Accessible Maps for the Future of Inclusive Ridesharing

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ABSTRACT

For people who are blind and low vision (BLV), 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 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 vehicles. Therefore, this paper presents and evaluates a multisensory smartphone-based map system designed to enable nonvisual tracking of summoned vehicles. Results from a user study with (*N*=12) BLV users suggest that vibro-audio maps (VAMs) promote superior spatial confidence and reasoning compared to current nonvisual audio interfaces in ridesharing apps, while also being desirable and easy to use. A subsequent expert evaluation based on improvements suggested during the user study indicate the practical utility of VAMs to address both current and future wayfinding challenges for BLV travelers.

CCS CONCEPTS

• **Human-centered computing**; • **Accessibility**; • **Accessibility technologies; Hardware**; • **Communication hardware, interfaces and storage**; • **Tactile and hand-based interfaces**; • **Touch screens**;

KEYWORDS

Accessibility, Ridesharing, Haptic Interfaces, Maps, Blind and Low Vision Users

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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 (e.g., at designated pick-up zones), rideshare users must rely 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 displaying 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 [34], 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 [2], and this demographic utilizes ridesharing services at significantly higher rates (2-3x) than other groups of people with transportation limiting disabilities [12]. Despite the comparatively high rates of use, understanding the arrival behavior of rideshare vehicles is a real problem among people who are blind and low vision (BLV), with specific concerns related to when the vehicle will arrive, where it will arrive, and if it will arrive at all [6, 17, 25]. Unfortunately, although ridesharing apps enable basic text-to-speech (TTS) through Apple's VoiceOver and Android's TalkBack, the onboard tracking solutions that address these problems among sighted users are largely inaccessible to BLV people. As a result, when waiting for a ride, BLV users are typically only provided the estimated time

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of arrival (e.g., 4pm or 5-minutes away) and sometimes the distance (e.g., 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, BLV users are left only with 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 automated vehicles will prioritize rideshared service models with a human driver no longer in the loop to provide assistance [28]. While call center support might be possible, it is probable that this support will come at additional cost or not be available at all. 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 vibro-audio maps (VAMs), nonvisual spatial applications combining haptic, auditory, and enhanced visual information rendered on touchscreen-based smart devices. The real-world utility of VAMs has been demonstrated for promoting cognitive map development for both BLV users and sighted users in nonvisual situations [18, 31]. However, the extant research, which largely relies on fixed, static maps, has yet to explore how real-time and dynamic location data can augment VAMs to further improve spatial understanding. By contrast, our prototype solution utilizes existing psychophysical design guidelines for tactual perception on touchscreens [22, 32] to develop the first (to our knowledge) real-time vibro-audio ridesharing solution rendered on a smartphone. The user study presented here (Section 4) evaluates the solution compared to a control condition using the audio-only approach currently available in commercial-grade ridesharing applications, with results demonstrating superior user confidence and understanding of a vehicle's route and arrival location. In a subsequent evaluation performed with a BLV navigation expert (Section 5), we assessed improvements made to the VAMs based on input from the user study and evaluated results indicating higher self-reported navigation confidence using VAMs.

Contribution Statement: The main contributions of this work include (1) to the best of our knowledge, the first real-time, dynamic vibro-audio element for nonvisual tracking on a smart device, (2) evidence from a user study with (N=12) BLV users and a subsequent expert evaluation that this solution increases navigation confidence and route planning for BLV users across various vehicle-rider spatial offsets (down the street, around the block, and on the next block) and (3) overall support for increased spatial understanding of maps using multisensory access.

2 RELATED WORK

The following reviews prior work with automated vehicles and BLV users, as well as the current state of the art for vibro-audio access on touchscreen-based devices.

