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Hands-free Haptic Navigation Devices for Actual Walking

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***Abstract*—In this survey, we give an overview of hands-free haptic devices specifically designed for navigation guidance while walking. We present and discuss the devices by body part, namely devices for the arm, foot and leg, back, belly and shoulders, waist and finally the head. Although the majority of the experimental tests were successful in terms of reaching the target while being guided by the device, the experimental requirements were wide-ranging. The distances to be covered ranged from just a few meters to more than a kilometer, and while some of the devices worked autonomously, others required the experimenter to act as Wizard of Oz. To compare the usefulness and potential of these devices, we created a table in which we rated several relevant aspects such as autonomy, conspicuity and compactness. Major conclusions are that outdoor devices have the highest technology readiness level, because these allow autonomous navigation through GPS, and that the most compact devices still require the action of an experimenter. Unfortunately, none of the hands-free devices are at a level of readiness where they could be useful to people with visual impairments. The most important factor that should be improved is localization accuracy, which should be high and available at all times.**

***Index Terms*—Navigation, hands-free, pedestrians, walking**

I. INTRODUCTION

An important part of daily life is going from one location to another. As long as these locations are familiar, there is no need for aids like a map or an assistive device, but as soon places are new or less familiar, some form of navigational guidance is useful. Nowadays, new cars have built-in navigation devices and pedestrians widely use smartphones for navigation, via maps, spoken instructions, or a combination of both. There are, however, situations, where visual or auditory input is not the best choice for feedback, for example, due to limited sight (firefighters in a building), attention needed elsewhere (crossing busy streets; sightseeing while talking to a friend), or impaired vision or hearing. In such situations, haptic guidance might be more appropriate. This holds also for situations where visual or auditory guidance might be perceived as too obtrusive.

Recently, we published a survey of hand-held navigation devices specifically designed for pedestrians [1]. However, haptic feedback is not limited to just hands, but it can and has been applied to various locations, such as hands, feet, head, back and belly. The hands are quite sentitive to haptic stimuli, but in some situations, hands-free solutions might be preferred because it feels more relaxed, is safer (not having to look on a smartphone while walking) or the hands are also needed for other tasks such as holding a shopping bag. In the case of persons with visual impairments, the hands might also be needed for holding a cane and/or a guide dog. The head is also quite sensitive, but for obvious reasons, clearly visible and conspicuous add-ons are usually not appreciated. The torso is relatively insensitive, but that is compensated for by having a large area and the opportunity to place the device in a vest or belt. It will be clear that all these body parts have advantages and disadvantages for the attachment of haptic devices. Therefore, in the current survey, we focus on hands-free devices.

We started our studies with collecting peer-reviewed papers, chapters and conference proceedings that on the basis of their title and/or keywords seemed relevant for haptic navigation while walking. Especially this latter requirement (‘while walking’) was important at this first stage, as this excluded all navigation devices meant for use in a car, aircraft or similar. Next, we checked whether the proposed devices were indeed tested in an environment, either indoors or outdoors, where participants had to use the device while actually walking. Of all papers that we had collected in this way, we checked the references and the papers that cited these studies. Finally, we made a distinction between ‘hand-held’ and ‘hands-free’ devices. Below we summarize all the inclusion requirements for the current study. These requirements were basically identical to those used in our previous study [1], except that we slightly changed requirement 4 (we reduced the minimal number of participants to two and we now explicitly required a clear description of the experiment, the results and the analysis) and we added requirement 8:

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

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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 two participants to avoid too preliminary studies. Exceptions could be made for extensive case studies (but this was not applicable to any of the studies). Moreover, we required a clear description of the experiment, the results and the analysis.
5) **Not just obstacle detection**
   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) **Hands-free**
   All devices had to be hands-free.
9) **No review papers**
   For all devices, we looked for the original source, so we do not include review papers.

In the following sections we present the haptic navigation devices by body part, namely devices for the arm (Section II, Table I), foot and leg (Section III, Table II), back, belly and shoulders (Section IV, Table III), waist (Section V, Table IV) and finally the head (Section VI, Table V). We will explicity mention whether visually impaired and/or blind users participated in the study and whether sighted partipants were blindfolded. In the Discussion section, we will compare the achievements obtained with the various devices by creating a table with some of the most important characteristics of the tested devices, namely autonomy of the device, covered distance in the experiment, compactness (size and weight), (in)conspicuity, and whether the device was tested with visually impaired, blind and/or blindfolded participants. We will discuss the suitability of the body parts tested and in this discussion, we will include the hand-held devices presented in [1]. We will also briefly discuss whether any of the devices are of potential use for persons with visual and/or auditory impairments. Finally, we will draw some general conclusions about the feasibility and the potential to use such devices outside the lab.

