Hand-held Haptic Navigation Devices for Actual Walking

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Hand-held Haptic Navigation Devices for Actual Walking

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***Abstract*—In this survey, we give an overview of hand-held haptic navigation devices specifically designed for and tested with pedestrians. We distinguish devices for indoor use and for outdoor use as the implementation is usually quite different. Outdoor devices make use of Global Positioning Systems (GPS) tracking built-in in smartphones; indoor devices use a variety of sensors, and tracking and localization systems and these are usually restricted to a small part of a building. Overall, the high success rates reported in the studies show that vibrotactile stimulation via a hand-held user interface is suitable for navigation instructions, as in all experiments (almost) all participants reached their goal. An issue for several of the indoor devices is that walking speeds were (much) lower than normal walking speeds and path efficiency was relatively low. However, these issues might be overcome with some training as in most studies there was hardly any practice time. Several of the outdoor devices seem quite close to taking the last step before commercial use. In the Discussion, we evaluate the suitability of the devices for persons with visual and/or hearing impairments. Especially devices that provide very specific instructions, such as, 'go straight' or 'go right', seem valuable for this population.**

***Index Terms*—Navigation, hand-held, hand-worn, walking, blind, deafblind, indoors, outdoors**

I. Introduction

In our daily life, we often have to navigate to unfamiliar places, such as to other cities or to streets or buildings in our own city. In the recent past, we had to study maps to find out how to reach our destination, but nowadays, we have ample access to navigation systems. New cars are standard equipped with sophisticated navigation devices: if you want to reach a destination, just type in the address and the device guides you to this location. Modern smartphones with GPS capabilities offer similar guidance to pedestrians. All such devices provide auditory or visual instructions, and often a combination of the two. However, there are circumstances where visual or auditory information is not ideal or not even accessible. Obviously, for persons with a visual or hearing impairment (or both) such devices are of limited use. But also if you need your attention elsewhere, such as when you are walking through busy streets, when you are sightseeing with a friend and talking and looking around, other types of feedback, and in particular haptic feedback, might be preferred. In this study, we are especially interested in haptic navigation devices for pedestrians. Such devices form a specific category as essential requirements are that they are lightweight and wearable or hand-held.

In the last two decades, several haptic navigation devices have been proposed and studied. Unlike vision or hearing, haptic devices are not limited to a certain body part (i.e., eyes or ears). Indeed, in the literature, we found devices specifically meant for hand, head, back, belly, foot, wrist, arm, leg, shoulder, neck, thigh, waist and torso. However, the majority of the devices was designed for the hand and therefore we will focus on hand-held and hand-worn haptic navigation devices. Many different approaches were attempted and the current survey will provide an overview of such approaches.

This research started with collecting peer-reviewed papers, chapters and conference contributions that on the basis of their title and/or keywords seemed relevant for navigation while walking. Thus, all papers describing devices meant for use in a car, aircraft or similar were excluded, if possible, on the basis of the title. For all papers that were included at this first stage, the references and citations were checked for relevance. Subsequently, also references and citations of these additional studies were checked. This iterative process eventually yielded a set of 519 publications. These publications were looked at in more detail by reading the abstract, looking at the method and/or checking the results and conclusions sections. We used the following hard inclusion and exclusion criteria:

1) **Real user test**
   We only included papers that report on user studies, so that excludes papers that only present or analyse a device.
2) **Actual navigation**
   Many of the studies just tested whether participants were able to recognize haptic instructions, such as specific vibration patterns. Although valuable in itself, in this overview, we required that participants had to navigate from one location to another.
3) **Actual walking**
   In addition to the previous criterion, we required that participants really had to walk from one location to another. This excluded studies with navigation on a screen or in a virtual environment where they did not have to walk.
4) **No preliminary studies**
   We required the studies to have a minimal number of three participants to avoid too preliminary studies. Exceptions could be made for extensive case studies (but this was not applicable to any of the studies).
5) **Not just obstacle detection**

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In many of the studies, the device only provided obstacle detection. Although this might be useful in some circumstances, it does not help the user to reach a certain destination. So, studies with devices that only signaled obstacles were excluded.

6) **Not in combination with speech or other auditory cues**
Some of the devices in these papers were meant as addition to verbal or auditory guidance. We only included such papers, if a haptics-only condition was also tested. These other conditions are only described if necessary for the comparison. This requirement was added because if a device was only tested in a combined haptic-auditory condition, one does not know whether or how much the haptic stimulation contributes to navigation performance.
7) **Not in combination with visual navigation cues**
We required that navigation directions were given haptically, although participants could still be allowed to use vision to avoid obstacles or to enjoy their environment. So participants were not allowed to use a visual map or street signs in combination with haptic cues to reach their target. We added the requirement because we are interested in whether or not haptic stimulation contributes to performance, which would be impossible to infer if a device was only tested in combination with visual information.
8) **No review papers**
For all devices, we looked for the original source, so we do not include review papers.

After applying these inclusion and exclusion criteria, we had a set of 86 papers meeting all requirements. At that stage, we decided to add one more inclusion criterion: the device had to be hand-held or hand-worn. This way we ended with a set of 29 papers. All other remaining papers will be part of a subsequent survey paper.

In the following sections, we distinguish two fundamentally different approaches, namely devices meant for use indoors and devices specifically meant for use outdoors. The difference between these approaches mostly lies in the way location information is obtained. Outdoor devices make exclusively use of GPS (Global Positioning System) tracking via a smartphone. As GPS tracking is currently mostly impossible inside buildings, different localization methods are needed for indoor devices [1]. In most cases, rooms and buildings were equipped with all kinds of tags, sensors or camera's connected to a computer using infrared signals, ultrasonic signals, radio signals, WiFi, Bluetooth, etc. As a consequence, such devices work only in a limited setting. In a few studies, the indoor solution could in principle also work outdoors, albeit within a similarly restricted area. These studies will be discussed in the indoors section if testing was done inside a building.