2.1 Ridesharing Literature with BLV Travelers

Understanding the needs of BLV 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 BLV 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 [6, 25]. However, results from interview-based work also suggest that BLV 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 [4]. 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 [3]. This body of work highlights that although rideshares provide a beneficial form of transportation to BLV 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 BLV 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 through auditory/conversational interaction [9], ultrasonic haptics [14], and mid-air gestures [15], far less is known about how to improve information access in the important pre-journey phase of the trip [16]. 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 BLV users have traditionally relied upon the use of physical tactile maps, which consist of raised elements and braille labels to convey spatial properties [11, 38]. While tactile maps have long demonstrated significant utility in developing accurate cognitive maps for BLV users that support novel spatial learning and in-situ navigation [1, 13, 21, 39], 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 in this research. Traditional tactile maps also rely on fabrication processes that are both labor and cost intensive [18]. To address these limitations, modern digital interactive maps leverage several technologies on commercially available devices to provide highly customizable rendering techniques [29]. This new class of accessible mapping has

Table 1: 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	Pulse	100%	.10s	10Hz
Error tone	No on-screen element	NA	NA	NA	NA

resulted in positive user performance on dedicated accessibility devices like pin-arrays [41, 42], force-feedback devices [29], as well as on touchscreen-based smart devices [18, 23, 31, 35, 37]. Many 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 VAMs, which have demonstrated similar or better performance when compared to traditional embossed tactile maps [19, 31]. 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 maps that provide participants dynamic pre-journey spatial information, which we compare with the current features available in commercial ridesharing applications.

3 VIBRO-AUDIO RIDESHARING MAPS

The VAMs used in this research were developed using Swift and presented via an iPhone 12 Pro Max using the phone's onboard vibratory motors and speakers. Vibrotactile parameters related to intensity, required line width (2mm), and minimum separation (4mm) were derived from psychophysical guidelines on vibro-audio interfaces established and validated from prior work [22, 31, 32] and piloted 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, verbal audio cues (see Table 1) supplement each vibration as the user's finger touches the map elements.

Vibration patterns allow the user to differentiate between various elements of the map. The grid lines and vehicle routes are both constant vibrations, however the vehicle route vibrates at a perceptually salient higher intensity (50% greater) 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 provides audio estimated time of arrival (ETA) updates.

Example VAM routes are 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.

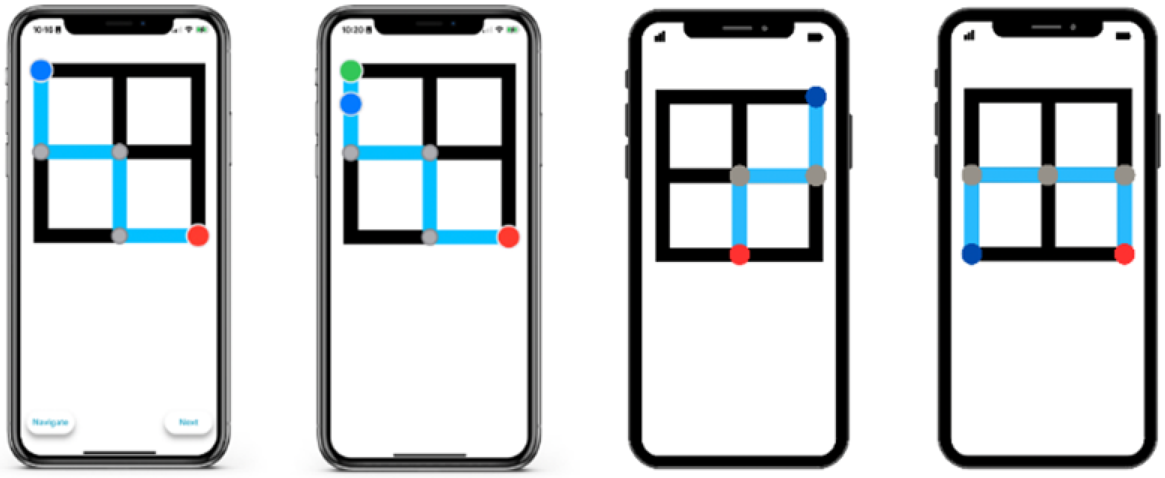

Figure 1: Vibro-audio Ridesharing Maps with the vehicle indicator at the start location (left) and moving along the route

Table 2: 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 (unknown)	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

4 USER STUDY

4.1 Participants

Twelve BLV participants (age 21-62, $M = 41.42$, $SD = 12.92$) participated in this research, representing a wide range of visual impairment, onset, and etiology (specific demographic characteristics are available in Table 2). Participants were recruited with help from a large nonprofit organization serving the blind and low vision community in an urban area and were compensated for their participation. No participants self-reported any known tactile sensitivity loss. This research was approved by a research university's IRB and written informed consent was obtained from all participants.

