Understanding the Power of Control in Autonomous Vehicles for People with Vision Impairments

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ABSTRACT
Autonomy and control are important themes in design for people with disabilities. With the rise in research in autonomous vehicle design, we investigate perceived differences in control for people with vision impairments in the use of semi- and fully autonomous vehicles. We conducted focus groups with 15 people with vision impairments. Each focus group included a design component asking participants to design voice-based and tactile solutions to problems identified by the group. We contribute a new perspective of independence in the context of control. We discuss the importance of driving for blind and low vision people, describe differences in perceptions of autonomous vehicles based on level of autonomy, and the use of assistive technology in vehicle operation and information gathering. Our findings guide the design of accessible autonomous transportation systems and existing navigation and orientation systems for people with vision impairments.

Author Keywords
Autonomous vehicles; blind; low vision; control

ACM Classification Keywords
• **Human-centered computing~Accessibility**

INTRODUCTION
People who are "legally blind" are unable to drive, but this may be able to change with the development and adoption of autonomous vehicles. Beyond making driving a more efficient process for existing drivers, autonomous vehicles (AVs) have also been praised for the ability to make transportation possible and easier for people who do not or cannot currently drive (e.g. people with motor impairments, children). One such group, people with vision impairments, has the potential to be greatly impacted with improved transportation options since an increasing 35 million people in the United States have a vision impairment (i.e. blind, low vision) or eye disease [26,51,54], which can make it unable for them to legally operate a vehicle.

Autonomous vehicle researchers and manufacturers have rightfully focused on making these vehicles safe for existing drivers. However, the lack of research on how to make AVs not only safe, but usable by people with disabilities such as those with vision impairments, will only further isolate use. Yet, this may isolate use by populations who some may argue need access to autonomous transportation most. We are now at the forefront of research on autonomous vehicles, a critical time for developing for accessibility and inclusivity.

Prior research on transportation with people with vision impairments has primarily discussed their use of public transportation and walking navigation aids [2,15,56,58]. We are just beginning to understand perceptions of the visually impaired regarding autonomous vehicles [13] and how to design autonomous vehicles for people with vision impairments [23]. However, autonomy is a spectrum, and recent work has suggested that semi-autonomous vehicles, where the driver may need to intervene, will be adopted sooner than fully autonomous vehicles, where no driver intervention is possible [46]. Therefore, this paper seeks to understand the differences in perceptions between semi- and fully autonomous, and how to better design accessible systems to support people with vision impairments in these vehicles.

In this paper, we present findings from design-based focus groups with 15 people with vision impairments focused on semi-autonomous and fully autonomous vehicles. Our findings show how people with vision impairments still find outlets to continue or learn to drive, decide on their preferred level of autonomy, and discuss how appropriate tools designed to support the autonomous driving experience for blind and low vision people should be based on known metaphors. Because the major difference between semi- and fully autonomous vehicles is a difference in control of the vehicle, we present a discussion on the nuances of control for people with vision impairments. Our findings amplify concerns in prior work around independence, access, and use of assistive technologies for visually impaired people by connecting control to independence. We use this work to inform the design of interfaces that can support them in autonomous vehicles. This work may have implications for designing tools for people with vision impairments in highly

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complex visual spaces, and situations where decision-making and control may be shared between a person and machine.

RELATED WORK

We use prior work on how people with vision impairments use existing forms of transportation; their perceptions of control, independence, and safety; and autonomous vehicle design to help guide our research.

Understanding control, agency, and independence

We draw on research in psychology, disability studies, and human-computer interaction to define agency, control, and independence and discuss their meaning in the context of technology design.

Agency and control are often interchangeably used. Disability studies scholars often describe *agency* as an external concept, being seen as a peer [44], while HCI scholars define agency internally as "the capacity to act" or one's ability "feel in *control*" of systems [18,28,32,50]. In psychology literature, control has been discussed in the context of "deprivation of control" with aging populations where lack of control can affect cognitive and emotional processes [34]. Agency or control is often associated with *independence*, in which independence can be defined as autonomy and being able to act independently from external influences. However, researchers continue to debate whether agency and independence differ [1,44].

A study on agency with people with autism shows that agency can exist without independence [44]. Findings show how participants felt a sense of agency while asking for support or help, being interdependent rather than independent. Lazar's work shows how art therapists and people with dementia participate in joint decision-making in sharing artwork, promoting interdependence over independence [29].

