finding did not support H2.

Figure 5 reports ease of use for both interfaces from 1-Very Difficult to 5-Very Easy. In general, participants rated both interfaces easy to use with all responses but one rated at a 3 or higher. This was particularly the case for the gestural-audio only condition, where five participants rated the interface as 5-very easy to use and one participant rated the interface as 4-easy to use.
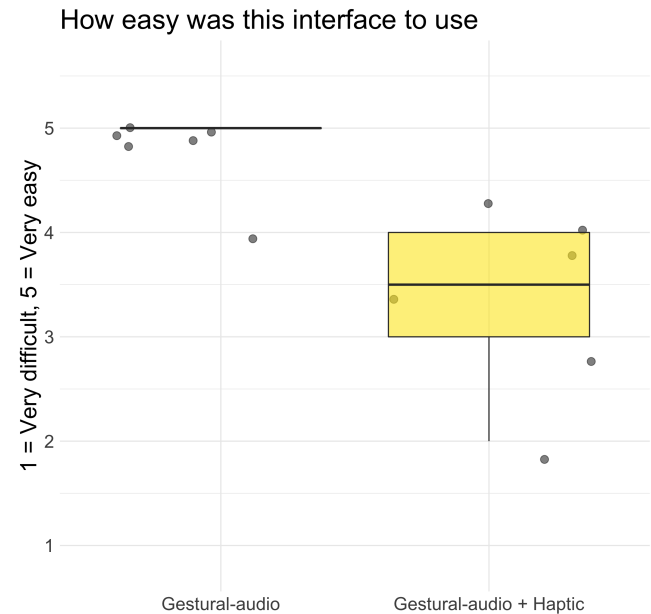

Figure 5: Ease of use

For subjective input on improving the haptic portion of the interface, every participant but one mentioned wanting stronger haptic feedback from the ultrahaptic device. Furthermore, participants noted wanting a frame of reference for where their hand should be or some cue to indicate the optimal position. This may have

contributed to why some of our participants failed the competency test for the haptic condition. For improving the audio portion of the interface, participants mentioned wanting to be able to customize several features including the speech rate, volume, units of measure (degrees vs. clock face positions), and the voice itself.

In the post-test for Studies 2 and 3, participants were asked to rate the extent to which they agreed with the statement, "I would want a hand-gesture navigation system." Figure 6 displays the results for both groups, which indicate positive support for gestural navigation. As reported in the Study 2 results, eleven (73%) in the Study 2 group indicated a four (agree) or five (strongly agree), whereas 7 (88%) in the Study 3 group responded agree or strongly agree. Although the unequal sample sizes make a statistical comparison inappropriate, these descriptive results are encouraging considering that the Study 3 group experienced a more realistic scenario using gestural navigation.
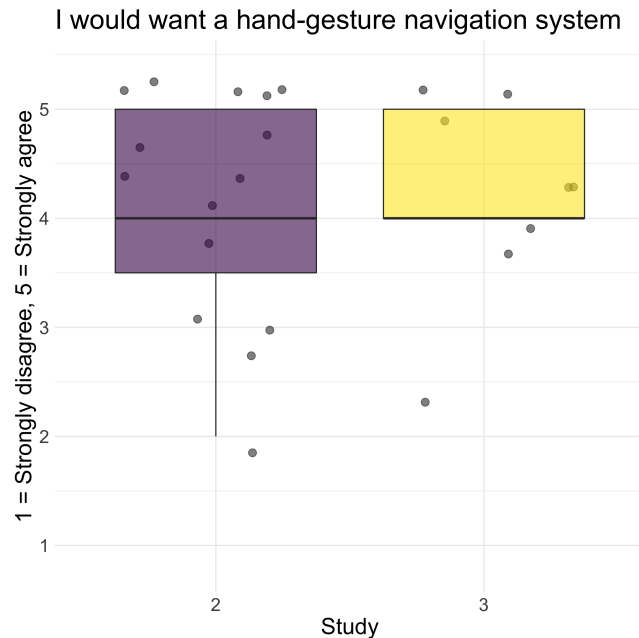

Figure 6: Participant's response to "I would want a hand-gesture navigation system" broken up by study

6 DISCUSSION

This research was motivated by the need for new accessible interfaces and interaction modalities to support autonomous transportation among people with visual impairments. Study 1 results demonstrate the importance of enabling vehicle control for this demographic, as well as the information required for human-in-the-loop control during fully autonomous vehicle (FAV) travel. In Study 2, we enumerate the first inclusively designed and accessible gesture set for FAV control, with results informing the development of a novel gestural-audio interface. The resulting experimental interface developed for and used in Study 3 promotes situational awareness and usability for altering the route, demonstrating strong support

from users in terms of ease of use and desires to use. Together, this research represents a critical step towards fully accessible FAV user experiences fundamental to our inclusive transportation future.