4.2 Study Design

Employing a within-subject design, the study involved two conditions counterbalanced between participants: 1) The experimental VAM and 2) an audio-only condition that reflected the nonvisual information currently available to BLV 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 rides that participants were tasked with imagining they would take with a summoned rideshared vehicle. One ride arrived in the correct amount of time (two minutes) to the correct location, one ride was delayed by thirty seconds (by stopping at an intersection), and one ride was rerouted "down the block" to an unanticipated pick-up point (the closest corner adjacent to the route). These scenarios were selected to match real-world challenges that BLV users face when using rideshare services and were derived from the existing literature, as reviewed in Section 2. Each ride 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 [24] to gain insight into the user's task-interaction and satisfaction with the interface. Directly following the ride, participants were asked three 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 [36], pick-up locations [5], and vehicle behavior [25]. The questions were as follows:

- After the vehicle arrived, I would be confident in locating and traveling to its location
- While waiting for my ride, I was confident that it would arrive at the estimated time
- 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.

4.3 Measurements

Given the non-parametric nature of the Likert data and the within-subject design, Wilcoxon signed-rank tests were used to analyze statistical significance from each experimental question individually. As the goal of the ride scenarios was to provide a breadth of different real-world BLV challenges, these data were analyzed together with condition (VAM vs. audio-only) as the sole independent variable. The dependent variables were based on the Likert responses for the respective tests: self-reported confidence in travelling to the vehicle's arrival location, confidence in the vehicle arriving at the estimated time, and the extent to which the interface provided sufficient information to understand the vehicle's behavior. For the think-aloud data, of interest was the extent to which the VAMs promoted effective spatial understanding and inferencing for users. Transcripts from the think-aloud task were reviewed by two researchers using content analysis to identify conceptual codes with a broad coding scheme [27]. 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*. Codes were reviewed by the researchers and counted for frequency between the VAM and audio-only conditions before being analyzed descriptively along with the post-test questions [27].

4.4 Procedure

The study included three phases: practice, experimental, and post-experimental survey. In the practice phase, the experimenter exposed participants to the VAM and the audio-only maps, 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"). Participants were then 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 fully 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 long was the route in total? Participants were also asked to verbally articulate all of the audio cues available on the map. If the participant incorrectly answered any practice 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.

After practice, participants began the experimental phase, where they were tasked with tracking the vehicle and thinking aloud by stating their thoughts throughout the pick-up time with special attention paid toward perception of the vehicle's behavior. 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 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 (VAM vs. audio-only) this information was inferred by monitoring the movement of the vehicle dynamic position indicator on the map combined with audio or the audio ETA/distance updates respectively. After each route, participants were asked the three Likert questions gauging confidence in traveling to the arrival location, confidence in its stated arrival time, and if sufficient information was provided.

In the post-experimental survey, participants were asked two Likert-style questions regarding the desirability and ease of use of the VAMs and given a chance to provide open-ended feedback about the experience.

4.5 User Study Results

Results comparing the VAMs with the audio-only interface demonstrated 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 these findings.

Overall, Figure 2 demonstrates that participants rated the VAM condition higher than the audio-only condition for each test question collapsed across the three routes: VAM confidence in navigating to pick-up location (*M* = 4.03, *SD* =1.32) vs. audio-only (*M* = 3.53, *SD* = 1.58), VAM confidence in time of arrival (*M* = 3.83, *SD* = 1.44) vs. audio-only (*M* = 3.69, *SD* = 1.41), and VAM sufficient

