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Vibrotactile guidance for trips with autonomous vehicles for persons with blindness, deafblindness, and deafness

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ABSTRACT

Autonomous vehicles are becoming a reality with great potential. However, persons with blindness, deafblindness, and deafness, who usually receive information and guidance from the driver, could miss information when travelling in an autonomous car. In this case study, 15 people with hearing and vision impairments explore and compare trips with and without vibrotactile guidance (using Ready-Ride or Ready-Move) in a simulated autonomous vehicle in real traffic (using a Wizard-of-Oz method). The study investigated if vibrotactile aid could enable persons with blindness, deafblindness, and deafness to use autonomous vehicles. Different phases of a trip (before, during, and after) were analysed. The study shows that people with functional impairments such as blindness, deafblindness, and deafness can perform trips independently if given information adapted to their needs through auditory, tactile, or visual information channels. It would be difficult for the target groups to travel without any additional communication aid, such as a vibrotactile guidance aid for all phases of the trip, especially for those with blindness. In all rides with the simulated autonomous car (Wizard-of-Oz set up) without vibrotactile guidance, the driver or assistant (in at least one phase of the trip) had to intervene for the research participants with blindness to complete the trip and continue the study. The study also highlights the usability of the vibrotactile guidance aid and identifies areas in need of improvement.

1. Introduction

About 30 million blind and partially sighted persons live in Europe (EBU, 2020) and is expected to increase along with the increase in age-related diseases (Pascolini and Mariotti, 2012; Saunders and Echt, 2007; World Health Organization, 2019). Irrespective of age, people with functional impairments make fewer trips on average than people without disabilities (Allu et al., 2017) as they cannot find adequate transportation options for their needs (Brouwer et al., 2008; Crudden and McDonnall, 2015; McKercher and Darcy, 2018). Mobility is a significant concern for blind people (Brinkley et al., 2018; Holmgren et al., 2016) and access to transportation affects their quality of life and the possibility of employment. Equality in society is highlighted in Agenda 2030 and the UN Global Compact goal suggesting that increasing access to mobility is a way of increasing equality (United Nations General Assembly, 2019).

Autonomous (so-called self-driving) vehicles (SAE International, 2018) are predicted to be a game-changer (Hancock et al., 2019) with the potential to radically change the possibility for independent travels for persons with functional impairments such as blindness, deafblindness, and deafness (Claypool et al., 2017; IBM Accessibility Research, 2017). Vehicles that can drive themselves with the help of sensors do not require a human driver; a technological advancement that could lead to "robo-taxis". Early in the debate on autonomous vehicles, persons with functional impairment were identified as a potential target group (Brinkley et al., 2018; Wiggers, 2020). Launched initiatives include mobility providers such as Uber (2019), the vehicle concept Accessible Olli (Mingjing, 2018), new software (Brinkley et al., 2019), add-on assistance technology (Insight, 2017), and additional tactile 4D displays (Brinkley et al., 2018; EVA project, 2017).

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However, despite these initiatives, there are growing concerns that people with functional impairment are not considered in autonomous vehicles design (Brinkley et al., 2018; Hersh, 2018; IBM Accessibility Research, 2017; McKercher and Darcy, 2018). Potential issues include locating and boarding the vehicle and using seat belts, activities that typically require human support; (Brinkley et al., 2018; Crudden and McDonnall, 2015). These challenges are also relevant when using and changing public transport modes (Low et al., 2020). An incomplete view of these challenges may partly be attributed to a knowledge gap in empirically-tested autonomous self-driving technology. Few studies have situated the vehicle in this target group with a focus on the travel steps: before (locating and entering the vehicle) – during (in the vehicle) – after (leaving the vehicle and reaching the final destination), see (Crosier and Handford, 2012).

Since the beginning of the 1990s, a research team at Örebro University, the Audiological Research Centre in Örebro (former Ahlsén's Research Institute), and the University Hospital in Örebro has been conducting research on vibrotactile aids for people with functional impairments (Ranjbar, 2009; Ranjbar et al., 2014; 2016; 2017; Stranneby et al., 2011; 2012). An approach that has been found to be successful, especially for those with blindness, deafness and deafblindness (Ranjbar, 2009; Ranjbar et al., 2009, 2014, 2016, 2017). The purpose of the projects has been to improve environmental perception, time perception, mobility, and independence and thereby increase the target groups' quality of life. The research team has developed two vibrotactile communication aids (Ready-Ride and Ready-Move) that enable communication from a distance and use skin sensitivity as an information channel – i.e., using vibrations transferred through the skin to convey information (Ranjbar et al., 2016; Ranjbar, 2019; Stranneby et al., 2012). Vibrotactile guidance could improve the experience and overcome some challenges with autonomous vehicles discussed above.

1.1. Purpose, goal, and research questions

This study investigates whether vibrotactile guidance technology (Ready-Ride/Ready-Move) can improve independent travel for people with blindness, deafblindness, and deafness. The goal is to identify the challenges and the potential of the technology in each phase of a trip (Table 1). The research questions are as follow:

What possibilities and limitations are experienced by the target groups during the three phases of a trip (before, during, and after) when travelling by autonomous vehicles?

How can vibrotactile guidance enable the target groups to travel independently using autonomous vehicles?

Table 1
The three phases of the trip, adopted from (Crosier and Handford, 2012).

Before	During	After
From the time the person reserves the transport (vehicle) until the person identifies the correct vehicle. • Reserving vehicle Detecting vehicle Locating vehicle Navigating to the vehicle Identifying the correct vehicle	From when the passenger opens the door of the vehicle until the passenger leaves the vehicle. • Opening/closing door Locating other people in vehicle Identifying correct seat Confirming correct route Identifying disturbances and delays on the way Determining arrival at destination	From when the passenger leaves the vehicle until the passenger reaches the final destination. • Confirming arrival and correct destination Navigating from vehicle to final destination

2. Method

2.1. Study design

This qualitative exploratory case study was performed in the field with RPs travelling in an (simulated) autonomous vehicle, with and without vibrotactile guidance. This study has been approved by the Swedish Ethical Review Authority (Reg. No. 2019-01380). A simulated autonomous vehicle was created using a WOz set-up: a standard vehicle was said to be an autonomous vehicle with the driver "acting out" the automated functionality with no or limited interaction with the passenger (Habibovic et al., 2016; Klingegård et al., 2020; Mok et al., 2015).