6.1 Importance of Human-in-the-loop Control

Despite being termed "fully" autonomous vehicles, Study 1 results suggest that BVI people desire to be in the loop of FAV vehicle control across common driving tasks. At a high level, these findings are in line with existing accessibility research in this domain [4], but provide additional granularity as to the situations in which control over driving behavior itself is important (of note, *altering a route* and deciding when the vehicle *starts and stops* its journey). By providing specific information types and driving tasks for which control is desirable, the results of this research elucidate specific connections between situational awareness and actionable behavior. That is, when information is provided to convey the situational awareness necessary to undertake control, and complemented with HMIs harnessing multisensory input/output functions, as we do here, the results indicate this demographic is able to independently operate FAVs with high ease of use.

It is worth noting that this desire for control extends beyond the BVI demographic and may well be true for all users. For instance, 92% of participants in an automated vehicle demonstration ride noted wanting shared control [31]. As designers and industry stakeholders develop the next generation of full autonomy, development efforts can (and should) be cognizant of user desires for input into the vehicle's decision space.

6.2 Advantages of Gestural-Audio

Audio interfaces are a common approach in navigation systems for providing navigational cues and spatial information. From in-vehicle GPS to accessible indoor systems (see [15] for review), audio navigation is a useful and natural approach for many users. Indeed, during Study 2, many participants naturally complemented their gestures with voice directions. For example, when pointing left, participants often also said aloud "Go left." This tendency can be capitalized on in future work to compliment navigation systems, not only in terms of usability, but also precision. As such, we argue that the gestural-audio system presented and validated here affords benefits compared to interfaces relying on voice input alone.

Although audio output is particularly applicable across environment and scenario, voice as a system input is not desirable in every scenario. Voice input can be imprecise, inaccurate in noisy areas, and can cause concerns for users related to privacy or in shared spaces [13, 15, 17]. Consider, for example, not wanting to wake a fellow passenger in a vehicle. Indeed, this need for additional inputs beyond voice is a significant advantage of our resulting multisensory gestural-audio interface. Not only can gestural-audio provide an alternative during situations where voice input is undesirable, but it could also reduce imprecision when performed in tandem with voice commands, as many participants naturally did.

Another major advantage of incorporating gestures in a navigation system is the applicability to people who are hard of hearing, deaf, or blind/deaf. Although not the focus of this work, several participants in Study 3 thoughtfully mentioned how our system should be explored and extended to promote inclusion among the

blind/deaf and across sensory impairments. Future incarnations of in-vehicle gestural-audio should also explore visual cues and enhanced visual cues/compensatory augmentations to further support sighted people and people with moderate visual impairment with significant residual vision. Indeed, gestural-audio could be well suited for all users to receive spatially salient information about the driving environment. By coupling in-vehicle UIs with onboard mapping and data software, future work could enable users to gesture towards any object in the environment (e.g., landmarks, other vehicles, signage) for more information and to undertake potential control actions.

One limitation of our approach is that the array of gestural-audio speakers currently encompasses 180 degrees opposed to a full cabin or 360 degree implementation. Given that user orientation in FAVs may not be fixed (consider that seat belts and typical vehicle seating arrangements may become obsolete), a truly spatialized, full cabin implementation would be most practical. Future work will involve computer vision recognition of user gestures without orientation limitations, opposed to the Wizard-of-Oz methodology used here.

6.3 Support for Haptics

Results from Study 2 demonstrate that BVI users desire combinations of audio and haptics in FAVs. Although performance did not improve using haptic cues in Study 3, we conclude this is not an indictment of the modality itself, but speaks to its specific and somewhat limited implementation in this work (see limitations section below). This is also likely an issue stemming from lack of exposure to haptic interfaces. People are generally accustomed to auditory UIs and navigation systems but have little experience with haptic UIs, despite promising results for spatial learning and behavior [14, 28]. Future work is necessary to explore how haptic cues can be successfully implemented in FAVs to leverage the intrinsic spatial advantages of this non-visual modality.