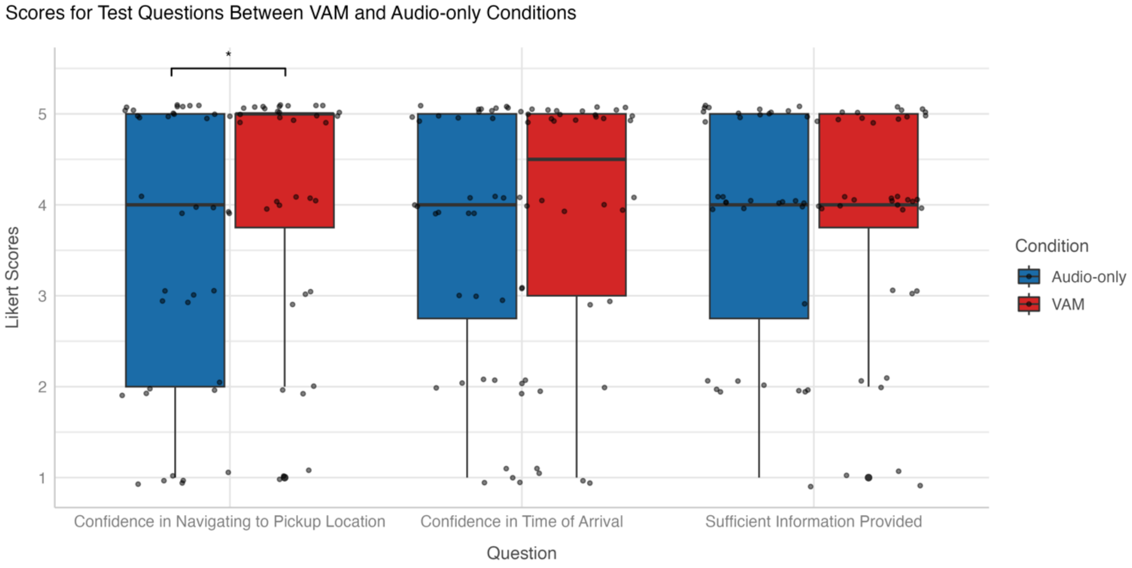

Figure 2: Boxplot showing participant scores (1 = Strongly Disagree to 5 = Strongly Agree) between VAM and Audio-only conditions

Table 3: Wilcoxon Signed-Rank tests for test questions between VAM and Audio-Only conditions

Measure 1	Measure 2	W	z	p	p
Navigation: VAM	Navigation: Audio-only	78.500	2.306	0.021*	0.725
Time: VAM	Time: Audio-only	65.500	0.312	0.773	0.092
Info: VAM	Info: Audio-only	124.500	0.313	0.761	0.092

information to understand vehicle behavior ($M = 3.86$, $SD = 1.25$) vs. audio-only ($M = 3.83$, $SD = 1.25$). As the data is within-subject and non-parametric, we conducted a series of Wilcoxon signed-rank tests to determine if these observable performance increases were statistically significant.

We interpret the statistically significant results ($p = .021$) with a relatively large effect size using rank-biserial correlation ($r = .725$) from Table 3 as supportive evidence that VAMs can improve assistance for BLV passengers in the critical task of understanding the vehicle's arrival location and to assist in passenger-vehicle meetup. Although the results from the other two questions were not significant, the high degree of agreement among participants (all questions received a median score of 4 or above), suggest that participants were confident in the arrival time and had enough information to interpret the vehicle's behavior in both conditions.

To further support and validate the self-reported data, we analyzed the sub-tasks during the think-aloud method where participants identified the halfway point of the route and potential delay/reroute. 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 vehicle had rerouted, with only two audio trials and one VAM trial missing the delay. 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 the maps and the vehicle's associated behavior.

Qualitative data analysis from the think-aloud transcripts provided a more nuanced perspective on the utility of the VAMs. The coding scheme used in analysis was purposefully broad and focused on the extent to which participants used explicit spatial cues (i.e., coded as *direct information)* 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 4) 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.

Frequency of the *direct information* codes (i.e., those derived directly from explicit spatial cues in the interface) vs. *inferred information* (i.e., those involving spatial inferencing or supposition by the participant) were counted from the transcripts. 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 postulate this result was due to participants having access to a greater degree of accessible spatial information in the VAM condition (i.e., the haptically perceivable relation of the vehicle indicator to the route and map grid), leading to participants naturally understanding and drawing more conclusions about the vehicle's behavior. As such, we interpret this result, which we further probed in the subsequent expert evaluation (below), as supportive evidence 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 3) 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.