There are also a few devices that did not yet reach the status of autonomous device for location tracking. In such cases, a 'Wizard of Oz' [2] approach was used, in which an experimenter determined the location of the participant and gave appropriate feedback. For these studies, we did not make the distinction indoors and outdoors, as all localization options were still open.

In this overview, we do not explicitly focus on devices for persons with visual and/or hearing impairments. However, it will be clear that especially for these persons, haptic user interfaces might be preferable over other types of interfaces. For all papers included in this study, we will indicate if persons with impairments were among the participants. Moreover, in the Discussion and Conclusion section, we will evaluate the usefulness of devices for these particular target populations, even if the devices were not (yet) tested with these target groups.

II. AUTONOMOUS DEVICES FOR INDOOR USE

Inside buildings, GPS tracking is usually not possible. However, an indoor environment offers the possibility to use fixed landmarks for navigation. Tags can be fastened to landmarks such as walls, elevators, stairs or the reception desk to help guide the user in the correct direction. Cameras, fastened to ceiling or wall, or attached to the chest or head of a user, can be used to determine the position of the user relative to the room. A clear advantage of indoor navigation as compared to outdoor navigation is that the other users will also be pedestrians, making the environment relatively safe for independent navigation, especially for users with visual impairments. Clear disadvantages of indoor navigation are that all rooms need to be equipped with cameras, sensors, etc. and that there can be possibly challenging situations with stairs and elevators. In Table I, we present the studies of hand-held and hand-worn haptic navigation devices created for indoor use and below we decribe these papers in some detail.

Ghiani et al. [3] created a hand-held device with vibration motors on thumb and index finger to indicate direction and distance. This device was tested in a museum with 11 blind participants whose task it was to reach certain artworks. The device is able to detect the position of the artworks through RFID (radio-frequency identification) tags specified in the museum database. Performance with this vibrotactile version of the device was compared with spoken instructions given by the same device. All users reached their goal with both types of feedback. The objective data (time to reach a goal) were not significantly different for the two types of feedback, but the users expressed a preference for the verbal instructions because they felt more confident. Although training might overcome this difference, the intention of the authors was to design an intuitive device that could be used directly without any practice, and thus they were not really satisfied with their results.

Amemiya & Sugiyama [4], [5] created a device (compact disc-size, diameter 120 mm, thickness 36 mm) that could generate pseudo-attraction forces by having a small mass repeatedly accelerate above threshold for a short time and accelerate below threshold for a longer time in the opposite direction. In this way, a kinesthetic illusion of pulling or pushing could be created. 23 visually impaired participants had to hold this device in their dominant hand, or if they also used a cane, in their free hand. With this device they were guided to a final destination via a route with 4 turning points. In a comparison condition they had to wear noise-canceling headphones that blocked all auditory input. Communication

TABLE I
AUTONOMOUS DEVICES FOR INDOOR USE

Reference	Participants	Localization	Stimuli	Task	Metrics	Outcome
Ghiani et al. (2008) [3]	11 (7f, 4m) B age: 27–66	Grid of RFID tags	*Vibrotactile* Vibrators on thumb and index finger indicating rotation direction	Navigate to artworks	Time taken, questionnaire	All participants reached their goal, but preference for verbal guidance; no difference in time taken between verbal and vibrotactile feedback
Amemiya & Sugiyama (2009, 2010) [4], [5]	23 (3f, 20m) VI age: 17–62	Bluetooth and infrared sensors communicating with portable computer	*Force* Pseudo-attraction forces	Following a route of about 32 m in a maze with 4 turns to destination	Success rate, walking speed, questionnaire	21 participants reached destination; no difference between conditions with or without noise-cancelling headphone; participants used normal walking speed; overall participants were positive about the device
Amemiya & Sugiyama (2009) [6]	23 (3f, 20m) VI age: 17–62	Image processing system, leds on device, computers, ZigBee link	*Force* Direction indicator held in both hands generating pseudo-attraction forces	Walk 5 times a few meters to a target in 1 of 8 possible directions	Success rate, total and per direction	11 of the participants walked in correct direction in all trials; 2 participants unable to do task; best performance for north, east, south, west
Robinson et al. (2009) [7]	20 (10f, 10m) age: 18–55	Geo-tagged information	*Vibrotactile* Vibration if device is pointed towards geo-tags	Find 30 targets and avoid obstacles in a corridor of 9-m length	Success rate, walking speed, questionnaire	Walking speed 38% of normal speed (44% with visual device); 96% of the targets were found; device is easy to use
Wachaja et al. (2015, 2017) [8], [9]	8 (2f, 6m) blindfolded age: 22–30	Laser scanner sensing environment and egomotion + map of environment	*Vibrotactile* Vibration motor in each handle of a walker, signaling left, right, straight, end	Walk along 4 different 30-m-long paths	Time taken, total length, preference scale	78% of the runs were shorter and 65% of the runs required less time with the predictive approach, but preference for non-predictive approach
Spiers et al. (2015, 2017, 2018) [10]–[12]	[10]: 3 (3m) age: 27–30 [11]: 13 (6f, 7m) age: 23–38 [12]: 94 (15VI)	Ubisense Real Time Localization System, Ubitag on hat, magnetometer on wrist	*Shape-changing* 'Haptic Sandwich' or 'Animotus' gives directions and/or distance via rotation and expansion	[10], [11]: Navigate to 10 invisible targets in a 5.1 m × 5.3 m space [12]: Navigate to 4 zones in dark space of 16 m × 7 m	Mean path efficiency, walking speed	[10]: Mean path efficiency 32–56%; orientation error rarely outside ±35° [11]: Heading information improves path efficiency; proximity indication increases speed; [12]: 83% of participants visited all zones; mean path efficiency VI: 40%, sighted: 49%; normal walking speeds
Spiers et al. (2016) [13]	7 (1f, 6m) age: 22–33	Ubisense Real Time Localization System, Ubitag on hat, X-OCS microcontroller	*Shape-changing* 'Haptic Taco' and 'Haptic Lotus' indicate proximity via expansion	Navigate to 10 invisible targets in a 5.1 m × 5.3 m space	Mean path efficiency	Mean path efficiency 24% for Lotus and 47% for Taco
Choinière & Gosselin (2017) [14]	19 (5f, 14m) age: 23–52	8 Vicon MX T-40 cameras + markers on body	*Torque* Torque and pulse frequency indicating proportional direction error	Navigate 2 routes, each consisting of 15 targets at a spacing between 1.5 and 4 m	Success rate, walking speed, questionnaire	All targets were reached; walking speed about 23% of normal speed; device considered intuitive