II. ARM

The Gentleguide created by Bosman et al. [2] consists of two wristbands with a vibration motor on each band and a receiver that picks up the navigation signals. Vibrations on the right or left wrist indicated turn right or left, respectively; vibrations on both wrists meant stop. 16 participants had to navigate 4 routes in a campus building, 2 with the GentleGuide and 2 while using available visual signage in the building. In the GentleGuide condition, participants could see the visual signage, but as they were not told their destination, this signage was not of use in performing the task. Using the GentleGuide, all participants reached their destination (a room on the same floor), but with signage one participant got lost. Only few errors were made: 1 with GentleGuide, 4 with signage. Walking speeds with the GentleGuide were only 8% lower than normal walking speeds, but with signage the reduction was 40%. Participants experienced the guidance of the GentleGuide as intuitive.

Marston et al. [3] asked their 8 blind participants to follow 80 m routes on campus while being guided via vibrations on their wrist. They compared two modes: vibrations indicated either that the participants were ‘on-course’ or that they were ‘off-course’. Participants were on course if their head direction was within a 20° angle of the intended direction. The on-course mode resulted in shorter mean times and shorter distances covered. However, the participants indicated a preference for the off-course mode as this mode seemed more natural. In comparison with auditory feedback, performance was similar.

Scheggi and colleagues [4] provided their 10 blind participants with vibrotactile bracelets on each arm. Vibration of the right (left) bracelet indicated that they had to turn right (left). The location of the participant was determined via a pair of camera glasses streaming to a remote experimenter. Participants had to walk 3 different routes with 2 or 3 turns in a building. In all trials the target destination was reached in what the authors considered an acceptable time. Comfort and informativeness of the guidance were rated 6 or higher on a scale of 1 to 7.

Aggravi et al. [5] developed haptic navigation bracelets for both arms with two vibration motors in each bracelet. Location of the user was determined via 8 passive retroreflective markers on the torso which were tracked by an optical tracking system. 7 participants had to walk twice along 5 different predefined paths in a room in 4 different conditions: either with sight or blindfolded and either with or without a predictive

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TABLE I
ARM

Reference	Participants	Localization	Stimuli	Task	Metrics	Outcome
Bosman et al. (2003) [2]	(7f, 9m)	By experimenter	1 vibration motor on each wrist	Follow route; comparison of signage vs haptic signals	Number of errors, relative walking speed	Feasible for navigation; easy to interpret turn instructions; almost normal walking speeds; just 1 error
Marston et al. (2007) [3]	B: 25–85 (8)	GPS	Vibration indicating on- or off-course	Follow routes of 80 m with 6 turns	Mean time, mean distance, questionnaire	Feasible for navigation; shorter times and distances with on-course mode; preference for off-course
Scheggi et al. (2014) [4]	B: 26–65 (4f, 6m)	Remote experimenter	2 vibration motors in bracelets on each arm	Follow route with 2 or 3 turns in building	Success rate, travel time, Likert scale	Feasible for navigation; 100% of targets reached; comfort: 6.3/7; informativeness: 6/7
Aggravi et al. 2015 [5]	19–65 (2f, 5m)	Vicon motion capture system	2 vibration motors in bracelets on each arm	Follow 5 paths of about 7–10 m in a room with/without blindfold or prediction	Mean distance error, mean haptic activation	Feasible for navigation; average distance error 0.24 m; no improvement for distance error but less haptic activation with predictive approach
Dobbelstein et al. (2016) [6]	16–55 (4f, 12m)	GPS	4 vibration motors around wrist	Navigate to target 450 m away via free route	Mental load, path length	All participants reached target, mostly via shortest route; mental load rate slightly lower than in angle detection task
Dim & Ren (2017) [7]	22–37 (7f, 8m)	By experimenter	1 vibration motor on each wrist	Follow a route with 18 turns on campus	Errors, missed commands, Likert scale	1.2% errors; 2% missed commands; preferred over vibrations on ears or feet
Strasnick et al. (2017) [8]	18–26 (4f, 6m)	Presumably by experimenter	6 DC motors with foam brushes or 6 vibration motors, spaced evenly around wristband	Walk 20 times to central position and then to 1 of 8 directions	Mean direction accuracy, Likert scale	Feasible for navigation; brushing and vibrotactile feedback equivalent in performance; vibrotactile feedback more comfortable than brushing
Lisini Baldi et al. (2018) [9]	23–49 (6f, 12m)	Vicon motion capture system	2 vibration motors in bracelets on each arm	Walk 6 times to target in 4×4 m room and avoid obstacles with/without vision	Time, travelled distance, minimal distance from agents	Faster, shorter travelled distance and smaller distance to agents with vision
Rector et al. (2018) [10]	8B, 6VI 24–72 (7f, 7m)	By experimenter	2 vibrating watches	Walk along straight (100 m) or curved (123 m) lane	Time, % time in lane, preference	Feasible for navigation but preference for and better performance with human guidance
Von Jan et al. (2018) [11]	22–29 (5f, 20m)	GPS	4 vibration motors around wrist	Follow two routes of about 675 m in push or pull mode	Walking speed, questionnaire	All participants always reached target; walking speeds not different between modes; pull mode ratings higher for 'in control' and 'more autonomous'; both modes reliable
Barontini et al. (2021) [12]	26 (4f, 6m) B: 51 (3f, 3m)	RGB-D camera on chest, processing unit on back	2 DC motors in band on upper arm; can tighten, loosen and provide (anti)clockwise or tangential force	Follow a 90–110 m path and avoid obstacles without seeing	Time to perform task, number of collisions, Likert scale	Feasible for navigation; easy and comfortable to use; valuable as supplement to white cane, not a replacement