2.2. Research participants study design

A total of 15 RPs – five with blindness (B1-B5), five with deafblindness (DB1-DB5), and five with deafness (D1-D5) – participated in the study. All five RPs with deafblindness had some degree of residual vision (see Table 2) or tunnel vision (Ranjbar and Stenström, 2013). The RPs were recruited using a snowball approach (Hersh, 2018) that originated from the test leader's professional contact network, social networks, and friends of the RPs. The RPs with blindness used speech, braille, e-mail, and SMS to communicate. All RPs with deafness and deafblindness used visual sign language, e-mail, SMS, and writing except DB1 who used tactile sign language and D3 and D5 who used also speech to communicate. Documentation on the RP's vision and hearing was obtained from medical records. The communication with all five RPs with deafblindness and two with deafness (D2 and D4) occurred via a sign language interpreter. D1, D3, and D5 activated their cochlear implants during the interviews. The DB1 and DB3 had previous experience with vibrotactile aids (Ranjbar et al., 2014; Ranjbar et al., 2017). DB1, whom an assistant usually accompanies, was accompanied by the interpreter. The RPs received 500 SEK for their participation in the study.

2.3. Equipment

A simulated autonomous vehicle was created using a WOz set-up (Dahlbäck et al., 1993); a standard vehicle was said to be an autonomous vehicle with the driver "acting out" the automated functionality with no or limited interaction with the passenger (Habibovic et al., 2016; Klingegård et al., 2020; Mok et al., 2015). For consistency and validity, the same driver and the same car were used for all RPs except one time (due to a technical malfunction/change of test leader). For ethical and safety reasons, the RPs were told that, a human "wizard" was acting out the automation at the start of the test. If the RPs could not proceed with the test (e.g., because they could not find the car), the driver or test leader guided the RP to the vehicle.

The study used two versions of vibrotactile aids: Ready-Ride and the more advanced Ready-Move (Fig. 1). Both provide the same functionality: transmitting information in a simple short or long pulse or a combination of short and long pulses where the assistant and the user agree on what the pulses represent. The difference between the two generations is the way of communicating (cable vs Bluetooth), the maximum number of vibrators (4 vs 7), the encapsulation of the vibrator sensors (giving Ready Ride a stronger sensation due to closeness to the skin), and the possibility to automate sequences of vibrations in the app (as opposed to pressing buttons manually).

An interview guide and questionnaire adopted from the study by Ranjbar and Stenström (2013) were used. The interview questions were organised to capture challenges and opportunities experienced by the RPs during the different phases of the trip (before, during, and after). The questionnaire evaluated the usability of the vibrotactile guidance aid. It consisted of a set of questions with alternative answers on a Likert scale (Allen and Seaman, 2007) where the RPs were asked to grade their experience ranging on a four graded scale (Not at all, A little, Pretty

Table 2
The detailed description of the RPs.

RPs ID	Age	Gender	Diagnose	Age of notification	Personal assistance (h/mon)	Near vision with corrected reading Jaeger test right/left (Runge, 2000)	Night-blindness	Visual acuity-right/left	Visual Field-right /left Goldmann V/4 object (Yanagisawa et al., 2017)	Pure Tone average (PTA) (dB HL) right/left
B1	43	M	B	Birth	0	Not applicable	No	No light perception		<20/<20
B2	42	M	B	Birth	0	Not applicable	No	No light perception		<20/<20
B3	33	M	B	Birth	20	Not applicable	No	No light perception		<20/<20
B4	69	M	B	Birth	0	Not applicable	No	No light perception		<20/<20
B5	63	F	B	24	40	Not applicable	No	No light perception		<20/<20
DB1	59	F	Usher 1	Birth	325	5p/5p	yes	0.4/0.6	<5 / <5	>110/>110
DB2	27	F	Usher 1	Birth	0	5p/5p	yes	12/12	12/12	>120/>120
DB3	21	F	Usher 1	Deaf (Birth). Deafblind (15)	0	10p/5p on 20 cm	yes	0.25/0.3	18/18	>110/CI-30
DB4	40	F	Usher 1	Birth	0	5p/5p	yes	0.4/0.5	18/18	>110/>110
DB5	38	F	Usher 1	Deaf (Birth) deafblind (30)	0	5p/5p	yes	0.6/0.7	15/15	>110/>110 CI-40/CI-40
D1	50	F	D	11	Normal vision					>110/>110 CI-25/CI-25
D2	42	F	D	Birth	Normal vision					>130/>130
D3	47	M	D	Birth	Normal vision					>100/>100 CI-25/CI-25
D4	44	F	D	Birth	5p	0.5/0 left = blind	Normal vision at the right eye			>110/>110
D5	45	M	D	Birth	5p	1.0/0.13	Normal vision			>100/>100 CI-25/CI-25

Fig. 1. Two vibrotactile aids were used in the study. A) Ready-Ride, B) Ready-Move.

much, Highly). The questionnaire was spoken and, when necessary, interpreted in sign language. The interviews were made in Swedish.

2.4. Stimuli

In consultation with the test leaders and RPs, a suitable scenario (e.g., a taxi ride from the home to the health centre and back) was developed based on the RP's current travel patterns (Interview A). A familiar route was chosen to ground the findings within the daily context and experience of the RPs and to increase validity and decrease confounding factors due to (un)familiarity with the location. The trip scenario included a start position, an end destination, and a suggested route. In one direction (start → end), the RPs travelled without guidance; in the other direction (end → start), the RPs travelled with guidance using one of the vibrotactile aids shown in Fig. 1. The distance and driving duration of the route chosen by the RPs varied between 1.5 km and 12 km (6.1 ± 3.5) and between five minutes and 22 min (9.3 ± 4.5), respectively.

The scenario included a trip to a friend's house (B3, DB2, D1, and D5), a recreational trip such as going to the library, summer house, sports place, café, university, work (B2, B4, B5, DB1, DB3, DB4, DB5, D2 and D4), or a healthcare trip (to the hospital; B1). D3 started from the hospital and ended at a shopping centre. All tests were performed during summer in daylight with a clear sky. The routes included city traffic.

2.5. Vibrotactile codes

Five commands (Arrived/Start, Turn left, Turn right, Interrupt/queue, and Stop) were coded as short (and long) vibrotactile coded pulses and used during the travel from the end destination and back to the start position (Table 3). The vibrations were used to represent both human and vehicle movement.

Ready-Move was placed on each arm wrist (Table 3). The DB1 and D3, who used Ready-Ride, put two of the four vibrators on each hand. They attached the third and fourth vibrators to their bra strap in front and back of their body, respectively. The vibrators on the right and left hand gave the information "Turn right" and "Turn left", respectively. The vibrator in front gave the information "Arrived/Start", and the vibrator in the back gave the information "Stop" by vibrating for 200 msec three times. For the information Interrupt/queue, the vibrator in the back vibrated once.