For stimuli, a keyword characterizing the type of stimulation is given in italics. Only the major metrics are mentioned. f: female, m: male, VI: visually impaired, B: blind. Age or age range (if available) are given in years.

about the location of the observer and the force instructions were realized via a portable computer, another computer at a distance, Bluetooth and infrared sensors on the walls. 21 of the 23 participants successfully reached their destination under both conditions and while using their normal walking speed. Almost all participants responded positively to the statements 'The guidance was easy to understand' and 'I expect it would be useful in disaster situations'.

Amemiya & Sugiyama [6] report another experiment with probably the same participants where they tested a somewhat larger haptic direction indicator which also generated pseudo-attraction forces and that had to be held in both hands (unless participants also used a cane). They used an image processing system to measure the position of the participant. Control instructions were sent from a computer to a microcomputer on the device and communicated via a ZigBee link. Via the device, participants were presented with 1 out of 8 possible directions, which they had to follow until they reached a target. The direction force was updated every 150 ms. About half of the participants (11) managed to walk in the indicated direction in all of their 5 trials. Two other participants did not manage that at all. The remaining participants reached their goal along a zigzag trajectory. Best performance was obtained for the cardinal directions north, east, south, west.

Robinson et al. [7] tested their 'SHAKE' device, a device the size of a bulky phone, that vibrates if the user points to a geo-tagged target. They compared performance with this device to that of a similar-sized visual device on which targets could be seen. 10 participants used the haptic device and 10 other participants the visual device. Walking speed was 38% of their normal speed using the haptic device and 44% with the visual device. The participants were able to find all targets with both devices and they found the devices easy to use. An advantage of the haptic device was that participants did not have to look at the device. The authors found their results promising, but they also saw the need for several improvements.

Wachaja et al. [8], [9] developed a walker with vibrating handles for elderly with walking disabilities and visual impairments to safely navigate through a room. Strictly speaking this device is not really 'hand-held', but as haptic information is given to the hands, we decided to include this study in our overview. Two lasers scanners were placed on the walker for sensing the environment and egomotion. These laser scanners communicate with a controller module which sends navigation signals (go straight, go left, go right, goal reached) based on a map to the vibration motors. The authors compared two controller algorithms, one with prediction that takes human response times into account when timing the navigation signal, and one that does not make use of such predictions. After two practice trials, the eight blindfolded participants had to navigate four different paths with both controller algorithms. With the predictive approach, 78% of the paths were shorter and 65% of the paths required less time, compared to the more standard (i.e. non-predictive) approach. However, the participants had a preference for the standard approach, possibly because it was not always clear how to interpret the signal changes of the predictive algorithm.

Spiers et al. [10] ran a pilot experiment testing their 'Haptic Sandwich'. This is a low cost 2DOF (2 degrees of freedom) shape-changing device that provides the user with both heading information (via rotation) and proximity (via extension) to targets. Location information of the participant was obtained via a Ubisense Real Time Localization System with sensors in the 4 corners of the room that detect the position of a Ubitag on the participant's head and orientation via a wrist-worn magnetometer. Participants were allowed to see their environment, but the hand-held device was covered with a fabric. The 3 participants had to locate 10 different invisible targets, which they managed to do successfully. Mean path efficiency, defined as the ratio between the optimal path length and the actual path length and expressed as a percentage, ranged between 32% and 56% and they only rarely made an orientation error of more than 35°.

The same device, now called 'Animotus', was tested in a theater setting [12] with 94 participants (the audience) of whom 15 with a visual impairment. The Animotus guided the participants in complete darkness from zone to zone where they were presented with an audio scene. The sighted participants walked slightly more efficiently than the participants with visual impairments, but walking speeds and number of actually visited zones did not differ between the groups. The authors saw lots of room for improvement and hoped their study will initiate further research into the development of inclusive technology.

In a subsequent study, Spiers et al. [13] introduced the 'Haptic Taco' and compared this device to their earlier developed 'Haptic Lotus'. Both these devices have only 1DOF, namely expansion to indicate proximity. The shape of the Haptic Lotus is similar to that of a lotus flower; by contracting the petals, this device communicates proximity. The shape of the Haptic Taco resembles a cube that can extend in two opposite directions. The same experimental setting as in [10] was used. Performance with the Haptic Taco was significantly better than with the Haptic Lotus for all 7 participants with a mean path efficiency of 24% for the Lotus and 47% for the Taco. Informally, their participants commented that they preferred the Taco over the Lotus, because the latter was experienced as more difficult. In a more extensive study they compared performance with the Taco to that with the Animotus [11]. As the Animotus has 2DOF, they also tested this device using only one of the degrees of freedom (either expansion or rotation). The experimental setting was again the same as in [10]. Mean path efficiency was significantly better in the Animotus 2DOF and Animotus 1DOF-rotation conditions, indicating that heading direction plays an important role in motion efficiency. Motion speed was higher if proximity was indicated. The advantage of the Animotus is that both heading direction and proximity are indicated.