Participants: Mean age or age range (if available) is given in years. f: female, m: male, VI: visually impaired, B: blind. Only the major metrics are mentioned.

approach. Feedback based on actual information necessarily involves a time delay, which the researchers attempted to overcome with their predictive approach. Vibrations in the right (left) bracelet indicated that the user had to turn to the right (left). The mean distance error was 0.24 m, which did not depend on condition. However, haptic activation (i.e. feedback via the bracelets) was less during the predictive approach. The authors seem to find this latter finding a negative result, but to us, obtaining similar errors with less feedback seems a positive result.

Dobbelstein et al. [6] created a wrist device with 4 equally spaced vibration motors. Instead of steering the user via a fixed route, the device only indicated the direction of the target. Simultaneous vibrations of the two top motors indicated that the target was within a 60° angle in front of the user. If only one of the motors was vibrating, the user had to change direction, even more so if a back motor was vibrating. The device was tested in a city, where participants had to find a target at 450 m from the start, which could be reached via various routes. All 16 participants reached the target without any problems and mostly via the shortest route. The mental load was experienced as slightly lower than in an angle detection task that was performed in the lab.

The aim of Dim and Ren [7] was to compare the suitability of several body parts to be used for wearable vibrational devices for navigation while walking. After two lab experiments, they selected the most promising ones for an actual walking experiment on the university campus. In all these devices, vibration on the right/left body part indicated turn right/left. For the arm they used watch-like devices, one on each arm. Their 15 participants had to walk 3 routes on campus with 18 turns (for each tested body part). The actual distance is not mentioned in this paper, but as the experimenter with a remote control walked at a distance of about 5 m behind the participants, each route will probably have been at least 200 m. With this wrist device, 2% of the instructions were missed and 1.2% of the instructions resulted in an error. This was significantly less than with the vibration motors placed on the foot, but similar to motors placed on the ears. Compared to feet and ears, participants preferred a device on the wrist.

Strasnick et al. [8] compared two haptic devices for navigation. The 'BrushTouch' consists of six cylindrical DC rotational motors equally spaced about a wristband. A soft piece of foam is attached to the shaft of each motor. Rotation of a motor results in a brushing of the foam against the skin. The 6 individual motors conveyed the following directions: N, NE, NW, S, SE, and SW. East (E) and West (E) were indicated by the vibration of 2 adjacent motors on the right and left sides of the wrist, respectively. The second device consisted of a wristband with 6 cylindrical vibration motors in the same configuration and with the same coding of directions as used in the 'BrushTouch'. 10 participants had to perform 20 trials with each device. They had to walk to a central location and then were cued in which of 8 directions they had to turn. With the devices accuracies of 83.5% (BrushTouch) and 84.5% (vibration device) correct direction recognition was obtained. The conclusion was that both devices are suitable for navigation. However, comfort of the BrushTouch was rated significantly lower than that of the vibration device.

Lisini Baldi et al. [9] continued the research of [4], [5]. Again, they used bracelets on each forearm, both with 2 vibration motors. Their 18 participants had to walk to a target area in a 4×4 m room in three conditions, once while blindfolded and once with normal vision. The three conditions differed in the type of agent that had to be avoided: another person, two other persons, or an obstacle and a person. All participants reached the target area, but in all conditions, performance with vision was faster than without vision, and travelled distance and distance to agents were shorter.

Rector et al. [10] tested various ways to guide blind or visually impaired participants along a straight (100 m) or curved (123 m) part of a track. The haptic condition consisted of vibrating watches on both their wrists. Vibrations on their right (left) wrist indicated that they were veering too much to the right (left). The haptic condition was compared to direct human guidance, verbal instructions, and beats in the ears. Human guidance yielded best performance (time taken, percentage of time in lane), while beats in the ears yielded worse performance. The order of preference was human guidance, verbal instructions, vibrations and beats in the ear, but guidance was possible in all conditions.

Like in several other studies, Von Jan et al. [11] created a device with four vibration motors around the wrist, indicating forward, backward, right and left. Two neighbouring motors vibrating simultaneously indicated a direction in between. The device was tested in two modes. In push mode, the participant received directions at times determined by the device; in pull mode, they had to lift their left forearm in order to receive directions. Participants had to walk along two different routes of about 675 m in either pull or push mode. In both modes, all participants reached the target and walking speeds were the same. Participants liked that they were in control in the pull mode, but indicated that both modes felt reliable.