Table 3
The information is coded as short (rl = 200 msec) and long (RL = 1000 msec) vibratory pulses in Ready-Move. R/r = right vibrator vibrates. L/l = left vibrator vibrates.

Arrived/Start	RL	Both right and left vibrator vibrates in 1000 msec
Turn left	L	Left vibrator vibrates in 1000 msec
Turn right	R	Right vibrator vibrates in 1000 msec
Interrupt/queue	rl	Both right and left vibrator vibrates in 200 msec
Stop	rl rl rl	Both right and left vibrator vibrates in 200 msec three times

2.6. Procedure

Prior to the test, written information about the test was given by email or phone (SMS/messenger). A sign language interpreter was present for those with hearing impairments.

The following stages (1–5) were performed (Fig. 2) on the same day for all RPs between May and August 2019.

1) **Interview A**. An initial interview with the RPs (a physical meeting at a location chosen by the RPs or via email/phone) created the stimuli (trip) scenario (see stage 2). The test leader explained the concept of autonomous vehicles. The interview was documented with one or more of the following: text, video, and audio. Each interview lasted about 20 min.
2) **First trip in the simulated autonomous vehicle:** The first trip within the created stimulus scenario was made by driving from the identified starting point to the end destination. They performed the scenario as they usually do but now with the simulated autonomous vehicle. During the trip, the RPs were asked to think aloud and express their feelings and thoughts. They could ask for help, which was recorded. At least one test leader was nearby the RPs to ensure their safety approaching and travelling in the vehicle when performing the trip. One test leader was driving and observing, and one was documenting (video recording).
3) **Interview B.** When arriving, a structured interview (Tables 4 and 5) to discuss the first trip and the occasions when the RP needed help from the driver was performed. Next, the test leader introduced the vibrotactile aids to the RP (Section 2.4). RPs chose the vibrotactile aid that best fit their preferences (number of sensors and ability to sense vibrations). The test leader and RPs also agreed on where on their body (arm, waist, hip, etc.) the vibrators were to be placed. The test leader and RPs practised with the vibrations until the RPs memorised the codes and could easily interpret them (which took, on average, about ten minutes). In total, this stage took about one hour.
4) **Second trip in the simulated autonomous vehicle- with guidance:** The trip was repeated according to the created stimuli scenario in stage 2 but with the selected vibrotactile guidance aid. The starting point for the trip was inside a building where the RPs were waiting for information from the test leader about when their vehicle had arrived. The RPs were told to vocalise or sign what command (see Table 3) they felt during the trip. RPs had the same support from test leaders and interpreters as during the first trip.
5) **Interview C**. After the trip, a structured interview regarding their experiences using the vibrotactile guidance was performed. The RPs also completed the questionnaire. The questionnaire was read out loud, and the test leader recorded the answers. The session was also audio recorded. The interview took about 30 min.

2.7. Analysing method

The results are summarised and described with no predefined hypothesis investigating the nature and elements contributing to the experience of using autonomous vehicles. The results of the interviews were transcribed and analysed using thematic analysis to create a narrative of experiences (Hayes, 1985). Observations and analyses of videos were compiled, and comments from the RPs and test leaders were noted. Descriptive statistics are presented as the sample size is too small for statistical analysis.

3. Results and analysis

The following sections present the main results of the interviews and observations.

3.1. Introducing vibrotactile guidance and automated vehicles

The possibilities and limitations of vibrotactile guidance are identified by organising the collected data into the three travel phases (Interviews B and C and observations).

3.1.1. Experiences before the trip

Autonomous vehicle without vibrotactile guidance (Table 4). To determine if the vehicle had arrived, and to locate, navigate, and identify the correct vehicle, the RPs with deafness and deafblindness (with sufficient eyesight) used their vision. Those who waited for the vehicle indoors (DB1, DB2, DB3, DB5, D1, D2, and D4) looked outside and checked if it had arrived. B1, who was waiting for the vehicle on the street, could hear the engine's sound but could not find the vehicle since it had stopped on the opposite side of the street and needed guidance from the test leader to find the vehicle. B2, B3, B4, B5, and DB1 could neither detect, locate, nor identify the autonomous vehicle without help from the test leader.

Autonomous vehicle with vibrotactile guidance (Table 4). All 15 RPs, especially those with blindness, were successfully guided by the vibratory tactile commands during the different travel stages: detecting, locating, navigating, and identifying the vehicle. All vibratory coded information in Table 3, except the code Interrupt/queue, was used in this stage. They were indoors when the vehicle arrived, and therefore, they could not hear or see it arrive, but those with good enough vision could use their vision to locate and identify the car and navigate to it. The RPs with blindness were dependent on vibratory information in all stages, from detecting that the vehicle had arrived to locating the vehicle.

3.1.2. Experiences during the trip

Autonomous vehicle without vibrotactile guidance (Table 5). All RPs with deafblindness and deafness who could see used their vision to identify the correct seat and locate other people in the vehicle. RPs with blindness detected where other passengers were seated by listening, feeling the seats with their hand before sitting, or asking politely if anyone was sitting in a particular seat. If they could not determine where to sit using these strategies, the test leader guided them where to sit. Most RPs needed information from the test leader to confirm that the vehicle was going to their destination. Some RPs used GPS apps adopted for the functionally impaired. The RPs who could see followed the road by looking out the car window or at the GPS display in the car.

Autonomous vehicle with vibrotactile guidance (Table 5). All RPs used the same strategies as mentioned above (i.e., without

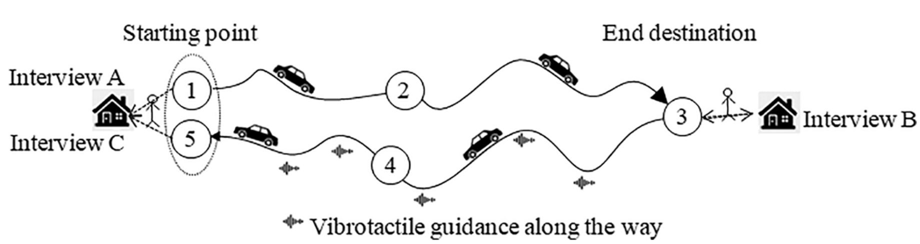

Fig. 2. Illustration of test procedure stages in the simulated automated vehicle: (1) Interview A; (2) Simulated autonomous vehicle trip *without* vibrotactile guidance; (3) Interview B; (4) Simulated autonomous vehicle trip *with* the chosen vibrotactile guidance aid; and (5) Interview C.