Choinière & Gosselin [14] created a haptic compass (palm-size, height a few cm) which had to be held in the dominant hand. Torque and torque pulse frequency indicated direction proportional to the error; no signal indicated that the target was in front. The experimental room was equipped with 8 Vicon MX T-40 cameras so that both position and heading of the participant could be determined by making use of markers on the participant's body. 19 blindfolded and hearing-blocked participants had to navigate two routes along 15 subsequent targets. All participants managed to find all targets, but their walking speed was relatively slow compared to normal walking speed. Participants found the feedback from this device clear and intuitive.

A. Summary

In general, the various localization and orientation techniques that are used in the navigation devices led to successful navigation indoors. Most participants managed to reach their target even without much training in advance. Although with some of the devices almost normal walking speeds were achieved, with other devices the walking speed could be significantly reduced to 38% or even 23% of normal walking speeds. Where path efficiency was reported, it ranged from 24% to 56%, which means that participants covered a distance 2 to 4 times as much as optimally necessary.

The tests were relatively small in scale: the experimental environment consisted mostly of just a single room or corridor, distances to be covered were short and only a few turns had to be made. This shows that the current state of the art is still far away from users navigating independently through a whole building by using a hand-held haptic device. On the other hand, the successful performances found in these studies should encourage the authors or other researchers to continue the research along these lines, as many of the approaches could, in principle, be extended to cover a much larger part of a building.

III. Autonomous devices for outdoor use

As GPS tracking works generally well outside and since this is widely available via smartphones and smartwatches, there are endless possiblities for outdoor navigation devices. Below and in Table II, we present an overview of different approaches.

Williamson et al. [15] used a phone with built-in GPS in combination with an inertial sensor pack that provides accelerometer and magnetometer readings and is also able to generate vibrotactile feedback. Via Bluetooth, the phone provided a 3G connection to a remote server. The task of the participants was to walk to a virtual centroid, that is, the centre of gravity of a group of 5 participants who started at different locations on campus at the same time. The first time they had to walk while using the device, the second time without the device. Instead of receiving instructions which path to take, they had to scan directions with the device and they received vibrotactile feedback if the centroid was within a 60° angle of the device. Based on this feedback, they were free to choose their own route. In total, 5 groups of 5 participants had to locate the centroid and all of them succeeded, both with and later without the device. Walking speeds in the two conditions were similar. On average, path length was 990 m in the first run and 570 m in the second run. This difference is not surprising as in the second run they already knew the location of the meeting point, but the authors wanted to compare performance with the device to an almost optimal situation. They conclude that the time participants needed with the device was only twice as much as walking straight to a familiar location, which indicates just a low overhead for non-visual navigation. The intended application for this device was that groups of people could be guided towards a meeting point.

In a follow-up study, 24 participants had to walk from a starting point to an end point 770 m away using the same device with the shortest path being approximately 1 km [16]. For 12 of the participants the direction angle was again 60° (static condition); for the other 12 this angle varied between 60° and 120° depending on the number of possible paths the participants could take from their current location towards the end point (dynamic condition). All participants managed to reach the end point using the device. Path lengths and times to destination were not different in the two conditions. Participants in the dynamic condition, who had a larger choice of routes, showed a tendency to choose the major paths of the campus. Participant in the static condition did not always have this option, as the directions from which they could choose were more restricted. The authors conclude that their alternative to turn-by-turn guidance works well and gives the users more freedom to choose their own route.

Pielot et al. [17] designed a tactile compass for a smartphone. While holding the smartphone in the hand, participants received vibration patterns that indicated direction to the next waypoint. The 21 participants had to navigate a route through the busy city centre of Offenburg. Performance with this device was compared to that with using a visual navigation system on the same smartphone and a condition in which the tactile and visual guidance were combined. All participants had to use each guidance method once and all of them succeeded in reaching their destinations. They found no differences in completion times and orientation losses between the methods, but in the combined condition, participants made less navigation errors than in either the tactile or the visual condition. The objective workload, defined in terms of walking speed, was larger in the conditions with tactile feedback, but this was not the case for the subjective workload. An advantage of the tactile feedback is that participants did not have to look on the device but could attend to their environment.

Azenkot et al. [18] compared three different methods to convey direction with a phone via vibrations. In 'Wand' the phone vibrates if the participant points in the correct direction. In 'ScreenEdge' the participant has to touch one of the edges of the screen of the phone and if this coincides with the direction the participant has to go, the phone vibrates. In 'Pattern' the participant receives 1, 2, 3, or 4 vibrations for forward, right, back or left, respectively. All 8 visually impaired participants had to navigate a route in a busy urban area along 16 intersections, using a different method for every 4 successive intersections. All participants managed to do so and average error rate was only 4%. None of the participants liked the Wand method, probably because of the higher experienced workload.

Rümelin et al. [19] termed their device 'NaviRadar', as it uses a radar metaphor to indicate direction and distance. The device consists of a mobile phone equiped with an external vibrator at the backside on which participants had to place their index finger. A first vibration symbolizes their heading direction and the duration of the break before a subsequent double vibration indicates the required direction, with short durations indicating to the right and longer durations to the left. The strength of the double vibration indicates distance, with higher intensity meaning closer. The NaviRadar gives continuous feedback. In an outdoor study, the authors compared their NaviRadar with two other means of navigation guidance, the 'PocketNavigator' [26], which also indicates distance and direction via vibration patterns of a mobile phone, and spoken instructions. Participants had to follow 3 routes of about 400 m with 10 turns, using each type of guidance once. All participants were able to follow the routes with all 3 devices, and all three devices received a high usability score. However, much less errors were made using the NaviRadar or spoken