Barontini et al. [12] created a haptic CUFF device, consisting of two DC motors attached to a band worn around the upper arm. The motors could apply a normal force by spinning in opposite directions and a tangential force by spinning in the same direction. With these motors they were able to give the instructions 'Start', 'Stop', 'Right' and 'Left'. Location of the user was determined via an RGB-D camera on the chest and a processing unit (a light laptop) on the back. The CUFF was first tested with one blind participant who had to navigate a 90 m-long corridor with several turns. She managed to reach the goal without problems and found the CUFF easy to use. The CUFF was then tested with 6 other blind participants who had to perform several short distance (7–11 m) walking tasks in a corridor, such as turn left, and pass through a door. 3 participants normally using a cane were tested in CUFF + Cane, and Cane only conditions; the other 3 were tested in a CUFF only condition. All participants were able to perform all tasks, but they were much slower in the conditions with the CUFF. Only few errors and collisions occured, indicating that the device was easy to use.

III. FOOT AND LEG

Velázquez et al. [13] implemented a 4×4 array of vibration motors in a shoe sole. Directions were indicated by whole rows moving forward (north) or backward (south), or columns moving to the right (east) or to the left (west). However, it seems more likely that the actual meanings of the patterns were forward, backward, right and left, respectively. Five blindfolded participants had to walk about 5 m around some chairs in a lab space and a blind participant had to walk a similar distance on a sidewalk around a lamppost. All blindfolded participants finished the route in less than 4 minutes, which seems quite long for such a short distance. Only two of the blindfolded participants made a few errors, the other three made no errors; the blind participant was much faster and also made no errors.

Velázquez et al. [14] tested a similar device with two blind participants in an outdoor space. With this device, the

TABLE II
FOOT AND LEG

Reference	Participants	Localization	Stimuli	Task	Metrics	Outcome
Velázquez et al. (2012) [13]	18–24 (5m) VI: (1m)	By experimenter	4×4 grid of vibration motors in shoe sole	Navigate a route of about 5 m	Time, number of errors	All participants finished $<$ 4 min.; only few errors; VI participant much faster and without errors
Velázquez et al. (2018) [14]	B: 31, 35 (2m)	GPS	4 vibration motors in shoe sole	Navigate outdoor routes of 380 and 420 m	Time, path efficiency; informal feedback	Path efficiencies $>$92%; feasible for navigation; intuitive; low cognitive demand; normal walking speeds
Schirmer et al. (2015) [15]	23 (8f, 13m)	GPS	2 vibration motors on ankle used in 2 modes	Navigate 2 routes of 700 m	Time, number of errors, questionnaire	Faster and fewer errors with Navigator mode; strong preference for Navigator mode
Bertel et al. (2017) [16]	24 (11f, 17m)	GPS	2 vibration motors on ankle	Navigate routes of 1.4 km	Time	Feasible for navigation; walking speed lower than with using TomTom Go on a smartphone
Dim & Ren (2017) [7]	22–37 (7f, 8m)	By experimenter	1 vibration motor on top of each foot	Follow a route with 18 turns on campus	Errors, missed commands, Likert scale	3.2% errors; 4% missed commands; less intuitive than devices on other body parts
Petrausch et al. (2018) [17]	(10)	By experimenter	3 vibration motors around ankle; signals left and right; all motors on warns for object	Navigate routes of 300 m while running	Completion time, number of errors, informal questions	Time taken similar to verbal instructions; more errors with device; intuitive guidance
Liao et al. (2020) [18]	(15)	Motion capture system	6 vibration motors around lower leg indicating direction	Navigate 12 times to target at 3 m distance	Success rate, motion efficiency, walking speed	Success rate $\geq$ 91%; motion efficiency $\geq$ 75% except for the swing condition; walking speed around 0.55 m/s
Liao et al. (2021) [19]	27 (8)	Drone with camera, PC	6 vibration motors around lower leg indicating direction	Navigate 8 times (4 conditions) to target at 16 m distance	Time in lane, moving speed	93% time in lane in constant feedback condition; no differences in moving speed
Pfeiffer et al. (2015) [20]	25 (4m)	By experimenter	Actuation signal is sent directly to human motor system (upper leg) to influence walking direction	Navigate 2 routes of 552 and 991 m	Questionnaire	Feasible for navigation; even ground worked better than bumpy ground

Participants: Mean age or age range (if available) is given in years. f: female, m: male, VI: visually impaired. Only the major metrics are mentioned.

directions were given by four vibration motors in a shoe sole: one located near the toe (forward), one near the heel (backward), one on the left and one on the right side. The participants had to navigate two routes of 380 and 420 m including street crossings. The haptic device only provided stimulation when needed. It took both participants about 6 to 7 minutes per route. Path efficiencies, i.e. the ratio between actual and optimal lengths, were higher than 92%. The two participants found the device intuitive and demanding just a low cognitive load.