Table 4: Representative examples of participant think-aloud responses for both conditions

VAM 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"
P11: "Turned south instead of north at the corner"	P12: "Getting closer and time is going down"

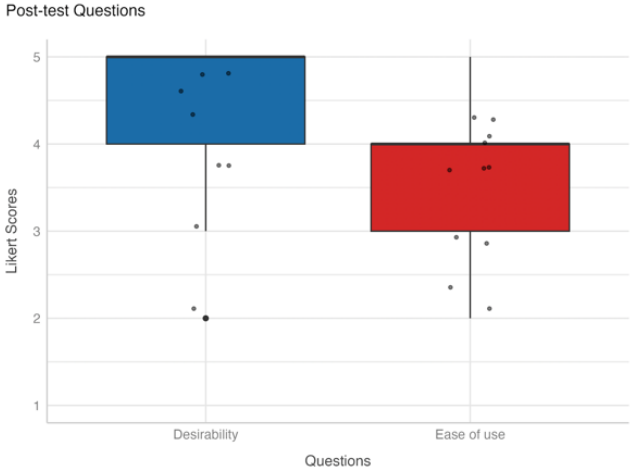

Figure 3: Boxplot for post-test scores (1 = Strongly Disagree to 5 = Strongly Agree) for desirability and ease of use of VAMs

Long-answer post-test questions focused on improvement for the VAMs and gave a chance for participants to share their thoughts more generally. Overall, participants were enthusiastic about the VAMs, but also provided areas of constructive feedback. Representative quotes included:

P6: "I like the vibration because you can track (the) car and feel where it is on the map."
P11: "I like the map, it gives me a cognitive map, helps with spatial context."
P10: "Include street names."

Notes for 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 turning, or changing route) to improve ease of tracking. Participants also mentioned that customization of the interface in terms of TTS audio speed would likely improve usability. Furthermore, participants thought the VAMs would also get easier to use with time and that they just were not very familiar with vibration and maps, which is a common finding in haptic map research [14, 18]

5 EXPERT EVALUATION

To assess the primary takeaway from the user study that VAMs can increase spatial understanding of the vehicle's behavior and user confidence in its arrival location, we invited an expert in BLV navigation to evaluate our prototype interface. The evaluator, who self-reported as congenitally blind with limited light perception and who also serves as one of the authors on this paper, has extensive experience with the design of nonvisual spatial interfaces but had no knowledge of the routes or improvements made to the VAMs used in the evaluation task. Of interest was evaluating the extent to which VAMs could facilitate route planning to the vehicle's location in the event that it arrives to an unanticipated pick-up point. The logic here is that it was not enough for users to merely self-report increased confidence in getting to the vehicle (as they did in the user study), without also understanding if that confidence can translate to successful route planning to the vehicle's location. As such, the expert evaluation focused on how VAMs could support BLV navigation during common vehicle-rider offsets during rideshare pick-ups: down the street, around the block, and on the next block.

5.1 Apparatus

The VAMs used in the expert evaluation were identical to the user study apart from two significant improvements that were adopted based on participant feedback. First, road name functionality was added to the roads and the intersections. Whereas in the user study, participants would hear "grid" when touching a non-route road, in this version, each road was named and could be heard along with the vibration pattern (see Table 1). Road names (e.g., State Street and College Ave), which were also available on the route, were selected based on a typical college town in the United States. These road names would automatically trigger when the vehicle was turning at an intersection (e.g., "the car is turning onto State Street") as well as on arrival (e.g., "the car has arrived at the intersection of State Street and College Ave"). Second, prior to the evaluation, the expert had the chance to customize the speed of audio feedback heard on the VAMs.

5.2 Evaluation

The procedure for the evaluation was highly similar to the user study. The expert had a chance to learn a practice map and its constituent parts prior to moving to the testing phase (see section 4.4 for the detailed procedure). During the testing phase, the expert was tasked with following the vehicle along the route, thinking-aloud while doing so. As in the user study, the evaluator was told that the vehicle could arrive to a different location than the route indicated and that they should notify the experimenter as soon as they suspected it might be diverting from the route.

Three routes were used in the testing phase, each arriving to a location separated from the user location indicator: one arrived down the street (Figure 4 left), one arrived around the block (Figure 4 middle), and the next arrived on an adjacent block (Figure 4 right). A key difference between the evaluation and the user study was that once the vehicle arrived, the evaluator was asked to move their finger back to the user location and to trace the most efficient path they could take to walk to the vehicle's location. Directly following the three tracing tasks, the evaluator was engaged in a semi-structured interview to gauge the effectiveness of the street names, speech speed customizability, as well as the overall effectiveness of the VAMs for understanding and planning a route to the vehicle when it arrives to an unanticipated location.