TABLE II
AUTONOMOUS DEVICES FOR OUTDOOR USE

Reference	Participants	Localization	Stimuli	Task	Metrics	Outcome
Williamson et al. (2010) [15]	25 (10f, 15m) age: 18–65	GPS of phone, inertial sensor pack, remote server	*Vibrotactile* Vibration indicating direction angle	Walk to a virtual centroid within space of 0.5 km $\times$ 0.5 km with or without device	Success rate, path length, walking speed	All participants reached centroid; average path length with/without device 990 m, 570 m; normal walking speed
Robinson et al. (2010) [16]	24 (14f, 10m) age: 18–65	GPS of phone, inertial sensor pack, remote server	*Vibrotactile* Vibration indicating (static or dynamic) direction angle	Walk to an end point 770 m away	Success rate, path length, time taken	All participants reached end point; no difference between fixed or variable direction angle in terms of distance and time taken; in dynamic condition, participants tended to stay on major paths
Pielot et al. (2011) [17]	21 (10f, 11m) age: 18–41	GPS of phone	*Vibrotactile* Temporal vibration patterns indicating direction	Follow 3 routes of about 450 m with device and/or map on phone	Success rate, time taken, error rate, walking speed, questionnaire	All participants reached destination with all guidance methods; fewer navigation errors in combined condition; walking speed lower, and subjective workload higher with tactile feedback
Azenkot et al. (2011) [18]	8 (6f, 2m) B/VI mean age: 53	GPS of phone	*Vibrotactile* 3 methods indicating direction via vibration	Walk along a busy urban route with 4 intersections per method	Error rate, questionnaire	Only 4% errors; less preference for pointing towards correct direction
Rümelin et al. (2011) [19]	12 (6f, 6m) age: 19–51	GPS of phone	*Vibrotactile* Temporal vibration patterns indicating direction and distance	Navigate 3 routes of about 400 m with 10 turns	Success rate, error rate, disorientation event rate, questionnaire	All participants could follow all routes; only few errors and disorientation events; positive usability satisfaction; neutral to low task load
Jacob et al. (2012) [20]	30 mean age: 22	GPS of phone	*Vibrotactile* Vibrations if pointing in direction of next point	Navigate 2 routes for about 2 to 4 minutes	Success rate, time taken, building of mental map	All users reached destination; walking speed higher in second trial; users were able to build a mental map of features along the route
Kawaguchi & Nojima (2012) [21]	4	GPS of phone	*Vibrotactile* Temporal vibration patterns indicating direction and distance	Navigate twice to destination at 400 m	Questionnaire	Participants capable to see surroundings while using device; enjoyable to use device
Spiers & Dollar (2016) [22]	4 (4m) age: 27–32	GPS of phone	*Shape-changing or vibrotactile* Animotus (see [10]) or 'Haptic Cricket' giving direction and proximity via vibrations	Navigate to sequence of 10 targets on 2 routes of 61 and 73 m	Time taken, mean path efficiency, questionnaire	Completion time shorter with Animotus; no difference in mean path efficiency; Animotus more intuitive and less annoying
Yasui et al. (2019) [23]	6 (3f, 3m) age: $\leq$ 9	GPS of phone with relay points	*Vibrotactile* Smartphone vibrates if directed towards relay points	Follow route of 140–210 m with 4 turns	Success rate, questionnaire	All children reached destination; positive evaluation
Gallo et al. (2020) [24]	24 (13f, 11m) age: 17–56	GPS of phone	*Vibrotactile* Vibrations if looking in wrong direction	Navigate a trajectory of 1 km with 9 to 14 intersections while running	Error rate, questionnaire	Only few errors made; usability of haptic feedback higher than audio feedback
Nasser et al. (2020) [25]	6 (1f, 5m) 4B, 2VI mean age: 28	GPS of phone	*Vibrotactile or thermal* Vibrotactile or thermal stimulation of cane	Follow directional instructions along a route of about 140 m	Success rate, questionnaire	Performance with thermal cues better than with vibrations; preference for thermal cane

For stimuli, a keyword characterizing the type of stimulation is given in italics. Only the major metrics are mentioned. f: female, m: male, B: blind, VI: visually impaired; age or age range (if available) are given in years.

instructions than with using the PocketNavigator. Task load was neutral to low for both NaviRadar and PocketNavigator and low to very low for spoken instructions. The authors are satisfied that their device works as well as spoken instructions and that it has the advantage that it can also be used in noisy environments or talking to others while walking.

Jacob et al. [20] compared three means of navigation, two haptic and one visual. The 30 participants were divided in 3 equal groups. Each group had to navigate from two different starting points to the same destination. In the HapticDestinationPointer condition, participants received vibrations if they were pointing the mobile device to their destination; closer to their destination, the pointing direction had to be more accurate. In the HapticNavigator condition, guidance was similar, but participants were guided from waypoint to waypoint instead of directly to the final destination. These haptic conditions were compared to a condition in which the participants were provided with a panoramic image, so that their destination could be seen clearly. All participants reached their destination in both trials. Participants using the panoramic image reached the endpoint faster, as they could see what their destination was. All walked faster in their second trial. After navigating the two routes, participants had to indicate start- and endpoints on a sheet on which just the main road around the study area was drawn. They were also asked to indicate features on the route that they remembered. They did not know this task in advance. As participants using the HapticDestinationPointer performed best in this latter task, the authors suggest that these participants could also attend their environment when using the device. Unfortunately, the authors do not provide any quantitative date or statistical analyses.

Also Kawaguchi & Nojima [21] used a phone to provide direction and distance information via vibration patterns. When holding the phone parallel to the ground, the participant can scan directions. The device starts vibrating if the pointing direction is within 30 degrees of the correct direction; vibration frequency increases if the pointing error becomes smaller. If the phone is not held parallel to the ground, distance information is given in a similar way: higher frequency for shorter distance. Their 4 participants had to find a specific but unknown destination at a 400 m distance, two times with this device and two times using Google Maps. A questionnaire after the experiment showed that participants were more capable to see their surroundings and they enjoyed their exploration more with the device than while using Google Maps. The intended use of this device is to allow tourists to just wander around exploring unknown areas but still not getting lost.