Schirmer et al. [15] tested a simple device with two vibration motors, one on either side of the ankle. They tested the device in two modes. In Navigator mode, target right and target left were indicated with the right and left motors, respectively. If the target was behind them, both motors vibrated with a high frequency. No stimulation indicated that they were heading towards their target. Compass mode worked only when users were standing still. Then vibrations indicated that the user had to rotate; when the vibrations stopped, the user was facing the right direction. Participants had to follow two routes, using each of the modes once. The time needed for completing a route was much shorter when using the Navigator mode and the users also made fewer errors. Moreover, the users had a clear preference for the Navigator mode.

Bertel et al. (2017) [16] made a device similar to the one created by [15] and tested that in Navigator mode. They did not implement the signal for a target behind the user; in such cases, the user was corrected by an experimenter. They compared use of this device to that of using TomTom Go on a smartphone. As gaze-direction was important for the analysis of the supplementary task, participants had to put on a mobile eye tracker (SMI Glasses 2.0 with sun filter shields and recording laptop). Participants had to follow a 1.4 km route in an urban environment. Their main finding of relevance here is that all participants reached the destination and thus is such a haptic device feasible for navigation. On average, the time

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taken was slightly longer with the haptic device than with the visual map.

Dim & Ren [7] not only tested a wrist device (see above), but also the feet were tested as suitable body parts for receiving navigational instructions. A vibration motor was placed on the top of each foot. Vibration of the left motor indicated turn left and likewise, vibration on the right meant turn right. Also with this device, 15 participants had to walk on campus via 3 routes with 18 turns each. 4% of the instructions were missed and the percentage of errors was 3.2%. This performance was significantly worse than with the wrist or ear devices and participants found this way of navigating less intuitive.

Petrausch et al. [17] created a simple device with three vibration motors to be worn around the ankle. Vibration of the right (left) motor indicated a right (left) turn. This was preceded by a warning signal at the same side. All three motors vibrating simultaneously indicated an object warning. The four participants had to run a 300 m long route with several junctions. Performance with the device was compared to guidance via spoken instructions. There were no significant differences in route completion times between the two methods of guidance. More errors were made with the device, but participants liked the intuitive navigation instructions from the device.

Liao et al. [18] created a device with 6 vibration motors around the lower leg. By manipulating the intensity of neighbouring motors, they could indicate directions in steps of 15°. 15 participants had to walk 12 times to a virtual target at a 3 m distance. Direction information could either be given continuously, only during stance, or only during swing states. Performance was compared to looking at a tablet with an arrow showing the direction. In almost all trials, participants reached the target. Walking speeds were much lower than normal walking speeds, but this was probably due to the small distance used in the experiment. Motion efficiency was significantly lower in the swing condition.

The same authors did a follow-up experiment outdoors on a parking place [19]. Using the same device 8 blindfolded users had to navigate a distance of 16 m while staying within a 1.2 m-wide track. Again the three conditions of the previous study were tested and in addition they tested a no feedback condition. Performance was significantly better in the continuous feedback condition than in the other three conditions, as users were able to stay 93% of the time in lane, as compared to 61, 77 and 79% in the other conditions. Effective moving speeds (16 m divided by total time) did not differ and were somewhat slower than normal walking speeds.

Pfeiffer et al. [20] tested a new way of actuated navigation. By direct electrical stimulation of the sartorius muscle in the upper leg, the system could influence the navigation direction. This influence could easily be counteracted and therefore the user remained in control. Four participants had to navigate two routes of 552 and 991 m, respectively. An experimenter walking behind the participant activated the actuation at turning points. Participants experienced this type of steering as positive, were able to walk relaxed and were even able to attend to, for example, a smartphone. Guidance worked better while walking on even ground than on bumpy ground.

IV. BACK, BELLY AND SHOULDERS

Ertan et al. [21] used a 4×4 array of vibration motors on the back. To indicate the cardinal directions, rows or columns of motors were successively turned on in the direction the user should move. Participants had to follow 4 short paths of 15 to 22 m. Only few errors were made, but the average time to complete a path was 90 s, which seems quite long.

Ross and Blasch [22] tested a shoulder tapping device to help visually impaired participants crossing the street. A central tapper between the shoulders produced a double tap if participants were on target. If they were slightly veering to the right (left), the right (left) tapper tapped in combination with the central tapper. If the veering were more substantial, only the right or left tapper tapped. Feedback could be head or body oriented. Performance with this device was compared to speech or sound instructions, and to a baseline with no device. The device resulting in the best performance was quite participant-dependent. Using their best device, veering and the number of hesitations were reduced significantly. However, over all conditions, the body-centered shoulder tapping device performed best, both in terms of participant preferences and in actual performance.