Table 4
Results from the first four questions in Interview B and Interview C regarding the journey phase "before the trip" highlighting the role of the vibrotactile aid.

Blindness (B)		Deafblindness(DB)		Deafness (D)	
Without vibrotactile aid	With vibrotactile aid	Without vibrotactile aid	With vibrotactile aid	Without vibrotactile aid	With vibrotactile aid
1) **How did you detect that the vehicle had arrived?**					
B1, B3: I heard the sound of the engine. **B2, B4, B5**: The test leader told me.	**B1-B5**: Via the vibratory signals	**DB1**: My assistant told me. **DB2-DB5:** The test leader told me.	**DB1-DB5**: I got information via vibrations.	**D1, D2, D5**: I saw the car. **D3, D4**: The test leader mentioned.	**D1-D5**: Via vibrations.
The use of vibrotactile aid: **B1:** 'I didn't hear the vehicle arrive, since we were inside the building. Due to the vibration, I came to know that the vehicle had arrived'. **DB4, DB5:** 'I found out because the vibrators vibrated. I was not sure since I am not used to the tactile aid and did not know if I understood and interpreted the vibratory codes correctly'. **D4:** 'I felt the vibration that the vehicle had arrived. It was easy to recognize'.					
2) **How did you find the way to the vehicle?**					
B1-B5: The test leader helped.	**B1-B5**: Via vibrations.	**DB1-DB5:** I could see and use different strategies. **DB1:** I asked the assistant, followed the test leader, and watched around.	**DB1-DB5:** I got help via vibrations.	**D1-D5:** I used my vision.	**D1-D5:** I could see and get help even via vibrations.
The use of vibrotactile aid: **B4:** 'It was not difficult when following the information from the vibrators. The problem was that there was an obstacle and I had to go around that, the information wasn't exact at that moment. The information could have been maybe two times the "Left" command'. **DB5:** 'I found the vehicle via the vibratory information. I have difficulty trusting the aid 100%. Imagine if anything comes unexpected in the way'. **D4:** 'I had to memorize different vibrations [different signals]. It vibrates right or left so I come to the vehicle. Nothing was difficult'.					
3) **How do you locate the vehicle at the pickup point?**					
B1-B5: I was guided by the test leader.	**B1-B5:** I used the vibratory information.	**DB1-DB5:** I could see but still got some help from the test leader or assistant in DB1s case.	**DB1-DB5:** I was guided by the test leader using tactile aid.	**D1-D5:** I could see.	**D1-D5:** I could see but also got vibratory information.
The use of vibrotactile aid: **B3:** 'Partly through the vibrators, also using the echo localization'. **DB1:** 'I was guided via vibrations. It was a strange feeling. You have to use and get used stepwise'. **D5:** 'I used my vision, but I was surprised that it worked. I got vibrations that guided me to the vehicle using the vibrations right and left. I didn't see the vehicle first because it was standing further behind and behind the bush'.					
4) **How do you know it's the right vehicle?**					
B1-B5: I had to ask the test leader	**B1-B5:** I got help from the test leader via vibrations	**DB1-DB5:** I could see the car but had to ask the test leader to be sure.	**DB1-DB5:** I got vibratory information.	**D1-D3:** I could see the car.	**D1-D3:** I got visual information but also got vibratory information
The use of vibrotactile aid: **B4:** 'I don't know. I have to trust the vibrations, if they misguide me, I will go to the wrong vehicle. Auditory information about how far from the car is there would be very helpful. They should also say where I am positioned, which side of the car, front of the car/back of the car or like that'. **DB5:** 'I found it by getting information from the vibrations. I just chanced by opening the door and sitting in the car. If it was the wrong car, the driver would throw me out'. **D3:** 'I recognized the car. It was necessary that I needed a new signal that this is the right car. Especially if there are several cars, I wouldn't know which is mine'.					

vibrotactile guidance); however, they also used vibrotactile information, which was provided to add information about the movement of the autonomous vehicle. Every time the car flashed right or left at turns, if there were disturbances such as traffic jams or red traffic lights, or the car arrived at the final destination or other stops, they received the information in coded vibrations (see Table 3). All vibratory codes in Table 3 were used in this stage. When the vehicle arrived at the destination, the RPs opened the door after receiving the vibrotactile signal for arrival. Also, RPs who could see seemed to benefit from the vibratory codes. These RPs thought that the vibrations helped relax and physically prepare for the car's movement (e.g., when the vehicle would turn or brake).

3.1.3. Experiences after the trip

Autonomous vehicle without vibrotactile guidance (Table 6). The RPs with blindness (B1, B3, B4, and B5) and DB1 had difficulty finding the final destination after leaving the autonomous vehicle. Because they could not see and had no clues, they needed help from either the test leader or the translator. B2 could easily find his final destination, which was his work, as the area was adapted with different beep sounds (installed in the infrastructure) as guidance. The four other persons with deafblindness and all five with deafness could see and could successfully find the final destination since it was known to them, although the RPs with deafblindness were more dependent on the current light conditions.

Autonomous vehicle with vibrotactile guidance. To determine their final destination, the RPs with blindness used clues (e.g., a clicking noise at the entrance), but the vibrotactile aid also confirmed this. B1 could feel the grass that indicated being near home, but the vibrations had confirmed the route or the correct path. DB1, who had a tunnel vision with a visual field smaller than five degrees, did not dare go by herself to find the final destination despite being familiar with the area and it being a sunny day. All vibratory coded information in Table 3 except "Interrupt/queue" and "arrived" was used in this stage to guide them, for example, to go to the left or right or stop until they could find a familiar point at the end destination.

3.2. Evaluation of the usefulness of vibrotactile guidance

The RPs were asked to choose one of two vibrotactile guidance tools. Most chose the Ready-Move because it seemed easier to use as it was only two vibrators placed on your wrist. Two (DB1 and D4) chose the vibrotactile aid Ready-Ride because it could deliver stronger vibrations than Ready-Move. All 15 RPs learned the five vibratory codes in about ten minutes. The self-reported experience of the vibrotactile guidance tool is reported in Table 7. As can be seen in Table 7, about 47% of the RPs needed help (Pretty big, Very large) from the vibrotactile guidance to perform the activity, and about 53% of the RPs did not feel the need for help or much help (Not at all or Little help). A majority of the RPs (73%) had some help (rated "Pretty much" or "Highly") from the aid to

Table 5
Results from the questions five to eight in Interview B and Interview C regarding the phase "during the trip" in the tests. The answers are shown in groups for each target group. Some quotations from the individuals (when guided by vibrotactile aid) are also provided.