Spiers & Dollar [22] also tested their Animotus (see above) outdoors and compared performance with this device with that using a new device, the ‘Haptic Cricket’, which gives heading and proximity information via different vibration motors. The 4 participants had to locate a sequence of 10 targets on 2 different routes on campus in a pedestrian area. In general the participants followed the correct route with both devices, with most of the obvious detours probably caused by unreliable GPS localization. Mean path efficiency was similar for the two devices, but the time it took to navigate the routes was significantly shorter with the Animotus. Participants also had a strong preference for the Animotus, because most likely the continuous vibrations of the Haptic Cricket were annoying and distracting. Moreover, the Animotus was judged as more intuitive.

Yasui et al. [23] developed a smartphone app for children for navigating a route. Because map reading is hard for young children, this app vibrates if it is correctly pointing towards a relay point on the route. All 6 children were able to reach their destination after walking 140–210 m in an urban setting. Overall the children were positive about this application.

Gallo et al. (2020) [24] designed a device for navigation while running, the so-called RunAhead. This device is strapped around the head and gives feedback if the participant looks in the wrong direction. Four different ways of feedback were compared: vibrations while holding a phone in the hand, music, audio cues or voice. The 24 participants had to run through a park along different tracks of about 1 km for the 4 types of feedback. Participants made only few errors and there were no significant differences between the types of feedback; also the perceived mental load was similar. Of all comparisons that could be made with usability, only the difference between haptic and audio cues was significant, with the advantage for the haptic feedback.

A very different approach was taken by Nasser et al. [25]. They developed two types of cane, one with thermal stimulation and one with vibrotactile stimulation. Four Peltier elements were fixed around the grip of a cane. If the top element became warm, this signaled stop; if the top, right, left or bottom element became cold, this signaled go, right, left and u-turn, respectively. Likewise, four tactors were fixed to another cane; if the top, right, left or bottom tactor vibrated, this signaled go, right, left and u-turn, respectively. All tactors vibrating at the same time meant stop. After a pilot with blindfolded sighted participants, they tested both devices with 4 blind and 2 visually impaired participants. They ran the test in an open field, where walking sessions for each cane took less than 5 minutes on average per device and the walking distance per device was about 140 m. All directional commands were given twice in a session in random order and with a 15 s gap in between commands. The thermal cues for go, stop and u-turn were perceived 100% correct; the cues for left and right, 80% and 93%, respectively. Performance with the vibrotactile cane was significantly worse, with a maximum score of 85% for stop and the other commands within the range 55–63%. All participants expressed a preference for the thermal cane. The relative success for the thermal condition might be surprising as thermal stimulation is necessarily slow, but apparently, if feedback is given well in advance of a decision point, this needs not be an issue.

A. Summary

All the hand-held devices for outdoor use made use of GPS tracking. Like in the indoor studies, all participants were able to reach their destination guided by the device. Many of the devices just generated vibration if the device was pointed in the correct (or in one case the incorrect) direction, instead of indicating ‘turn right’, ‘turn left’, etc. Other devices

TABLE III
WIZARD OF OZ APPROACHES

Reference	Participants	Stimuli	Task	Metrics	Outcome
Sokoler et al. (2002) [27]	7	*Shape-changing* TactGuide: 4 pegs indicating relative direction to thumb	Find cardboard boxes in office building	Informal observations and feedback	Participants dealt easily with the direction information if allowed to use other sensory information to avoid collisions with obstacles
Lin et al. (2008) [28]	4 (m) age: 21–25	*Vibrotactile* Rhythmic vibration patterns	Navigate to 2 targets on campus; several turns needed	Success rate	Perfect performance
Lim et al. (2015) [29]	3 (1f, 2m) mean age: 30	*Vibrotactile* Vi-Bros: vibration on smartphone + smartwatch	Navigate a 100-m-long route with 4 turns	Success rate, informal feedback	All participants reached their goal; interaction with this device was eyes-free; users preferred this device over visual map guidance on smartphone
Orso et al. (2016) [30]	24 (15f, 9m) mean age: 24	*Vibrotactile* Vibration on thumb, index or middle finger to indicate left, straight, right, respectively. Compared to torso	Navigate route with 8 turns in city center	Success rate, semi-structured interview	All participants were able to navigate the route without any errors; no difference in travel time between glove and vest; the glove was preferred because of its light weight
Dim & Ren (2017) [31]	15 (7f, 8m) age: 22–37	*Vibrotactile* Vibration on left or right ring finger to indicate turn; vibration at neck to indicate start/stop. Compared to ears, wrists and feet.	Follow 3 routes with several turns on campus	Error rate, subjective ratings	Found to be feasible for navigation; no difference in performance with feedback on ears or wrists, but better than on feet; preference for feedback on fingers, wrist or neck

For stimuli, a keyword characterizing the type of stimulation is given in italics. Only the major metrics are mentioned. f: female, m: male; age or age range (if available) are given in years.

used temporal patterns to indicate the direction or stimulated different parts of the hand. Unfortunately, the devices, methods and tasks in the various studies are too diverse to conclude which of the stimulation methods to indicate direction works best. Several of the devices also provided an indication of the distance. Interestingly, in many of the studies, participants had to cover a substantial distance (several hundreds of metres) and also the experiments in busy city centres were successful.

IV. WIZARD OF OZ DEVICES

While the devices in the previous sections allow for autonomous navigation, there are also various devices developed that were tested in a more preliminary phase of the design. These devices do not yet have a navigation system that can locate the user and determine the trajectory to the target, but they do have the possibility to give haptic navigation instructions to the user via a hand-held device. Instead of having such an advanced localization compoment, they opted for a ‘Wizard of Oz’ approach: one of the experimenters is watching the actions of the participant and sends at appropriate locations navigation signals to the device. While these tools are not ready for real-life applications, they can still give interesting insights into the functioning of vibrotactile navigation devices. Here, we do not distinguish indoor and outdoor devices as Wizard of Oz approaches can be chosen anywhere. An overview and a summary of the findings of these papers is given in Table III.