Yet, independence is a clear theme when designing technologies to support people with vision impairments. Assistive technologies for people with vision impairments such as screen readers and screen magnifiers are often designed with the goal of being able to operate a computer or mobile device independently [1]. Similarly, research like Szpiro et al's work has shown how people with vision impairments wish to remain as independent as possible [52]. Further, blind people are often advised to take orientation or mobility (O&M) classes that help them learn to position themselves in their environment and use navigation tools like white canes. The goal of these classes is for someone with a vision impairment to be able to independently navigate their environments.

Different from prior work which focuses on autonomy/independence for people with vision impairments, this paper also considers the role of control in transportation and navigation decision-making processes.

Transportation needs of people with vision impairments

Designing to support autonomy in transportation and effective navigation for people with vision impairments has been a long-standing challenge within HCI and engineering research. Prior work has focused primarily on public transportation use and walking navigation. Accessible public transportation solutions have been designed such as Mobi, which provides bus times and disability support features for different bus routes [60], and GoBraille and MoBraille, which provide real-time feedback about bus arrival times to deaf-blind people [2]. There has also been considerable research on walking navigation systems [20,59]. Prior work to understand blind navigation describes the different types of mobility aids blind people use, importance of feedback, and concerns about safety [9,59]. Adding to this work, Easley et al. discuss the importance of landmarks for situational awareness of blind people walking in indoor and outdoor environments [21]. Each of these studies work to understand how people with vision impairments independently navigate their environment or how tools can be designed to help them do so.

Recent work on accessible navigation and transportation is beginning to pick up where previous systems and disability studies researchers left off more than 15 years ago in designing autonomous wheelchairs [7,8], by investigating autonomous vehicles for people with vision impairments [13]. Most recently, Brinkley et al collected consumer preferences data of people with vision impairments about their perceptions of autonomous vehicles. Findings show that in addition to the purported benefits of increased independence and time savings, participants had concerns with liability, situational awareness, and assistance. This work discusses opportunities for increased independence and focuses on smartphone-based designs for helping people with vision impairments interact with autonomous vehicles. However, this research lacks a specification and discussion between levels of autonomy.

In this paper, we address the gap in studying varying levels of autonomy in autonomous vehicles. The formal autonomous vehicle classification system developed by the Society of Automotive Engineers (SAE) defines six levels of autonomy from no to conditional to full automation [47]. According to SAE International, no automation (level 0) involves "full-time performance by the human drivers of all aspects" of driving. Conditional automation (level 3), which we refer to as semi-autonomous in this paper is defined as "an automated driving system [where] all aspects of the dynamic driving task" are the responsibility of the system and there is "the expectation that the human driver will respond appropriately to a request to intervene." We refer to SAE's definition of full automation (level 5), which states that there is "full-time performance by an automated driving system of all aspects" of driving "under all roadway and environmental conditions that can be managed by a human driver" [45]. We argue it is important to understand differences in design for these levels of autonomy because each can provide radically different driving experiences.

Further, Brinkley's work identifies ways that smartphones can be used to support people with vision impairments in autonomous vehicles. In this paper, we extend this work to think about tools beyond smartphones that can be useful for visually impaired people, but also consider existing design research in the broader space of autonomous vehicle design.

State of autonomous vehicle design

Autonomous vehicles are becoming increasingly popular for their potential to provide transportation to people with disabilities, but, most of what we know about design and use is still from the perspective of sighted drivers, who have extremely different navigation behaviors than people with vision impairments [57]. We know that major factors in determining adoption of autonomous vehicles by sighted people are trust [14,16], safety [6], and control [37]. As such, people have tried to design tools to interpret trust [38]. Others have thought about how tactile interaction and wearable technologies could be used as interfaces to manage control through tactile and haptic input and feedback [39]. With these technologies, researchers have studied the design of voice and gesture interaction in autonomous vehicles [53], particularly to address driver transition challenges where the vehicle asks the driver to intervene in a safety-critical scenario. Recent work reviews the current state of control transition types and solutions, but most of these fixes rely on some level of vision [36,41]. Solutions that do use audio feedback are ineffective for people with vision impairments such as work that uses relative localization commands for people to take control of the system such as "turn here" or "there" [49], which are unhelpful when the driver cannot see where "here" is. Our study builds on prior research on voice and tactile interfaces and aims to provide design recommendations for designing for control and accessibility.