Blindness (B)		Deafblindness(DB)		Deafness (D)	
Without vibrotactile aid	With vibrotactile aid	Without vibrotactile aid	With vibrotactile aid	Without vibrotactile aid	With vibrotactile aid
5) **How do you know if there are other people in the vehicle and where they are?**					
B1-B5: Tentatively feel and sit. Can hear if the passengers are talking. The driver informs otherwise don't know.	**B1-B5:** I wouldn't know if no one said anything.	**DB1:** I can see and was informed by the translator. **DB4:** I can see if it is light **DB2, DB3, DB5:** I could see.	**DB1:** I can see and also smell. **DB1-DB5:** I can see when it is light and feel with my hands if it is dark.	**D1-D5:** I used the vision.	**D1-D5:** I used the vision.
The use of vibrotactile aid: **B3:** 'That wasn't something I thought about. I just assumed it was the right door; vibrations told me to go left and stopped when I reached the door handle. Gave the hint that I should take that seat/door'. **DB2:** 'It was difficult to see since the window was not transparent. It was difficult to know via the signals if I had to sit in the front or back of the car. It is easier for left and right signals'. **D5:** 'For that matter, I used my own vision to see the number of people in the vehicle. But I relied on the signals that made me reach the right door that place would be for me'.					
6) **How do you know that the vehicle is on its way to the right destination and which route it intends to take?**					
B1-B5: I trust the driver. **B2-B5:** I used GPS apps.	**B1, B3:** I trusted the driver. **B2:** It was a familiar route for me and I have memorised the stops, and turns. **D4:** Only through the vibrations. **D5:** This I don't know. Maybe I have to use my GPS to be sure.	**DB1:** The interpreter informed me. **DB2, DB4:** I can see and recognise the location. **DB3, DB5:** I trusted [the vehicle].	**DB1:** I saw a little bit and the interpreter informed me. **DB2:** I trusted the driver and saw the light and the bus station. I used the map to quickly check the location. **DB3, DB4:** I knew the way. **DB5:** I trusted the driver.	**D1:** I can see and know the multiple routes to get to the destination. **D2, D3:** I don't know. **D4:** Looking all the time during the journey. **D5:** I looked out the windows and looked at the car's GPS.	**D1:** I knew the way and hoped that it was correct. I trusted the driver. **D2:** I recognised the car, could see the road and also got the signals. **D3:** I did not know. **D4:** We were driving the same way. **D5:** using my vision and trying to locate the places through the windows.
The use of vibrotactile aid: **B4:** 'Only through the vibrations. If there was a GPS telling the name of the streets, it would have been better'. **DB5:** 'I simply trust the vehicle; otherwise, I look at the map to see where I am and if it seems right […] I would have been uncertain whether it had to be blindly trusted by the car'. **D2:** 'If you commute a lot on the same roads, then you usually recognise the turns so you assume you went right. But the vibrations announced the turns right, left, slow down, stop. The experience was very relaxed because otherwise I had used my vision and tried to locate the places through the windows'.					
7) **How do you get information about disturbances/delays along the way?**					
B1, B2, B3: I ask the test leader. **B4:** I hear from the radio. **B5:** I don't know.	**B1:** I don't care. **B2, B5:** There was no one. **B3, B4:** Through the vibrations.	**DB1:** I asked the translator. **DB2-DB5:** I used the vision/had no information.	**DB1:** The assistant informed me. **DB2:** Through the vibratory signals. **DB3-DB5:** I see.	**D1:** I knew and wasn't worried. **D2-D5:** I see. I see but don't understand what has happened.	**D1-D5:** I could see and also got information via vibrations.
The use of vibrotactile aid: **B4:** 'I didn't get any information. I just noticed that sometimes it was driving slowly and sometimes fast. Vibratory said to me when it stopped. It was good that I got the information a little bit before, it was similar to seeing and being prepared. If the window was open, I could have heard the cars around us stopping and moving and all'. **DB5:** 'I got information via vibrators which had the same vibratory patterns for different disturbances. I do not know if I have benefited from such info. I'd rather have different vibrations for different disturbances, e.g., a ribbon for red light. A vibe for queues. A vibration for obstacles, etc.'. **D2:** 'I don't know. When stopped at a red light or traffic signal, I got vibrations as Morse code "s". Both vibrators vibrated the "s"'.					
8) **How do you know that the destination has been reached?**					
B1-B5: The test leader informed me.	**B1, B3-B5:** Via vibrations. **B2:** I recognised the speed and obstacle close to the parking.	**DB1-DB5:** I could see.	**DB1-DB5:** I could see and via vibratory signals.	**D1-D5**: I could see.	**D1-D5:** I could see and via vibrations.
The use of vibrotactile aid: **B4:** 'Through the vibration (long) signal, vibration gives a signal to go ahead, move out of the vehicle'. **DB1**: 'There were vibrations informing me that the destination was reached (two long vibrations on left and right side)'. **D4:** 'For that matter, I used my own vision to see the number of people in the vehicle. But I relied on the signs [from the tactile aid] that made me reach the right door that place would be for me'. **D3:** 'I got the vibration that we had arrived'.					

perceive the correct command during the journey. The RPs considered the vibrotactile aid to be "Highly" easy to understand (80%) and easy to use (80%). All the RPs felt the vibrotactile aid was "Pretty" or "Highly" reliable. All three groups thought that they "Perhaps", "Probably", or "Surely" would use the aid in other activities.

As the last question, the RPs were asked if they had any suggestions on how the communication aids could be improved. They suggested more detailed information about events both inside and outside the car. Vibratory coded signals could also be explored using clear patterns with different strengths depending on the importance of the event (DB5). They also wanted the device to be the size of a watch to make it easy to place inside clothing together with bracelets and a watch. Preferably also integrated with already existing devices, e.g., mobile phone and/or smart watch (DB5). The RPs were provided with five vibrotactile commands. However, they were interested in additional information. For example, the RPs wanted information about passengers in different seats to make it easier to find an empty seat. In addition, one RP (B4) asked for information about the route passing various landmarks, the destination, and good and adapted lighting (especially for persons with deafblindness, who often suffer from night blindness). They also wanted vibratory codes with different intensities to indicate potential dangers, accidents, and malfunctions. In addition, one RP also asked for more information

Table 6
Results from Interview B and Interview C regarding the phase "after the trip". The results are presented in more detail in groups for each research group. Some quotations from the individuals are provided.