The TactGuide display, a flat smooth ellipsoidal shaped surface, designed by Sokoler et al. [27] features 4 small pegs that can raise to indicate direction relative to a reference dot. Each combination of a raised peg and the reference dot, both felt by the thumb, indicates one of four directions (forward, back, left, right). This device was tested by 7 participants in a treasure hunt game in an office building. Using the directional instructions given by the device, they had to find a number of cardboard boxes. This was easy to do as long as they also could use environmental information via their other senses to avoid collision with obstacles.

Lin et al. [28] created rhythmic vibration patterns to signal turn right, turn left or stop. Participants were asked to navigate a route on campus. By varying the *tempo* of the vibration patterns, they could also give an indication of distance, that is, whether users had to turn right away or after the next block. These patterns were presented to a device held in the users’ right hand. An experimenter played the role of Wizard of Oz by operating the device via an interface. The 4 participants had to reach 2 targets, one after the other, at different sides of the university campus, both targets requiring several turns. All 4 participants managed to do so.

Lim et al. [29] tested a combination of a smartwatch (on left arm) and a smartphone (in left hand) as navigation aid in a shopping centre. The three participants had to reach a goal at 100 m distance, which required 4 turns. At intersections either the smartphone or the smartwatch vibrated to indicate right or left, respectively. These instructions were given by an experimenter. The direction signal was preceded by a short alternating vibration to warn that a direction signal was coming. This so-called Vi-Bros interface was compared with map guidance on the smartphone. In both conditions, all participants reached their destination, but they preferred

Vi-Bros because it was intuitive and easier. Moreover, using Vi-Bros there was no need to look at either of their devices.

Orso et al. [30] tested a glove for navigating through the city center of Padua. Vibrations on the thumb, index finger or middle finger indicated turn left, go straight and turn right, respectively. The routes they had to navigate included 4 right turns and 4 left turns. Performance with this device was compared to that when wearing a tactile vest that gave similar instructions. The experimenter gave the instructions (i.e. vibrations) at fixed spots. All participants were able to follow the routes without making any errors and there was no difference in travel time between the two devices. The glove was the preferred device, probably because of its light weight. However, although the tactile vest was indeed more bulky, most of its components were not used in the current application making such a comparison a bit unfair.

The aim of the study by Dim & Ren [31] was to compare the suitability of different body parts for vibration feedback during walking. Here we report the results obtained with vibration motors attached via a glove on the two ring fingers and compare that with performance with vibration motors on wrists, ears or feet. An additional vibrator, used to indicate start or stop, was placed in the neck. Participants had to navigate 3 routes with several turns on the university campus. An experimenter with a remote control walked a short distance behind the participant. Performance in terms of errors and missed commands with feedback on the fingers, the wrists and the ears was similar and better than on the feet. There were no significant differences in subjective ratings for intuitiveness, perception and comfortability between the body parts, but participants preferred feedback on fingers and wrists.

A. Summary

In general, the Wizard of Oz devices were also rather successful in navigating participants through the environments, both indoors and outdoors. This indicates that the navigational instructions were perceived correctly, even during walking. Especially the three studies that took place outdoors [28], [30], [31], show that haptic instructions are quite suitable in environments where there is a lot of distracting visual or auditory information, such as in a city centre or on campus.

V. Discussion and Conclusion

The oldest papers we cite in this overview are from 2002 [27] and 2008 [3], [28], indicating that research into hand-held haptic navigation devices started relatively recently. For indoor devices this seems to be related to advances in sensor and actuator technology. For outdoor devices this will certainly be due to the reliable GPS tracking systems that nowadays are embedded in all modern smartphones. This will make such devices also cost-effective as the smartphone will often be the most expensive part of the navigation device and almost all potential users will already own such a smartphone. Most of the haptic navigation devices that were tested showed high success rates, even without excessive training. A major drawback for many of the devices was that walking speeds were significantly lower than normal walking speeds and path efficiency was much lower than 100%. Another concern is that GPS tracking systems work well in open spaces, but accuracy drops significantly in urban areas. This might not be a big issue for sighted users, but for users with severe visual impairments this will be detrimental.

A specifically mentioned application in some of the papers was to make sightseeing or walking with a friend more relaxed. By not having to attend to a map (a real one or one on a smartphone) and not having to listen to spoken instructions provides the opportunity to enjoy the environment more or to talk with a friend while walking. Devices that provide a direction angle are also valuable in this respect, as they provide the user with quite some freedom to choose their own route while still knowing that globally they are going in the right direction. A reduced path efficiency is not really an issue for such applications. Navigation solutions like these were appreciated by the users. An indoor application guiding users to artworks also worked quite well.

When comparing devices, it is important to take the metrics used in a study into account. Reaching a destination is important for determining success rate, but without mention of the number of errors, path efficiency or walking speed, comparison with other studies is tricky. Moreover, the intended uses of the devices were also quite different, such as 'efficiently reaching a destination' or 'enjoying the environment while walking'. Obviously, different metrics are applicable to determine the success of such different uses, so care should be taken when evaluating and comparing devices.

In general, the devices meant for outdoor use seem to be at a much further stage of development than most of the indoor devices. This has to do with the availability of GPS tracking that is only available outdoors. Indoors much more complicated systems had to be developed, either equipping the rooms with all kinds of sensors or having the participants wear a camera or some other positioning device, often in combination with a computer system. Moreover, these types of hardware are room specific and not suitable for large buildings with numerous rooms. In contrast, smartphones with a dedicated haptic navigation app will work outdoors without any additional apparatus. In conclusion, several outdoor devices seem quite close to being commercially attractive, while the indoor devices need further development.