This paper draws on recent research in disability studies and autonomous systems to expand on how HCI researchers and the ASSETS community can think about designing autonomous vehicles for people with vision impairments. The research questions we address in this paper are:

1. How do people with vision impairments (blind and low vision) perceive autonomous vehicles with different levels of autonomy and control?
2. What are the implications of these perceptions on the design of future autonomous vehicles for people with vision impairments?

METHODS

Procedure

To investigate how to better design accessible voice and tactile systems for people with vision impairments in autonomous vehicles, we conducted design-based focus groups. While interviews can help understand individual driving experiences, conducting focus groups allowed us to better understand consensus (or lack of) of opinions towards the use of autonomous vehicles. Prior work also used a focus group approach [13], but we focus on differences in levels of autonomy, followed by design ideation sessions with people with vision impairments. Each focus group began with a definition of semi-autonomous and fully autonomous vehicles based on SAE's classification systems [47]. Participants were then asked about any prior experiences with driving, perceptions towards these types of vehicles, to compare to other forms of transportation, and any perceived challenges to using the different levels of autonomous vehicles.

To understand how people would envision autonomous vehicles supporting varied levels of control for people with vision impairments, we then followed this traditional focus group discussion with design sessions where participants created artifacts to illustrate their ideas. In the design sessions, participants had access to popsicle sticks, cork stoppers, clay, rubber bands, cotton balls, and pipe cleaners. The session moderator identified each of these objects and explained their placement on the table. Prior work [48,55] suggests scenario-based approaches can work well for involving people with vision impairments in design and ideation sessions. Therefore, we presented participants with two scenario-based prompts for which to design solutions to challenges they described in the focus group discussion or challenges identified in previous research (e.g. [13]).

Scenarios

In the first activity, the researcher asked participants to design an audio or voice-based solution. However, conducting focus groups with sighted people can suffer from one person dominating the discussion [25], and design-based group activities with people vision impairments can be challenging to facilitate discussion in general [5,48,55]. Therefore, participants were asked to "act out" their solution with one group member acting as the driver and another acting as the vehicle. In the voice activity in the first focus group, participants were asked to work together and brainstorm how autonomous vehicles could address the safety concerns of a driver. In the second focus group was asked to design a voice solution to help a blind person navigate obstacles in a driver transition request. The groups had different prompts depending on what they focused on in their discussion prior to the design components.

Tactile interfaces for people with vision impairments have potential use cases in other contexts [24,31]. Therefore, in the second activity, participants were asked to design a tactile solution to address the challenge in the scenario. All groups were asked to work together to design an artifact they could touch or feel to help a blind driver understand their car's location relative to other vehicles in the driving environment. This activity resulted in the creation of several artifacts participants envisioned as solutions to the design prompt.

Analysis

All focus groups were video recorded to capture the process of designing. We also took photographs of the artifacts participants created in the design component of the focus groups. Recordings were transcribed by a researcher. We used an iterative coding approach to analyze the transcript data. Four researchers began the coding process with open coding, noting anything in transcripts related to current and perceived autonomous transportation experiences for people of vision impairments. Two of these researchers then used the open codes to agree on a list of twelve axial codes to describe groupings of open code categories. To mitigate coder bias, a sample of the transcripts were coded by both researchers. Coding of the sample was reliable (Cohen's kappa = 0.75, $p < 0.05$, CI. [0.74,0.99]) Upon reaching this level of agreement, each researcher coded one transcript. Following this step, both researchers discussed themes amongst the axial coding categories and formed themes around the most salient concepts - perceived control, ways to design for control, and driver identity. We discuss each of these in more detail below.

Recruitment

After being approved by Our Institution's Institutional Review Board, we recruited participants through word-of-mouth and local e-mail list-servs for people living in a mid-sized Midwestern city in the United States. In addition, we partnered with the National Federation of the Blind, which advertised the study recruitment information at a regional board meeting. Participants were eligible to participate if they were at least 18 years old with a non-corrective vision impairment (blind or low vision).