Blindness (B)		Deafblindness(DB)		Deafness (D)	
Without vibrotactile aid	With vibrotactile aid	Without vibrotactile aid	Without vibrotactile aid	With vibrotactile aid	Without vibrotactile aid
9) **How do you find your way from the vehicle to your final destination?**					
B1, B2: By hearing the clicking sound at the entrance. **B3:** The test leader guided me. **B4, B5:** The test leader guided me to a familiar point from where they could find the destination.	**B1:** I felt at home and felt the stretch of grass that felt home, vibrations confirmed the route or the correct path for me. **B2-B5:** I was guided by vibrations.	**DB1:** I was guided by the translator. **DB2-DB5:** I followed the test leader.	**DB1-DB5:** I could see and the destination was known and could find it by myself. The destination was also confirmed by the vibrations.	**D1-D5:** I could see and follow the test leader.	**D1-D5:** I could see and also used vibratory information.
The use of vibrotactile aid: **B1:** 'I actually felt at home and felt the stretch of grass that felt home, vibrations confirmed the route or the correct path for me'. **DB1:** 'I can see and got help from the vibrations. I just followed the vibrations'. **D4:** 'I knew the area, but still I was guided using the vibrotactile commands'.					

about the ongoing events: 'It would be great to get information about things happening inside and outside the vehicle. I would also like to know about traffic jams, if the vehicle is stopped at these signals, and if the driver is bringing more passengers' (DB2). Some RPs also suggested the ability to control the vehicle (DB4).

3.3. Using autonomous vehicles in daily life

The following section characterises the issues experienced in current travel patterns of the RPs, providing insights into the needs and challenges of travelling by autonomous vehicles (Interview A, C).

The travels of persons with blindness and deafblindness are limited to familiar places and activities (e.g., social activities with friends, parents, and other organised activities and visits to markets and holiday cottages), sports activities (e.g., gym, riding, hiking, and swimming), and work. In general, the perceived travel needs were found to be similar across the groups.

The importance of the familiarity with the destination and transport mode is also highlighted (D4, DB5, D2). DB5 explains the care that needs to be taken: 'I ask for help. If it's unfamiliar, […] I go slowly and check and hope there are no obstacles on the way. […] I wouldn't want to walk and miss the entrance of my vehicle and then come back the whole way'. To enable travel, all the RPs had developed strategies, often including time and space considerations such as looking for distinct cues, using a landmark, and deciding on a particular time of day. However, some RPs also take chances or simply miss their ride: '[…] they are driving close to me very slowly, and I just assume that it's mine. Sometimes they stop at the wrong place, and I don't know where they are. I have missed many taxis like this' (B4). Safety issues were also noted: 'You never know with whom or where you are going. It's a bit of an unsafe feeling. Sometimes there are other people in the taxi, and they seem a bit weird/awkward. You never know where they are taking you' (B5). D2 shared experiences of great uncertainty and mistakes: 'I saw that the driver took a different route, but I trusted her. […] The driver took the long route to the countryside. I thought we had another passenger to pick up. But later realised that he thought I was some other passenger. I was sad, scared and even cried'.

All three groups, especially persons with blindness and deafblindness, needed and desired to travel more. However, they are anxious about travelling as they are afraid to get lost, especially when having to change transport mode (e.g., from a train to a bus): 'I want to visit friends in different cities, go to healthcare facilities, specific boutique, fetch packages, go and look for places for music' (B3). DB3 expressed the need for company and a longing for individual freedom when travelling: 'I do not travel by myself. I have to learn. I always go with my mother and therefore haven't learned to travel by myself. I have seen that other persons with deafness and deafblindness travel by themselves. I want to do the same'.

When reflecting upon travel possibilities with autonomous vehicles, they were sceptical but saw the potential. The RPs draw upon previous experiences with travelling. Lack of information about the transport, such as the route, road work, obstacles, and changing mode of transport, is experienced as the most challenging problem by the participants. In general, the RPs were pessimistic about transport, especially taxis. For example, B3 expressed disappointment with waiting times and service: 'sometimes the taxi service for disabled can be delayed even for >40 min. […] They even ask me to guide them to the location'. B4 mentioned challenges in finding the right seat and getting lost: 'In a train with two floors, it is very difficult to find my seat'. […].

DB5 even 'hates taxis' as the service does not live up to waiting time expectations: 'I stay in front of the door and wait. We don't know when it will come, sometimes five minutes, sometimes 20 min. Therefore, I don't go by taxi […] I prefer taking the bus'. DB5 also expressed a need for real-time information: 'I wish there were a display showing where the car is and how long it is left to arrive. […] If I rush, I will fall over my cat or my child or even other stuff in the way'. Despite drawbacks, taxi drivers usually help by holding the rider's arm and guiding them to the vehicle or telling them if they should go right, left, or forward: 'It has happened at times that I have opened the wrong car and almost sat down…' (B4). DB2 will ask 'the driver [for help]', and B3 found that taxi drivers often provide help: 'If there are a lot of cars, the driver helps me'.

All three target groups need help to determine when the vehicle has arrived and to find the way to the vehicle, the right seat, the next bus, train, or taxi (i.e., if they have to change the transport), a place to put luggage, the correct gate at the station, and information about the stops, delays, changes, problems, or accidents along the road. The RPs with blindness needed auditory and tactile help, and those with deafblindness (with remaining vision) and deafness needed visual and/or tactile help. They all required information during all three phases of the trip (before, during, and after), especially when travelling by taxi since taxis seldom arrive at the scheduled time. The quotations below address issues related to finding the right vehicle and the pickup point: "I know the time they should pick me up. I always look out and look through the window or go out the door and check. It would be great to have a signal or something on my phone so that I don't have to wait and check" (DB4). "If I go by train, sometimes the train has to change to a bus, and then I have to give more attention. I try to check or write to someone or use my cell phone to check. I need to be focused and concentrate all the time, which takes a lot of energy…" (D2).

Table 7
Results from the questionnaire after travelling without and with the vibrotactile guiding aid were categorised according to functional impairment. The numbers in each cell are also visualised as blue bars to facilitate comparison.