This survey focusses on hand-held and hand-worn devices, but obviously these provide not the only solution as navigation aid for walking. Devices for head, back, belly, foot, wrist, arm, leg, shoulder, neck, thigh, waist and torso have also been proposed and tested, but these are mostly in an earlier state of development than the hand-held outdoor devices. Moreover, many of these other devices are often more bulky, because the sensitivity of other body parts is lower than that of the hand and fingers. Another disadvantage of devices for other body parts might be that these are harder to put on or off. And especially the devices for the head are probably too obtrusive to be appreciated by users. On the other hand, hands-free devices have the advantage that the hands can be used for other tasks (carrying a bag, holding a cane, etc.).

A. Devices possibly suitable for Users with Visual Impairments

Most of the studies described in this paper did not focus specifically on users with visual impairments, so only few B/VI users were among the participants. However, that does not necessarily mean that these devices are not suitable for such users. Of the outdoor studies, only [18] and [25] included B/VI users. The cane with vibrotactile or thermal feedback tested by [25] is a device that comes closest to a device B/VI users normally use. Participants needed only a short training period and after that they were able to follow the navigation instructions. Especially with the thermal instructions, performance was nearly perfect. A distinct advantage of such a device is that users do not need to hold an additional device in their other hand. This device seems almost ready to be introduced to the market.

In [18], B/VI users received navigation instructions via their hand-held phone. As performance was near perfect, this suggests that following vibrational instructions of a smartphone while walking with a cane is well possible for B/VI users. Of the three techniques tested, participants did not like the ‘Wand’ technique, which involved pointing their phone in different directions until a vibration indicated that they were pointing in the direction they had to go. As the devices proposed by [20], [23] use a similar technique, these devices seem less preferable for B/VI users. However, the other two techniques of [18], ‘ScreenEdge’ and ‘Pattern’, worked well and were appreciated. A characteristic feature of both techniques is that they provide relatively simple and explicit instructions like ‘turn right’, ‘turn left’, ‘go forward’ etc. This suggests that several of the devices discussed in this paper will be suitable for B/VI users as long as the instructions are straightforward. Devices providing a direction angle, such as in [15], [16], will not be suitable for this target group, because users are only given a choice of directions that possibly do not even contain an actual path.

As mentioned earlier, the accuracy of GPS tracking systems depends on the environment, with good accuracy in open spaces, but severely reduced accuracy in the neighborhood of high buildings. Inevitably, users with visual impairments will always need the support of a cane or guide dog in addition to their navigation device, not only to overcome such GPS inaccuracies, but also to avoid obstacles.

Indoor solutions were quite different from the outdoor devices. In [3]–[6], [12] users with visual impairments participated. Overall, participants reached their goal, but walking speeds were mostly quite low. However, such low speeds were also found in the other studies with blindfolded sighted participants. Probably, longer practice times will improve walking speeds. In [4], [5], the participants were positive about the device, but in [3] they preferred verbal instructions. In general, the use of the indoor devices is quite limited as the space in which they work is very small and mostly limited to one room or corridor. This is not only a limitation for B/VI users, but for all users.

Although several of the devices worked well for persons with visual impairments, haptic guidance may not always be the preferred solution for persons without auditory impairments. For such users, spoken instructions might be clearer and thus preferred, as was the outcome in [3]. Moreover, holding both a cane or a guide dog in one hand and a navigation device in the other hand seems far from ideal. A haptic navigation device that also detects obstacles could, in principle, take over the role of a cane and thus free one of the hands, but it would involve a camera or some other way to detect the obstacles, making the device much more complex. It would also require quite some training time as users will need to learn to use and especially trust such a new device.

B. Devices possibly suitable for Users with Deafblindness

None of the devices described in this paper were tested with participants with hearing impairments. However, there is no reason to expect that performance of participants with hearing impairments will be different from performance of sighted persons without hearing impairments. Obviously, this will be different for most persons with both hearing and visual impairments. For such persons, the same devices may be suitable as concluded above for B/VI users. An important difference is that for them spoken instructions almost never can be an alternative or additional option. Devices that provide explicit instructions seem most suitable. However, it is clear that more research is needed to be able to conclude that such devices indeed work, are acceptable and will be appreciated by users with deafblindness.

C. Concluding remarks

The high success rates of the experiments show that vibration motors are suitable for transferring directional feedback to the user. Especially for the indoor devices, the major issue for the haptic navigation feedback is the resulting slow walking speed. For most of the devices this is due to the user and not to the device taking too much time to provide instructions, so training might overcome this issue. This seems realistic as in general only very brief practice sessions (just a few minutes) were given to the participants, so it will be easy to improve on this issue. Another issue is the limited path efficiency, so that users travel a greater distance than strictly necessary. For sightseeing this needs not be a problem, but for reaching a destination, especially indoors, this is not desired.

Especially several of the outdoor devices seem (almost) ready for taking the final step towards commercial use. Also for users with visual impairments, haptic navigation devices could be of use, as long as the instructions are quite specific. For this group of users, it will be essential that the position information is correct, so that they are not guided off the path.

All devices were tested at least in a haptics-alone condition. However, in practice, devices combining haptic, visual and/or auditory feedback might be the preferred solution (at least for sighted and hearing users). The haptic feedback might then be used during walking, but if in doubt or when planning the route, a map of the area might be useful. Or if users prefer spoken instructions, they can use the haptic feedback in situations where spoken instructions would be obtrusive (for example, if too close to other people), or when such instructions become inaudible (for example, in a busy street).

With smartphones becoming more and more sophisticated, haptic navigation apps for outdoor use could become widely available in the near future.

While most of the studies show a high success rate and participants were mostly able to reach their destination, it should be noted that all these devices were tested only for a short period of time (less than an hour). Also, although in questionnaires participants were often positive about the navigation aid, it remains to be seen whether they would actually use such devices on a regular basis.

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