7 LIMITATIONS

The limitations of this work primarily concern the somewhat simplistic nature of Study 3. First, as mentioned, the Wizard-of-Oz approach utilized could be extended in future work to include computer vision recognition of gestures. While we argue that mid-air gestural interaction is ripe for accessible multisensory interaction coupled with audio and/or haptics, more investigation is necessary to explore the ideal sensory combinations and devices beyond gestural-audio with haptics and gestural-audio without haptics, as studied here. The task in this study was also simple in nature, with users only completing a predefined action (i.e., find the coffee shop) opposed to the vast state space of decisions that people will likely want to make in FAVs, as supported by our Study 1 results. These findings may also generalize beyond the BVI demographic. As such, future work should explore how all users, BVI or otherwise, can utilize gestural-audio across more complex driving actions and demands "in the wild" opposed to the controlled environment used in this research.

8 CONCLUSION

Fully autonomous vehicles hold enormous potential to transform the lives of people with disabilities by fundamentally increasing independence, mobility, and personal freedom. This project, consisting of three experiments with people who are blind or low vision (n = 23), explored the user-driven design of an accessible, non-visually dependent, human machine interface. Results indicate that gestural-audio holds the potential to enable people who are blind or low vision to independently operate fully autonomous vehicles. The interface test also provides compelling evidence for conveying situational awareness and increasing control across the spectrum of vision loss, with strong implications for all people during situations of reduced visibility (e.g., at night) or limited information access (e.g., in unfamiliar environments).

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CHAPTER 8: CONCLUSION

Although the current state-of-the-art for commercially available autonomous vehicles is semi-autonomous operation, where the vehicle automates only specific aspects of the driving process, auto-manufacturers are increasingly transferring driving tasks from a human operator to a computer to ensure the rapid advancement towards fully autonomous and completely driverless systems. The majority of behavioral driving research with this new class of vehicles has focused on current semi-autonomous operation, with significantly less being known about the features necessary to meet the needs of users leveraging fully autonomous capability, as is the focus of this dissertation research. To address this problem, this thesis advances the most comprehensive approach to fully autonomous vehicle design for people with visual impairment to date with, downstream consequences and broad impacts for all users.

Outcomes of this programmatic dissertation research include both practical and theoretical contributions. By focusing on complete trip accessibility, the research challenges the assumption that transportation starts and stops in the vehicle and encourages solutions that transcend vehicle design to include external hardware and software implementations (e.g., on a user's phone). In so doing, integrated findings across the research program inform approaches seeking to increase accessibility for the entire trip via inclusive solutions to pre-journey challenges as well as accessible in-vehicle interactions.

During the pre-journey phase of research, results suggested the importance of new technology and policy to support multisensory access across the trip (Chapter 2). Specific challenges related to safe navigation to the vehicle were identified, including obstacle avoidance and vehicle localization and entry, which informed the prototype solutions presented in this dissertation research combining multisensory (audio, haptic, and augmented visual) supports. These solutions were then evaluated

through a series of user studies and prototype evaluations, with strong support from users in terms of usability and performance during navigation tasks (Chapter 3). Building on these pre-journey solutions, accessible maps were also explored as a way of facilitating understanding of vehicle arrival behavior in both current rideshare services and future FAVs, with results demonstrating the practical utility of vibro-audio maps (Chapter 4). Taken together, results suggest that if designed inclusively and accessibly, transportation technology can surmount pre-journey travel to transit challenges for people with visual impairment by harnessing multisensory cues and nonvisual information flow.

In the in-vehicle phase of this dissertation research, initial results suggested the importance of situational awareness across the range of vision loss. That is, people need effective information and understanding of the driving context and vehicle's surrounding environment to meaningfully interact with FAVs (Chapter 5). Building on this evidence, further results suggested the practical utility of new nonvisual interfaces leveraging ultrasonic haptic feedback to provide situational awareness when paired with adequate user training (Chapter 6). Though awareness resulting from accessible information flow has value in and of itself, this dissertation research sought to explore the extent to which situational awareness could be leveraged to enable actionable control behavior. As such, the in-vehicle phase culminated in Chapter 7 to identify the types of control BVI users desire in FAVs, with results suggesting high desires for control across a range of driving tasks, particularly with regard to manipulating the route. To enable this control, the first inclusively designed and intuitive gesture set for autonomous vehicle control was identified and evaluated through a novel interface combining gestural-audio and ultrasonic haptic feedback. Results of this effort speak to the overwhelming support among users for new gestural-audio interactions for accessible control in the future of transportation (Chapter 7).