	Blindness (%)	Deafblindness (%)	Deafness (%)	Total (%)
10) How much help did you need from the communication aid when performing the current activity?				
Not at all	0 (0.0%)	1 (20.0%)	0 (0.0%)	1 (6.6%)
A little	3 (60.0%)	2 (40.0%)	2 (40.0%)	7 (46.7%)
Pretty big	1 (20.0%)	1 (20.0%)	2 (40.0%)	4 (26.7%)
Very large	1 (20.0%)	1 (20.0%)	1 (20.0%)	3 (20.0%)
11) How much did the communication aid help you perceive the right command during the journey?				
Not at all	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Somewhat	0 (0.0%)	2 (40.0%)	2 (40.0%)	4 (26.7%)
Pretty much	0 (0.0%)	2 (40.0%)	1 (20.0%)	3 (20.0%)
Highly	5 (100.0%)	1 (20.0%)	2 (40.0%)	8 (53.3%)
12) Is the communication aid easy to understand (Are the vibrations clear)?				
Not at all	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Somewhat	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Pretty much	0 (0.0%)	3 (60.0%)	0 (0.0%)	3 (20.0%)
Highly	5 (100.0%)	2 (40.0%)	5 (100.0%)	12 (80.0%)
13) Is the communication aid easy to use?				
Not at all	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Somewhat	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Pretty much	1 (20.0%)	1 (20.0%)	1 (20.0%)	3 (20.0%)
Highly	4 (80.0%)	4 (80.0%)	4 (80.0%)	12 (80.0%)
14) Does the communication aid feel reliable (don't miss, don't disconnect)?				
Not at all	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Somewhat	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Pretty much	1 (20.0%)	4 (80.0%)	2 (40.0%)	7 (46.7%)
Highly	4 (80.0%)	1 (20.0%)	3 (60.0%)	8 (53.3%)
15) Will you want to use communication tools in other activities?				
Not at all	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Perhaps	1 (20.0%)	1 (20.0%)	4 (80.0%)	6 (40.0%)
Probably	1 (20.0%)	1 (20.0%)	1 (20.0%)	3 (20.0%)
Surely	3 (60.0%)	3 (60.0%)	0 (0.0%)	6 (40.0%)

4. Discussion

4.1. Possibilities and limitations for autonomous vehicles for functionally-impaired persons vehicles in daily life

The RPs in this study want to travel more than they currently do. Many RPs choose not to travel due to the risks, including the fear of becoming lost (Ranjbar, 2009). Today, RPs make their daily trips (e.g., to work, gym, hospital, and parents) without any significant problems when a vehicle, route, and place are known, and they can use different guiding apps. The limitations appear when the place is unknown, when new obstacles arise, or when they need change transportation modes. Today, there are concerns that people with disabilities cannot find adequate transportation options for their needs (Brouwer et al., 2008; Crudden and McDonnall, 2015; McKercher and Darcy, 2018). Here, automated cars can provide a single mode of transport to a unique destination. Automated cars also can enable independent travel (without an assistant), greater flexibility, and increased reliability. For the RPs, autonomous cars could combine the experienced benefits of a bus in terms of predictability and the experienced benefits of a taxi in terms of flexibility in the choice of destination and time of travel. For these reasons, the RPs see automated vehicles as potentially improved means of transportation.

However, despite the high expectations of autonomous cars (Hancock et al., 2019), this study confirms previous findings (Brinkley et al., 2019; Meurer et al., 2020; Pakusch et al., 2020): autonomous cars may not work for persons with blindness, deafblindness, or deafness without adequately considering the target groups. The interviews and the trips with the autonomous car highlight the need for human intervention (and the driver's role). Without the vibrotactile aid, several RPs needed help from the test leader or interpreter for the test to proceed. All RPs experienced limitations of autonomous vehicles, but mostly for those with limited or no vision.

Interestingly, navigation and guidance are merely one part of a journey (Crosier and Handford, 2012; Low et al., 2020). There is also a need to communicate with other people inside and outside the vehicle (e.g., call centre (Sangwon et al., 2020)) and a change in travel plans (Meurer et al., 2020) and to customise information for specific user needs (Diels et al., 2017). These are all important aspects to consider when designing more independent travel conveyances. However, there are also other challenges to overcome, such as accepting the technology. The target groups were initially sceptical towards autonomous vehicles because of the insecurity and being afraid of getting lost, hurting themselves, or causing harm to others. When provided more information about the autonomous vehicles, the RPs were more in favour of the transport mode and could consider using the vehicle in their daily travel: "It would be a luxury if I just push a button; the car can come and pick me up. I would feel pleasure to just have a car like this" (D2).

The study confirms previous studies (Brinkley et al., 2018; 2019; Claypool et al., 2017; Holmgren et al., 2016; Wiggers, 2020) that identify the benefits of autonomous vehicles for impaired persons but highlights the initial concerns of using the transport mode without additional aids. The results also show that the promises and benefits of autonomous vehicles and independent travel for impaired persons are unlikely to be fulfilled unless the service also integrates guidance to and from the vehicle. Today, there seems to be a significant gap between traveller needs and the possibilities of autonomous vehicles, so there is an excellent opportunity to design services based on an understanding of the trip from start to end. This holistic perspective is necessary if society wants to ensure independent mobility for everyone irrespective of impairments.

4.2. Vibrotactile guidance for independent travel with autonomous vehicles

Without the vibrotactile guidance aid, several RPs (especially those with limited vision) needed help from the driver or interpreter for the test to proceed. However, using vibrotactile guidance aid, all RPs could complete the trip in this study without help from the driver or interpreter. The study shows that vibrotactile guidance provides a possibility for improving orientation when finding the vehicle, getting information along the way, and reaching the destination, are important aspects for independent travel. The study shows that the RPs would be able to perform trips in an autonomous car independently if they receive sufficient information adapted to their functional needs and in an appropriate information channel (auditory, visual, or tactile).

All three groups were positive and received tactile information. However, after testing the aid, RPs suggested that the vibrations should vary in intensity depending on the importance of the information (e.g., an imminently dangerous situation should be indicated by the most intense vibration setting).

There are limitations to how much information can be sent with the haptic codes used in this experiment. That is, a user can only remember a limited number of codes. Training could improve this, but a limited number needs to be used at least when starting to learn the tool. This study shows that the vibrotactile aid could bridge the interaction between the autonomous vehicle and the RPs; in a similar fashion, it enables people of the target groups to enjoy horseback riding (Ranjbar, 2019). The vibrotactile tool Ready-Ride has previously been successful as a tool for horseback riding (Ranjbar, 2019).

Interestingly, the Horse (H)-metaphor (Damböck et al., 2011) has been used to understand the division of control and responsibility between autonomous vehicles and humans. It is said that the relationship between humans and autonomous vehicles is very much like that between the horse rider and the horse. This study shows that the vibrotactile aid could bridge the interaction between the autonomous vehicle and the RP as it does for horse riders. The study also highlights that they would like to control the trip and the vehicle by giving directions and having the flexibility, for example, to change direction and final destination. In the vibrotactile solution tested in this study, the participants could only receive information; they could not control the vehicle. The design challenge of giving commands to the vehicle and considering the needs of impaired persons is an area for further research.