Participants

We recruited 15 people (average age = 59 years old, female = 7) for two design focus groups sessions, which lasted between 60-90 minutes. Although many participants were older, there were differences in the level of vision loss (blind vs. low vision) and the age at which participants lost their vision, all signs of diverse experiences in the sample. Four people participated in the first focus group and 11 people participated in the second focus group. While the size of the second focus group was not ideal for small group design activities, to provide a more effective design experience, we

Table 1 - Description of people who participated in the focus groups

PID	Age	Gender	Age Lost Vision	Vision Description	Driving Experience?	Design Group #	Focus Group #
1	50	M	Birth	born blind	Yes	1	1
2	67	M	61	totally blind, diabetes	Yes	1	1
3	38	M	28	totally blind	Yes	1	1
4	73	F	60	totally blind	No	1	1
5	69	F	63	blind in one eye, limited in the other, legally blind	No	2	2
6	44	M	no response	no vision	No	3	2
7	57	M	50	20% vision	Yes	2	2
8	69	F	33	totally blind - left eye is 20/30, right eye is 1250	Yes	2	2
9	77	M	18	blind, can't see	Yes	3	2
10	58	F	Birth	legally blind, cannot drive, some peripheral vision	Yes	2	2
11	45	M	Birth	legally blind, optic nerve atrophy	Yes	3	2
12	72	F	5	total	No	2	2
13	54	F	Birth	legally blind, light perception	No	3	2
14	35	M	Birth	legally blind, see silhouettes	No	3	2
15	76	F	Birth	very poor vision, born blind, incubator	No	3	2

split this group into two smaller subgroups for the design session component where one group consisted of six participants, and the other of five participants. This resulted in two focus group sessions, but three design groups.

RESULTS

We begin by describing the importance of driving expressed by participants. We continue with their perceptions of semi- and fully autonomous vehicles. From their discussions, we draw out the how they speak about autonomy and differences in control. Lastly, we present how participants describe voice and tactile tools to better control autonomous vehicles.

Pride of Driving and Improved Quality of Life

Despite being legally unable to currently operate a vehicle, several participants confided how they continue to drive, to varying degrees. P11, who is low vision, described driving with a telescope despite being legally blind. Some have driven out of curiosity like P3 who said, "*I've been blind since I was 28, but I have, thanks to my sister, I've driven a car 2 blocks, totally blind*." Others like P7 operate vehicles more regularly - "*I warm the car up, the vehicle, for my wife every day. That's why. I start it up and pull it out the garage. So, it takes a skill to do that*." This quote also shows the pride that P7 takes in not only being able to do something independently, but help someone else.

Also, participants often described any prior experience with driving with pride. For example, P7 introduced himself and said, "*that's what I did for a living as a transportation equipment operator for public transportation*." Similarly, P2 said, "*…I drove taxi for about 20 years*." Driving as a career was and is something still important to these participants probably explained by driving often being associated with independence for people with vision impairments [13]. P2 did not want to give up this independence and control even when his visual abilities started to decrease saying, "*...as I was losing my sight, early in the morning, darkness come, I couldn't see so what I would do is stay in the middle and I would blow my horn*." With his vision loss, P2 had to give up his career and like what other participants described, also lost a sense of independence.

People perceived the biggest strengths of using autonomous vehicles to be improved independence and quality of life. Participants mentioned the forced reliance on other people as being a downside which often preventing them from accessing vital resources. P11 said, "*It might be different from the point that we have more independence. We don't have to rely on other transportation or doctor*." Although the independence resulting from increased self-reliance has been cited as one of the expected benefits of autonomous vehicles [13], these quotes also highlight the tension between independence and interdependence, which is something that people with disabilities constantly grapple with in transportation and non-transportation contexts [2,30]. Moreover, quotes show how increased transportation independence is strongly connected to desired control over when and how they access resources.

Beyond health access, people described improved access to other resources. For example, P14 said "*for 2 years, I spent over $1000 a month in transportation.*" Similarly, P11 said

> "*another thing that is huge in my mind would be the time savings. It would be the quality of life because a vocational rehabilitation counselor could easily say, 'well you can take public transportation to a job.' But, when you map it out, by the time you get to a bus stop, change over to another bus, take it into a city, they could easily say 'Oh well a commute of 2 and a half hours 1 way, it's doable.' It's doable but technical[ly] having a driverless car to take you 2 and a half hours to go by public transportation when an autonomous car could take me 25 minutes, that's a significant leap*."

Similar to other work, access to affordable and reliable transportation to jobs is a major concern for people with disabilities [19]. Accessible transportation could also make it easier to try new activities with P5 saying,

> "*it might be a good idea because we would be able to get out of our houses and do things that you couldn't do before because you had no transportation or whatever and nobody is going to do it for you.*"

However, excitement about autonomous vehicle use also comes with concerns. For example, P3 said, "*You ain't gonna have a choice but to trust them if they have an automatic vehicle to come to your house to take you here, to take you there, you better get in*." These last two quotes show the tension between potential independence and trust where participants recognize access to transportation means access to new places, but this access is dependent on trust.