Data collected included the interview and think-aloud responses, touch data from the route planning tracing task, and time differential between when the vehicle diverted from its route and the evaluator's response. Each are reported in the following.

5.3 Results

The evaluator correctly identified each route divergence prior to the vehicle arriving to its final location. Although there was measurable delay between when the vehicle diverted and the evaluator identifying it (13.1s, 5.65s, and 6.67s), some of this delay can be attributed to being engaged with the think-aloud task. Touch data

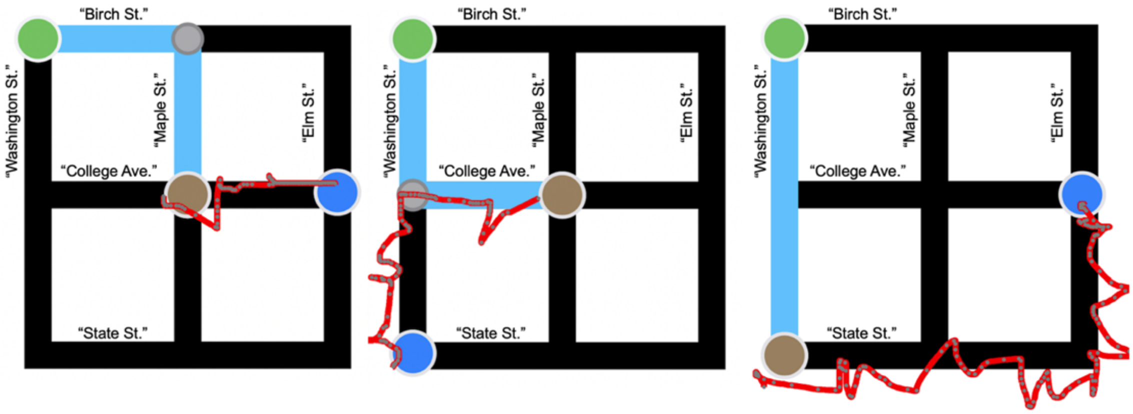

Figure 4: Touch data for tracing task down the street (left), around the block (middle), and on the next block (right). The green circle is where the vehicle starts, the blue circle is the vehicle at its destination, and the larger gray circle is the user's location.

from the phone's screen consisted of x,y coordinate pairs (as represented by the gray points and red line in Figure 4) between the user location (gray circle) and the vehicle's arrival location (blue circle). These data demonstrate that the evaluator correctly chose the most efficient path for finding all three vehicle arrival locations, with all points landing on or near the optimal route. Note that variation about the line is expected given nonvisual "zig-zag" exploration strategies often used with vibrotactile line tracing [31] and is therefore not an indication of inaccuracy. As such, we interpret these results as the evaluator having a strong understanding of where the vehicle arrived in relation to their location. This interpretation was further supported by the think-aloud and interview responses.

Much like in the user study, the evaluator used descriptive language about the vehicle's behavior during the think-aloud task while tracking the vehicle with the VAM. Some notable examples include: (Route 1) "The car continued down Birch Street, but it should've taken a right", and (Route 2) "This is a grid so in this location there [will be] two direct lines to the car. Does it matter which one I use?" Following the tracing task in Route 2, the around the block scenario (Figure 4 middle), the evaluator mentioned that they knew they could have taken another equally efficient route: "I could've gone another way too. If I knew it was safe, I could have gone across the hypotenuse, which would have been even shorter." We interpret realizations such as these as supportive evidence that the VAM helped develop a cognitive map of global layout structure sufficient to enable spatial computation and behavior that are required for route planning. Interview responses further supported this finding, as well as the effectiveness of the improvements made to the VAMs based on user study feedback.

In the interview, the evaluator was supportive of audio speed customization. "It was helpful because when it is too slow, I find it distracting so it should always be user adjustable." They also thought street names were a good addition to help cognitive mapping. "Street names provide a kind of a frame of reference...it helps me to put it into my schema of roads and layout. It just makes it feel more natural for me. . .I think of a spatial image, like a kind of a cognitive map and it makes it much easier to think of the space and match what I'm feeling from direct experience with what I'm having in memory." When asked how the VAMs compare to current ridesharing apps, the evaluator mentioned how "[on current apps] I can kind of get the idea of 'oh it's 10 minutes away, it's 2 miles, there must be something going on' because I know that would only be 3 minutes. But I don't have any idea of where it is on the map. I don't have any idea of what's happening. I don't know where the car is. I just have like these kind of isolated numbers that are independent of the physical location of the car. So here I could actually feel where the car is." They went on to bring up how using these apps can be frustrating compared to how their friends use them: "When you can see it on the map, you have a lot more knowledge. I feel like they always have a lot more knowledge about what's happening, whereas I'm just guessing. So being able to track the car just makes me feel comfortable that it's getting where I expect."