Jones et al. [23] tested a 4×4 grid of vibration motors placed on the lower back. Their 5 participants had to follow a path on a 3×3 grid of cones on a field. The cones were placed 5.5 m apart. The navigational instructions were ‘right’, ‘left’, ‘forward’, ‘turn around’ or ‘stop’. Three additional vibration patterns signaled ‘arm horizontal’, ‘arm vertical’ or ‘hop’. Of the 40 patterns that each participant had to recognize, only 1 error was made. The authors conclude that the tactile instructions could be followed while walking, but that it is too early to conclude that this guidance would also be suitable in a more challenging environment.

Prasad et al. [24] created a vest with 6 vibration motors, one on each shoulder for signaling right and left, two below these on the shoulder for signaling forward, and two on the chest for alerting the user for objects. Participants had to navigate routes of about 120 m, once with the vest and once while using the PocketNavigator [29], an app on a smartphone that indicates navigation directions via vibrations. While walking, the participants had to attend to the Gyro game on their phone with the instruction to try to achieve a high score. The vest was found to be feasible for navigation. The cognitive load seems somewhat lower than with the PocketNavigator but completion times were not different.

Orso et al. [25] tested a vest for navigating through the city center of Padua. The vest contained 29 vibration motors, but only one on each shoulder and a set on the abdomen were used in the current experiment. Stimulation on the right (left) shoulder indicated turn right (left), stimulation on the abdomen meant straight. Navigation performance was compared to that using a glove. The routes participants had to navigate (once with each device) included 4 right turns and 4 left turns. 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,

TABLE III
BACK, BELLY AND SHOULDERS

Reference	Participants	Localization	Stimuli	Task	Metrics	Outcome
Ertan et al. (1998) [21]	19–30 (12)	Infrared system	4×4 array of vibration motors on the back	Follow 4 routes of 15 to 22 m	Time, number of errors	Feasible for navigation; each path took about 90 s to navigate, 0–3 errors for each subject and path
Ross & Blasch (2000) [22]	VI: 62–80 (15)	GPS	3 'contact' speakers on shoulders	Street crossing	Veering, preference	Feasible for navigation; less veering; preferred over speech or beats
Jones et al. (2006) [23]	22–26 (2f, 3m)	By experimenter	4×4 grid of vibration motors on lower back	Follow path of 110 m; perform movements	Number of errors	Feasible for navigation
Prasad et al. (2014) [24]	20–30 (12)	GPS	2 vibrations motors on each shoulder, and 2 on chest	Follow 120 m long route	Time, questionnaire	Feasible for navigation; lower cognitive load than via vibrations on hand-held phone
Orso et al. (2016) [25]	24 (15f, 9m)	By experimenter	Vibration motors on shoulders and abdomen	Navigate route with 8 turns in city center	Success rate, travel time, semi-structured interview	No navigation errors made; no difference in travel time between vest and glove; preference for glove because of its light weight
Lobo et al. (2017, 2018) [26], [27]	[26]: VI: 54 (6) [27]: 28 (7)	Motion capture system	24×3 grid of vibration motors on abdomen; intensity denotes distance, column denotes direction	Walk twice to 6 targets at distances of 3, 4, and 5 m	Spatial error, trial duration, success rate	Targets almost always reached; walking speeds lower than normal walking speeds; oscillatory movements to pick up information
Stratmann et al. (2018) [28]	26–37 (3f, 9m)	By experimenter	Pneumatic airbags or vibrations motors on each shoulder	Follow route within 4 m^2	Error rate, questionnaire	Feasible for navigation; pneumatic and vibration systems found equally usable; vibration rated as more "urgent"

Participants: Mean age or age range (if available) is given in years. f: female, m: male, VI: visually impaired. Only the major metrics are mentioned.

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.

Lobo et al. [26], [27] created a device for the abdomen with 72 vibration motors (3 rows of 24 motors each). With this device, they spanned an angle of 60° in steps of 2.5°. Direction information was given by activating the appropriate column and distance was indicated by intensity (higher intensity when closer to target). Participants had to walk twice to virtual targets at distances of 3, 4, and 5 m. In [26] they tested 6 blind participants, in [27] 7 blindfolded sighted participants. All participants reached the targets in almost all trials. Mean spatial error was 68 cm in [26] and 37 cm in [27]. Mean time to reach the target was 34 s in [26] and 30 s in [27]. The authors warned that comparing performances of the two groups of participants is not really fair as there were significant differences in age and mobility. The authors observed that most participants made oscillatory movements with their torso to pick up direction information.

Stratmann et al. [28] compared two methods giving navigational instructions on the shoulder: pneumatic airbags and vibration motors. Vibration or pressure on the right (left) shoulder indicated turn right (left). Stimulation on both shoulders meant forward. Participants had to follow a short route on a 4 m^2 square field. Performance with both methods was better than 97% correct. The usabilty of the shoulder tap was rated higher than the vibration, but perceived urgency was higher with vibration.