We extend prior work which identifies challenges people with vision impairments have concerning trust of autonomous vehicles [13]. When asked about their perceptions towards autonomous vehicles, P7 said, "*actually the whole subject is one word and that is trust - trust technology. Will I be able to trust the whole ordeal?*" In addition to concerns about trust and safety as noted in prior work [13], we also noted how control played into aspects of trust with participants expressing concerns about trusting something of which they had limited control. For example, P11 said he was concerned with "*...putting too much faith in what it can do in terms of not realizing the extent that I, as a driver, would still have to take control...so, thinking it's going to do more than promised*." Here, P11 describes 'over-trusting' autonomous vehicles and not realizing boundaries of what he is expected to do compared with what the vehicle is expected to do. Relatedly, participants were concerned with trusting the vehicle's performance such as P15 who said, "*Will the car get away with you? Will it get away? Some cars just done that*." Many participants laughed at this question, but followed it with a serious discussion about what would happen if the vehicle malfunctioned.

Here, many participants described their continued interest in driving as current transportation options (e.g. relying on family members, public transportation) gives them limited control over when and how they travel to different places, and limited their perceived independence. But, there are trade-offs to being afforded control and independence such as liability and vehicle error handling, which people were not yet completely comfortable handling.

Control Differences in Level of Autonomy

From this discussion our findings begin to show nuances in the ways in which participants considered controlling autonomous vehicles based on prior experiences with driving.

For example, participants described challenges being passengers in existing vehicles. P13 wanted "*to know the same thing about the locks – where are they, how to get to them*" P5 described "*more concerned about, how, you know some doors, you lock the door and just get out and driver has more control over there so I want to know how to unlock the doors just in case I want to get out*." Although participants also described wanted more control over the air conditioner system and radio, this concern of locks importantly connects concerns of safety to control. Similar to prior work on interpersonal safety of blind people with other sighted people [10], our research suggests interpersonal safety can also relate to perceived or desired safety from person to machine.

Lack of experience with driving also affected participant's desired levels of autonomy in an autonomous vehicle. For example, P4 said, "*I wouldn't want to be in a vehicle like that because I know nothing about operating a vehicle anyway so I would have to be in the fully autonomous.*" Similarly, P8, who had never driven before, said,

> "*I may get behind the wheel and get nervous so you know, the car will say 'you go over to the left' and you're getting ready to make a left-hand turn and turn your signal on. Okay I don't want to get in the position where I forgot my right and left, you know what I'm saying?*"

Unlike prior work, we defined different types of vehicle autonomy for focus group participants, semi- and fully-autonomous, recognizing that autonomy is a spectrum [47]. Interestingly, participants agreed that semi-autonomous vehicles, which may require some driver intervention, would be best for people with previous driving experience. P3 said, "*if you've never drove, then a semi won't be for you because you have to know how to drive.*" Further, P14 said,

> "*if you were made aware that your vehicle was malfunctioning, you should still be able to stop it. You know, if the car starts making erratic motions and people are blowing their horn, you know everything needs a way out and you should at least be able to stop the thing and say 'I'm done.'*"

Generally, participants who had driven before, like P14, wanted the option to intervene and control the vehicle. Yet, there were understandably concerns for how to be able to do this as a person with a vision impairment.

Participants in both focus groups struggled to envision themselves, as a person with a vision impairment, operating an autonomous vehicle. P1 said, "*I would think the semi-autonomous vehicle would be like safer than the autonomous vehicle because you know, you would have a person to take over should the system malfunction,*" distancing himself from the person who would be operating the vehicle. This was something the facilitator needed to clarify in both focus groups suggesting that an identity shift may need to happen for people with vision impairments to be envision themselves as not only users of autonomous vehicles, but also ones with agency over the vehicle's' actions.

When the facilitator asked participants to think about themselves being the driver, there were other concerns. Interestingly, not everyone was concerned with the mechanical features of the car malfunctioning, rather they worried that the voice and tactile systems for control would not work as expected or misinterpret a user's actions. For example, P3 questioned, "*what if I needed to take over? You know sometimes computers they just don't hear you. They'll be like, um no*." Similarly, P14 wants "*...the ability for you to take over and still have some type of tactile signals given to you and say 'this is not working. This is not going to work' and you can still achieve your, you know, independence*."