Autonomous technology holds great promise for improved quality of life. All the RPs desired independence, as exemplified in the following quotation: "It would be a dream not to be dependent on the assistant. […] I would be more independent and feel free." (DB1). However, several door-to-door mobility needs must be addressed to enable independent travel in an autonomous car. More importantly, this study points out that the needs of the RPs for vibrotactile guidance aid are very diverse and depend not only on the type but also the degree of functional impairment, especially for persons who are vulnerable without aid.

4.3. Methodological and ethical considerations

It should be noted that the study sample included only five RPs from each category, which is too few to represent the group, although enough for a case study (Yin, 2002). It is recognised that the study results are influenced by the type and degree of impairment of the RPs. It would be interesting to include a larger sample size to confirm the results in future studies. In particular, the amount of vision influenced their experience of the vibrotactile guidance aid and how much help they would need when travelling in an autonomous car. The variability of impairments and perceived value is in accordance with, e.g. (Williams et al., 2013) showing the need for adaptability of technical solutions to the needs of individuals.

Using the WOz set-up (Dahlbäck et al., 1993) within a "whole journey approach" (Crosier and Handford, 2012) is not without its challenges. In this case, the RPs were informed about the WOz set-up before the test due to practical and ethical reasons (i.e., respecting the participants' vulnerable situation). Originally, WOz had ethical implications as it requires withholding information from participants (i.e., a real human being – the wizard – is in control of the technology). We are aware that letting the RPs know this beforehand may have influenced the experience of what it would be like riding in an autonomous vehicle. However the vulnerability of the RPs was regarded as more important than the necessity to hide the actual study setup. Although, the findings are in line with other WOz set-up studies exploring autonomous vehicles that use the original set-up of the method (Habibovic et al., 2016; Meurer et al., 2020; Mok et al., 2015). Letting the RPs experience a real trip helps address the so-called "envisioned world problem" (Woods and Christoffersen, 2001) as the access to autonomous vehicles today is limited.

Because a personal route was chosen for each of the RPs, all participants had different but generally known routes. The effect of using the vibrotactile guidance for autonomous cars would potentially be even more significant when travelling to unknown places. As the scenario included a return trip the last ride (with the vibrotactile aid) could possibly be considered more known to the participant. In future studies, measures should be taken to ensure that all destinations are equally familiar to the participants.

4.4. Design considerations to make autonomous vehicles more accessible

Grounded in the needs and experiences of the RPs travelling by the autonomous car, the following reflections can be made regarding making autonomous cars more accessible for people with functional impairments. The identified issues are, to some extent, not only relevant for autonomous cars but any (public) transport made by the RPs.

Before the trip:

- Timing: Real-time information should synchronise with planned and actual arrival times. RPs expressed that unreliable arrival times are a big concern, indicating that existing services need to improve the accessibility of information.

- Position: Knowing exactly where the vehicle stops. Identifying and locating the vehicle is the first step of a successful trip. In the study, it was observed that RPs needed guidance from the test leaders for precise positioning. Accuracy within half a metre is probably necessary.

During the trip:

- Seating: Information where there are empty seats.
- RPs mention situations of attempting to take already occupied seats by mistake, leading to uncomfortable situations.
- Customisation of information and modality: Users should be able to choose content and level of detail, for example, route information about streets and crossings. In the study, it was found that RPs used information from the vibrotactile aid and other navigation tools according to their individual needs and preferences, meaning that individual adaptations cannot be based solely on type of functional impairment.
- Visibility of interior: There should be an intense light in the car both at the entry/exit and the back seat with a bright, easily readable display.
- RPs mention lighting inside and outside the vehicle as an important feature to facilitate interaction in and around the vehicle, finding buttons, to see where to step out, being aware of traffic etc.
- Communication: Information should be communicated with the car using different modalities adopted to the functional impairment of the one using it. The study shows that the ability to use autonomous cars depends on the type and degree of impairment. All RPs experienced limitations of autonomous vehicles, but mainly for those with limited or no vision.
- Two-way communication. Allow for two-way communication and the ability to control the vehicle. RPs expressed a need to control the car and not only receive information from it, e.g., stop for shopping or turn back. RPs expressed a need to communicate with the car or with a remote person; a concierge-like service to ask questions if there are concerns about going the wrong way. RPs also expressed the need for flexibility and the ability to control the itinerary, e.g., to make unplanned stops.
- Information about the route. RPs expressed that they wanted information about landmarks and activities outside the vehicle. It is also observed that when orienting themselves to known places, they use positions in the environments or landmarks as guidance.

After the trip:

- Security: Information should be provided about what is happening outside the car.

  RPs mention feeling insecure when not knowing the environment outside the car, e.g., about surrounding traffic.

- Accuracy and obstacles: Accurate information should be provided about the position of the arrival and whether there are any obstacles nearby to ensure a safe exit and continuation to the destination. The study results show a need for obstacle avoidance for safe exit, especially if the car stops at different places and is not tied to dedicated stops.

Future development of guiding technology:

- Device integration: The vehicle should be able to connect to existing mobile devices and not as additional stuff to wear when going out as these users need to take many other objects such as walking canes, devices, and chargers. Most of the RPs in this study preferred to use the vibrotactile guidance aid to communicate via an app. According to the RPs, using your own mobile and connecting to an existing tool such as a smart watch is preferable in many cases.
- Haptics: The design of haptic communication needs further development, e.g., the vibrations should vary in intensity depending on the degree of importance of the information. The RPs suggest signal variations to increase the severity of information given.

5. Conclusion

The study confirms previous indications that autonomous cars may not work for impaired persons by simulating a ride in an autonomous car. Without the vibrotactile guidance aid, several RPs needed help from the driver or interpreter for the study to proceed (especially those with no or limited vision). At the same time, the study shows that the RPs could perform their trips independently if they received adapted information and used their functional sense as an information channel (auditory, visually, or tactile). There is a potential gap between traveller needs and the possibilities of autonomous vehicles if designed without accessibility considerations. There is an excellent opportunity to develop services based on understanding the trip from start to end. The results point out that the needs of the RPs for vibrotactile guidance aid are very diverse and depend not only on the type but also the degree of functional impairment. The study also highlights the usability of the vibrotactile guidance aids in the context of autonomous cars and identifies areas for improvement. Design aspects of making autonomous vehicles more accessible for these target groups are provided.

CRediT authorship contribution statement

Parivash Ranjbar: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Pournami Krishnan Krishnakumari:** Data curation, Methodology, Validation. **Jonas Andersson:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – review & editing. **Maria Klingegård:** Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

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

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