The research efforts and experimental results from this comprehensive series of dissertation studies contributed substantially to materials developed, including an award-winning travel-to-transit

solution for safe and efficient navigation among BVI users (the AVA app) and a patented gestural-audio

system providing novel human-in-the-loop control in FAVs. However, a few limitations should be

recognized in terms of the scope of methodologies used throughout the research, as well as the

generalizability of results. For instance, in Chapter 2, the policies reviewed include only those in the

United States. As FAV technology proliferates worldwide, understanding how global transportation

policy impacts accessibility will be paramount. Furthermore, the qualitative methods utilized to inform

the development of AVA in Chapter 3, particularly for action-solution pairing identification, were limited

in comparison to similar methods used in later chapters (i.e., in chapters 6 and 7). This limitation was

due to the abbreviated nature of the Inclusive Design Challenge and can be addressed in future work

through formal coding of user interview, focus group, and survey data seeking to pair technological

solutions to known accessibility challenges in automated vehicles. It should be noted that the user

studies presented throughout this research also leverage hypothetical scenarios (e.g., the survey in

Chapter 5) and Wizard-of-Oz methodologies (e.g., the gestural-audio interface in Chapter 7), and the

results are not intended to be representative or generalizable to the blind and low vision demographic

as a whole. Accessible technology research often relies on convenience sampling and relatively small

sample sizes to inform future design and development work, as was done here. Nonetheless,

discussions presented throughout the six papers inform both future policy and technology development

of value to FAV researchers, designers, OEMs, and end-users.

Future work should consider how to effectively implement the materials and interactions

advanced in this dissertation across form factor and context. Results from the first paper (Chapter 2)

indicate that policymakers and scholar-activists must also consider how to promote multisensory

inclusion as AIs replace the current requirements of human drivers. Results from Chapter 3 and Chapter

6 indicate that pre-journey solutions like the AVA app and new in-vehicle solutions like ultrasonic haptic

feedback will only be as effective as the extent to which users are trained to use them. This speaks to a larger need for heightened emphasis and support for accessible technology training and instruction that is proactive instead of reactive to emerging technology. Though researchers can and should consider how to design interactions inclusively and intuitively (e.g., the mid-air gesture set identified in the culminating in-vehicle work presented here), extending research results from Chapter 7 to effective user training modules will undoubtedly increase adoption and usability. This need for user training could be elucidated by more formal qualitative methods than used in this research. Future work should also consider how the next generation of wearable and mobile computing can translate smartphone-based apps like AVA and external hardware-based solutions (e.g., the speakers used in the gestural-audio interface) to more naturalistic and comfortable interfaces. For instance, emerging head-referenced smartglasses may well provide superior wayfinding and navigation cueing for BVI users than handheld devices. Likewise, headphones with accurate head-referenced transfer functions will likely enable flexible spatialized audio that can be used anywhere opposed to in fixed locations. The combined results from the dissertation research program speak to the high level of interest in accessible FAVs among the BVI demographic and suggest that more research and industry development is critical to ensure that this technology is usable across the complete trip at the consumer level.

Implementation of this dissertation research is predicted to enable usability and confidence in autonomous driving systems, while also paving the way for autonomous driving experiences that are critical to user safety, efficiency, and accessibility. Broad impacts from a future where FAVs are inclusively designed will include increased access to mobility with life-changing benefits in terms of workforce participation and quality of life. As such, accessible autonomy has the transformative potential of achieving independence and mobility for all.

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Paul Fink was born and raised in Johnson, Vermont. After graduating from Stowe High School in 2010, he attended the University of Vermont and earned his Bachelor's degree in Education. Always interested in policy, Paul worked for U.S. Senator Bernie Sanders before entering the University of Maine's Student Development in Higher Education Master's program in 2015. He earned his M.Ed. in 2017 and entered the Spatial Information Science and Engineering program at The University of Maine shortly thereafter. During this time, Paul served as Day One Technology Policy Fellow for the Federation of American Scientists, Legislative Graduate Fellow for the Maine Chapter of the Scholars Strategy Network, Machine Assisted Cognition and Human-centered Driving Intern for Toyota Research Institute, and Graduate Research Assistant at the Virtual Environment and Multimodal Interaction (VEMI) Lab. Paul has also been instrumental in securing extramural grants and prizes, presenting results in international conferences and symposia, and in teaching the graduate level Human-Computer Interaction (HCI) course each fall. Paul is a candidate for the Doctor of Philosophy degree in Spatial Information Science and Engineering from the University of Maine in August 2023.