Further, some participants were concerned about the level of technical expertise needed to operate an autonomous vehicle. For example, P14 commented that "*of course there would have to be special training in order to use [an autonomous vehicle]*." Similarly, P1 said, "*You'd have to have some push button keyboard in order to make it work and then you would have to know how to operate the keyboard!*" Although we did not measure technical skill or expertise of participants, these existing measures have to be continually updated to align with current technologies [22]. These measures also primarily focus on graphical components of online and offline content (e.g. PDF, widget), which do not align well with measuring digital literacy or self-efficacy with people who may use these interfaces, but with assistive technologies.

Metaphors for Autonomous Vehicles

Assistive Technology and Orientation and Mobility

The design component of the focus groups confirmed common design approaches for voice-based and tactile systems in autonomous vehicles. Most interestingly, three participants described solutions that were directly inspired by existing assistive technologies and orientation and mobility (O&M) skills including refreshable Braille displays, probing canes, and screen readers. For example, P14 described a tactile solution in which, "*as you're driving with your hands at 10 and 2, you can use your thumbs ...[to] get some type of tactile feeling of what's going on there. So, it'll work kinda like a Refreshable Braille Display that can move up as vehicles are approaching on the left and right.*" Similarly, P2 described a tactile solution for navigating potholes by saying,

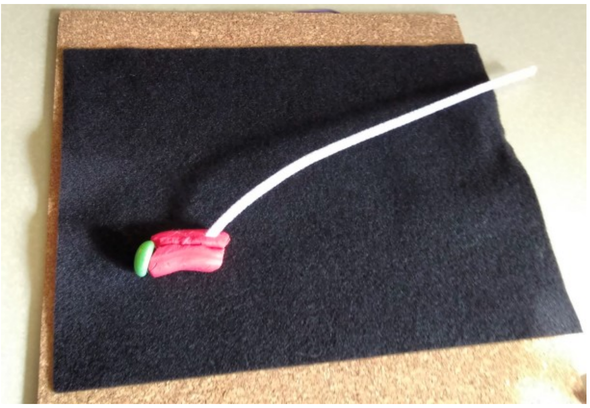

Figure 1- P2's pothole navigation device modeled off a white cane

> "*you push this button, then it would go around those potholes, make adjustments. So, the button will be on the dashboard and this little stem will be on the outside tapping as you go along, just like my stick*."

Just as a probing cane or white cane helps people with vision impairments locate and avoid obstacles in their walking environment, a cane-like device for an autonomous vehicle may help people control obstacle avoidance by allowing people to recognize and avoid obstacles in the driving environment.

Sound is also an important sense for people with vision impairments. In response to developing voice or audio-based solutions, participants described systems similar to screen readers and sonar. For example, P3 and P2 began a discussion about voice identification. P3 said,

> *"Everything in the car would have to talk. Whatever you push, it would need to tell you what you're pushing. It don't matter if it's the radio or cigarette lighter. It would have to tell you what you're pushing. If it don't tell you, you don't know what you're pushing.*"

In response, P2 commented that his solution was "*just like the screen reader*." Beyond voice, P14 considered audio response systems like, "*walking aids to go around with the visually impaired...You would hold [them] up as you walk and as objects came closer...once it became within range, it would beep as you got closer to it...It would beep and it would also let you know a certain direction, so if you held it up and someone walked across that beam, you knew that, at least something was moving there because it's no longer beeping*." Here, he describes a directional sonar-like system for obstacle detection based on a system for blind people.

Siri and GPS

Beyond assistive technology metaphors, participants also described preferring to interact like they do with other voice interfaces. The following describes how one group presented their voice solution:

P3/driver: "*...Put the key in the ignition. Turn it, now everything is starting to talk.*"

P2/vehicle: "*Ok. Where are we going?*"

P3/driver: "*Ok I'll punch in 1503 Drive Lane. That's a friend's address.*"

P2/vehicle: "*Ok Mr. [*P3*], we're going to that address you mentioned and we're on our way.*"

P3/driver: "*How is the traffic going to the house?*"

P2/vehicle: "*Ok P3, everything is clear. We're riding smooth.*"

P3/driver: "*Alright. Seatbelt is on. Everything is good. We're driving down the road.*"

P2/vehicle: "*Right. What's your destination? It's that address?*"

This script taken from participants in the first focus group shows how they envisioned being able to interact with an autonomous vehicle using a conversational tone and style, with "*the driver [being able to] tell the car where he's going*" (P6). Moreover, the vehicle would interact with the drivers/riders conversationally. Participants often compared this to how they speak to conversational agents like Siri. For example, P2 said, "*I can ask Siri on the iPhone where I'm at and what's my location and it tells you how to get there with the GPS.*" P2 describes how voice and being able to control