V. WAIST

Tsukada and Yasumura [30] investigated navigation performance while participants used their ActiveBelt. This belt contained 8 equally spaced vibration motors that indicated the required direction. Users were tested during 15 minutes in both a static and a dynamic condition with 4 different vibration intervals. Overall performance in the static condition was almost perfect, with only one participant being hesitant about the non-cardinal directions. In the walking condition, performance depended on the pulse interval; for intervals of 250 and 500 ms participants mostly failed, but for intervals of 1000 and 1680 ms, all participants walked a few more steps, stopped, and then turned to the direction of vibration.

Van Veen et al. [31] created a belt with 8 equally spaced vibration motors that indicated direction to the next waypoint. Vibration duration was always 1 s, but the pause duration between subsequent vibrations depended on condition. In 4 of the 5 conditions, the pause duration depended on the relative or absolute distance to the next waypoints. 10 participants had to navigate 10 routes of about 375 m, two routes for each condition. All participants completed all routes without problems and with normal walking speeds. There were no sig-

TABLE IV
WAIST

Reference	Participants	Localization	Stimuli	Task	Metrics	Outcome
Tsukada & Yasumura (2004) [30]	21–30 (6)	By experimenter	8 vibration motors equally spaced around belt	Navigate path during 7 minutes	Observations, interview	Feasible for navigation, but depends on pulse interval
Van Veen et al. (2004) [31], Van Erp et al. (2005) [32]	18–24 (6f, 6m)	GPS	8 vibration motors equally spaced around belt; 5 vibration conditions	Navigate 10 pre-defined routes of 360 to 390 m	Effective speed, success rate	No problems with completing routes; no performance difference between conditions; normal walking speeds
Heuten et al. (2008) [33]	24–40 (3f, 4m)	GPS	6 vibration motors equally spaced around belt	Follow paths of 375 and 430 m	Deviation, travel time, questionnaire	Feasible for navigation; walking speed slightly slower than normal; intuitive to use
Grierson et al. (2009) [34]	30 (60f, 3m), 67 (4f, 5m)	By experimenter	4 vibration motors equally spaced around belt	Navigate 4 routes of 150 m and 4 routes of 300 m	Number of errors, travel time, questionnaire	No nagivation errors made; older participants walk slower than younger ones; participants felt confident and found the belt useful
Pielot & Boll (2010) [35]	20–30 (7f, 7m)	GPS	12 vibration motors equally spaced around belt	Follow a route of 800 m	Errors, travel time, workload, spatial knowledge acquisition	Compared to TomTom: similar workload, similar travel time, similar spatial knowledge acquisition, fewer collisions, more errors, more often disorientation
Elliott et al. (2010) [36]	Exp 1: 19–35 (15m) Exp 2: (18m)	GPS	8 vibration motors equally spaced around belt	Exp 1: follow route of 1800 m; Exp 2: follow route of 1800 m at night	Deviation, travel time, response time	Exp 1: all waypoints reached; faster than with HCS; larger deviations, because easier to avoid obstacles; Exp 2: faster than with PLGR and LW; more targets detected than with LW; overall higher evaluation ratings
Calvo et al. (2013) [37]	(12)	GPS	8 vibration motors equally spaced around belt	Follow a route of 1020 m along 15 waypoints	Success rate, errors, travel time	All participants were successful; travel time and number of errors were not different from visual or auditory conditions
Srikulwong & O'Neill (2013) [38]	29 (13f, 11m)	GPS	8 vibration motors equally spaced around waist	Follow pre-defined route of 1.3 km through streets	Time, walking speed, errors	Shorter time and faster speed with belt than with visual map; no differences in number of errors
Flores et al. (2015) [39]	B: 18+ (10)	3 Hokuyo laser rangefinders	8 vibration motors, equally spaced around belt	Follow 6 paths of about 13 m twice	Path efficiency, travel time, average speed	Compared to audio instructions: slower speed, closer to ideal path, lower path efficiency, preferred
Dura-Gil et al. (2017) [40]	34 (2f, 2m) B: (1f, 3m)	By experimenter	8 vibration motors equally spaced around belt (3 on back not used); 3 vibration patterns	Follow 6 times a path of 40 m	Deviation, questionnaire	No difference between blind and sighted participants; guidance provided was experienced as normal to well
Gkonos et al. (2017) [41]	27 (2f, 8m)	By experimenter	8 vibration motors equally spaced around belt	Follow route partly indoors, partly outdoors	Success rate, travel time, errors	Feasible for navigation; more errors and slower than with map; faster than when combined with chest vibrations
Jimenez & Jimenez (2017) [42]	23 (4f, 18m)	By experimenter	4 vibration motors, 1 high, 1 low on midline, 1 right, 1 left of midline	Follow path in lab	Errors, time	More errors and longer time than with audio guidance; faster after training with audio guidance
Korn et al. (2020) [43]	23 (14f, 11m)	By experimenter	6 vibration motors equally spaced around belt	Follow 2 routes of 23 m, with or without checkpoints	Time, questionnaire	Without checkpoints: faster, and higher ratings for confidence, level of control, transparency, guidance and future potential
Kayhan & Samur (2022) [44]	27–42 (1f, 2m) VI: (1m)	RGB-D camera, microcontroller on belt	2 skin stretch devices on belt	Run 400 m on standard athletic running track	Time, warnings, lane violations	Reduced numbers of lane violations and directional warnings compared to verbal instructions; VI user slower