The evaluation interview ended talking about potential improvements to the VAMs. The evaluator suggested it would be helpful to have either an audio or vibration-based indicator that would direct your finger to the vehicle if you lost it while tracking. They also mentioned that the training phase used in both the user study and the evaluation would be helpful for future projects: "A lot of blind people don't use a lot of maps. And so I think that the learning part, the practice mode, would be useful for teaching people how to use it. Like maybe this could be used with something called Orientation and Mobility, which is a training process that many blind people use with Orientation Mobility Instructors: specialists that teach people how to safely navigate and use basic skills, like street crossing. . .you could set up mock scenarios almost like this, but give the users, the client's, their home neighborhood. So not only would it teach them about their neighborhood, but they could learn about how cars are moving."

6 DISCUSSION

User study results with ($N = 12$) BLV participants demonstrated that ridesharing maps augmented with vibro-audio cues significantly improve confidence in locating a vehicle's arrival location. Although results suggested that the audio-only interface performed as well as the VAMs for understanding delays and the vehicle's behavior in general, for example *if* there was an arrival destination change, the VAMs promoted better understanding of *where* that new arrival destination would be. These results were corroborated by a subsequent expert evaluation where tracing data from the phone's screen indicated that VAMs could be used to plan routes to the vehicle's arrival location. This finding suggests that accessible VAMs hold the potential to solve the critical user-vehicle meetup challenge for BLV travelers in the future of automated vehicles. Beyond the practical appeal of this solution, VAMs also facilitated 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 automated systems.

6.1 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 during 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 BLV travelers, especially in future automated vehicles [4, 7, 8]. We contend, therefore, that VAMs hold the potential to compliment a growing research area aimed at improving situational awareness for BLV users [14, 15], both during pre-journey tasks like waiting for a ride to arrive, as well as during vehicle travel. Though a limitation of this study was that it only explored the former (and notably in a controlled experimental setting), 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 (ideally "in the wild" to increase ecological validity). The novel real-time user interface elements that allow for this dynamic spatial tracking should also be further explored, as discussed in the following.

6.2 Multisensory Real-time Tracking Without Vision

This work complements a growing body of work pairing vibration and audio-based feedback to improve graphical access and education [10, 20, 26], as well as mapping [18, 30, 31, 33]. Apart from applications in the gaming space [40], the vast majority of vibro-audio solutions to date have relied solely on static user interface elements opposed to real-time tracking of moving objects. 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 and manipulating playheads on video and song progress bars), as well as for 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.

6.3 Limitations and Future Work

Future work should center on increasing the small sample size, generalizability, and ecological validity of this work, as the study only explored pre-journey navigation in a controlled experimental setting. As such, future work should investigate the ways in which accessible maps combining multisensory cues can promote situational awareness and actionable spatial reasoning and behavior (ideally "in the wild") for both pre-journey and in-vehicle travel. Importantly, this would necessitate exploring more complex roadway layouts than the simple grid system used here, as well as VAMs at different scales and vehicle speeds. Moreover, additional research is needed to compare VAMs with other nonvisual navigation aids and investigate their utility when rendered on different devices with various vibration capabilities. It is worth mentioning that using think-aloud methods with an audio-based interface may introduce confounds so future work should also explore alternative approaches for soliciting users' reasoning during interaction, with more in-depth qualitative analysis of the transcripts than were presented here.

7 CONCLUSION

This paper presents a novel VAM solution enabling real-time nonvisual vehicle tracking for BLV ridesharing users. A user study with (N=12) BLV 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. A subsequent expert evaluation suggested that the navigation confidence indicated by the user study would translate to accurate route planning and wayfinding 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 automated vehicles.

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The VAM code and supporting libraries will be made available to interested researchers by request. This will include the custom vibration and audio modules, as well as graphics and objects used for the ride scenarios.

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