Figure 2 – P13's solution for determining the car's location relative to other vehicles

the flow of conversation could help with context awareness. Others described how voice may help with driver transitions like P3 who said, "*the car, when you had to take over, it would tell you, you know just like a GPS*." Similarly, P2 mentioned how the voice system could help with context awareness saying, "*just like we have GPS right? You're riding along and it'll tell you what street you on*." Participants overwhelmingly described GPS and Siri as 'model' voice interfaces. And, although we did not gather information on the types of voice interfaces participants use daily, their comments suggest they are familiar with and enjoy the interaction styles of these systems.

These quotes describe participants' expectations for everything in the vehicle to be accessible and controllable by voice, not as a feature like voice assistants are for sighted people, but to be usable. Participants also agreed that voice would be necessary in emergencies. For example, people in the first focus group discussed a scenario where the car's tire comes off and P2 says, "*the car is gonna say 'we're riding on rims.'*" Although participants laughed, they did continue by describing how the car would, at times, need to initiate control over the voice interface, notify the driver of the malfunction, and take steps to resolve the problem by calling a roadside assistance service.

Tactile Interactions

While tactile interactions were presumed to be a major interaction style since people with vision impairments may use Braille, a tactile writing system, it seemed that some participants preferred voice over touch. For example, P3 said,

> "*say you wanted to be headed east, but for some reason your car is not telling you you're not headed east, if you had …a compass that you can touch and it can tell you, 'We're going east. We're going south. We're going north.' If you could touch it, it can tell you which direction you're headed*."

Here, P3 describes how a tactile context awareness tool, a compass, could serve as a backup to if the voice system were to malfunction. When referring touch, most participants described vibration-based solutions. With clay, P7 built a vibration system in the tactile design activity that would help with obstacle awareness saying,

> "*the indicators are under your 10:00 and your 2:00 grip and under your left hand and right hands, you got a vehicle on the right, it would vibrate. You got a vehicle on the left, it would vibrate so vibration.*"

Similarly, P13 created a vibration system shown in Figure 2 where a "*middle bar right in the middle would beep or do something when something's in your way and then these [other bars] will vibrate or beep and then you will know where the actual object is.*" This concept of 'feeling the obstacles' was present throughout both focus groups with P2 wanting "*a button that you start feeling potholes*". Similarly, P4 described how "*when this car starts, you know, leaning, the rubber [band] will pull it back in place*." In this example, P4 explains how she would be able to feel when the car has corrected itself by touching a rubber band representation of the car on the road. These solutions use direct manipulation for participants to socially construct a representation of their surrounding environment with cars and other obstacles.

These findings describe how participants prioritize voice, vibration, and touch for context awareness.

DISCUSSION

Our findings highlight a critical discussion surrounding control and transportation for people with vision impairments. We show how this control is connected to existing experiences in non-autonomous vehicles, perceived independence, and the ability to operate a vehicle. Following, we discuss control in the context of Bandura's concept of control and what our findings mean for the design of autonomous vehicles to support people with vision impairments.

Control as a Spectrum

From our data, we see how participants described social norms and expectations of how people with vision impairments should use autonomous vehicles. Similar to prior work on the geography of disability and investigating transportation needs, participants agreed that autonomous transportation can support a variety of people in accessing new activities of daily life [13,35]. However, they agreed that desired control is a spectrum that is dependent on individual differences such as prior driving experience, comfort with autonomous transportation, and extent of vision loss. Participants also described how vehicle factors such as the vehicle malfunctioning and appropriate feedback during driver transition requests affect their desired control levels. Therefore, our findings describe a spectrum of desired control for using an autonomous vehicle independently, comparable to the spectrum of vehicle autonomy. An open challenge remains how to provide better mechanisms for non-visual control in autonomous vehicles during and after driver transition requests

Connecting Control and Independence

Our data sparks a deeper conversation about control in the context of transportation for people with vision impairments. Similar to prior work, participants mention control and safety [10,40], independence and safety [2] and independence and mobility [13] but also discuss control and independence. Participants described a perceived lack of control with their transportation needs, often needing to rely on other people to drive them places and not having access to critical information during a trip. This resulted in a complex tension between wanting some control, which a semi-autonomous vehicle provides, but not feeling comfortable operating a semi-autonomous vehicle independently. However, only providing access to fully autonomous vehicles could be detrimental to people with and without vision impairments. Researchers in psychology use perceived-control models to explain how loss of control may reduce "attentional capacity" [27]. As such, providing better control mechanisms in autonomous vehicles are not only preferred, but needed.

Designing for Control

Wanting better control of transportation and navigation systems is an existing concern for people with vision impairments where people often use multiple devices at once for increased control, accessibility, and coordination of information [2,24]. However, it is important to recognize this problem could continue to exist in autonomous vehicles unless tools are designed to address their needs.

Our findings directly connect to Bandura's definition of agency or control where intentionality, forethought, self-reactiveness, and self-reflectiveness are defined [4]. We discuss how each of these components could be considered in designing autonomous vehicles for people with vision impairments with varying levels of control.

Intentionality, making plans or strategies for an action, was discussed by participants who wanted fully autonomous vehicles to help them plan and inform them about their route, similar to interacting with voice-based systems like GPS devices and Siri. As such, tools for planning should **allow for conversational route planning**.

Forethought, or understanding likely outcomes, can be realized in the design of semi- and fully autonomous vehicles for people with vision impairments by giving them opportunities to recognize what a result of action in a vehicle is intended to do. Participants articulated how they wanted to understand the car's initial intention by voice where all buttons 'talk' and clearly identify the action. Therefore, designers can help users **understand outcomes through voice-based identification** of their in-vehicle environment.

Because driving happens in such a dynamic and fast-paced environment, we think about *self-reactiveness*, being able to change plans, and *self-reflectiveness*. We use self-reflectiveness not only as Bandura originally mentioned in terms of changing future plans based on reflection and past actions, but also as being able to reflect on their currently changing environment. We presented participants with the scenario of designing solutions to understand the world around them in the tactile design activity. Although they were informed that they could also incorporate voice or audio, no group incorporated sound in their artifact, suggesting that participants saw **tactile solutions as most appropriate for self-reactiveness towards and self-reflection of their surrounding environment**.

Researchers are now studying information flow between driver and vehicle to support reactiveness and reflectiveness. This includes the design of driving simulators [38] and how to maintain attention in safety-critical vehicle transition scenarios [33]. Similar research needs to understand how to allow drivers with vision impairments to "pull" information from the vehicle while receiving content that is presented to the driver. Interfaces including tactile and/or audio feedback have been used in studies with older adults operating vehicles [43] and people with vision impairments using mobile devices for public transportation or walking navigation [3,57]. Our findings extend this prior work by showing how voice and touch can be used together as control mechanisms to help facilitate independence and autonomy in different autonomous vehicles.

Metaphor-Based Autonomous Vehicle Design

Moreover, our findings can help inform the design of systems to support people with vision impairments in autonomous vehicles if researchers focus on metaphor-based design. As in prior research, technologies designed based on scrapbook, voicemail, and picture frame metaphors, can be effective tools providing easy engagement for older adults and older adults with vision impairments [11,12,17,42]. Our participants often used assistive technology metaphors such as screen readers and refreshable Braille displays to explain their design artifacts, suggesting these metaphors may be beneficial in easing learnability, and could decrease anxiety of operating an autonomous vehicle. However, as 'vision impairment' describes a wide range of individuals with vision loss, there may be differences in the types of technologies people with vision impairments are familiar with depending on their assistive technology use, level of vision impairment, and age at which they lost their vision. Therefore, a **toolkit of metaphor-based tools** may need to be designed to best support people with vision impairments in autonomous vehicles.

Limitations

There are a few important limitations to discuss when considering the generalizability of our findings. First, the average age of our sample was older. Younger adults with vision impairments may have differing views on the use and design of autonomous vehicles. Also, vision impairment includes a range of visual abilities. Our sample was diverse but this meant low vision and blind participants, who may have had different prior experiences with driving, were designing together. We do not intend to conclude that our findings are generalizable to the broader population of people with vision impairments, but this diversity of abilities was helpful in understanding diversity of experiences.

CONCLUSION

In this paper we contribute a discussion of control and independence in the context of accessible autonomous transportation for people with vision impairments. We go beyond prior work on the design of autonomous vehicles for people with vision impairments by discussing trade-offs between semi- and fully autonomous systems, and how assistive technology metaphors can be used for better vehicle design. Our findings may help 1) designers of navigation systems and autonomous vehicles for people with vision impairments and 2) researchers studying nuances between control and independence at the intersection of disability studies and HCI.

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