Participants: Mean age or age range (if available) is given in years. f: female, m: male, B: blind, VI: visually impaired. Only the major metrics are mentioned. HCS: handheld compass system; PLGR: alphanumeric handheld GPS system; LW: helmet-mounted Land Warrior visual system.

nificant differences in effective speed between the conditions. The same experiment was also published in [32].

Heuten et al. [33] created a belt, termed Tactile Wayfinder, with 6 equally spaced vibration motors placed at ±30°, ±90° and ±150°. Navigation directions were indicated with either one motor, if the required direction was in the direction of one of the motors, or by the weighted strengths of two neighboring motors, if the direction was in between. Participants had to walk along 2 routes of 375 m and 430 m with several turns or curves. Apart from technical problems one of the participants experienced, all participants were able to follow the routes at slightly slower walking speeds than normal. Travelled distance was often shorter than the total distance between waypoints, but that was because participants were already guided towards the next waypoint if they were less than 15 m removed from a waypoint. Participants found the instructions of the belt intuitive.

Pielot & Boll (2010) [35] tested a follow-up version of the Tactile Wayfinder in the crowded city center of Oldenburg and compared this to using a TomTom device. This newer belt consisted of 12 vibration motors that could indicate direction. By using different vibration rhythms, they gave information about both the waypoint they were heading to and the direction of the subsequent waypoint. The participants had to follow 800 m long routes with both devices. To measure spatial knowledge acquisition after arriving at the end point, participants were shown photos of decision points and they had to recall in which direction they had to go on this point. They also had to draw their route from start to end. There were no significant differences in spatial knowledge acquisition between the two devices and also perceived workload and navigation time were the same. With the Tactile Wayfinder there were fewer near-collisions with other pedestrians, but more navigational errors were made and average disorientation time was longer. Due to these latter findings, the authors conclude that replacing a conventional navigation system by just tactile cues might not be the best idea.

Grierson et al. [34] used a belt with vibration motors at the 4 cardinal directions. Older and younger participants had to walk 4 150 m long routes with 3 decision points and 4 300 m long routes with 6 decision points along corridors. No directional errors were made. Older participants had a slower pace than younger participants. All participants found the belt useful for navigation and they felt more confident navigating with the belt than without.

Elliott et al. [36] tested their Personal Tactile Navigator (PTN) in three quite challenging experiments. The PTN consisted of a belt with 8 vibration motors indicating direction and whether the user was within a distance of 50 m from a waypoint. In all 3 experiments, the participants were soldiers. In experiment 1, performance with the PTN was compared to using a traditional handheld compass system (HCS) and an alphanumeric handheld GPS system (PLGR). The 15 participants had to navigate 3 routes of 1800 m consisting of legs of 600 m using each device once. To increase workload during their walking, participants had to respond as quickly as possible to questions compiled from the US Army Board study guide. With the PTN all waypoints were reached, whereas this was 95% and 86% for PGLR and HCS, respectively. They were faster with PTN and PLGR than with HCS. Deviations from the route were larger with the PTN. Participants explained that with the PTN is was easier to traverse around obstacles and still complete the route fast. The participants rated the PTN as very positive. In experiment 2, the PTN was compared to PLGR and a helmet-mounted Land Warrior visual system (LW). This latter device was also hands-free, but in front of one eye a display showing a map and targets was placed. New participants had again to navigate 3 routes of 1800 consisting of legs of 600 m using each device once and with different secondary visual tasks. The experiment took place at night in excessive fog and rain conditions. When using the PTN, participants were faster than with the other two devices and they detected more targets (in secondary task) than with LW. Overall, the PTN obtained highest evaluation ratings for most of the aspects tested. The authors conclude that their PTN is suitable for use in challenging circumstances and can even outperform visual displays.

Calvo et al. [37] tested a belt with 8 equally distributed vibration motors indicating the required heading direction. They compared performance to that using a map on a phone or 3D audio information via headphones. With each type of guidance, participants had to walk along a route of about 1 km with 15 waypoints on a university campus. All 12 participants managed to follow the routes with all 3 devices and there were no differences in the number of errors made or the travel time. The authors conclude that it will be justified to further develop multimodal navigation devices.

The TactNav device created by Srikulwong and Neill [38] consisted of a belt with 8 vibration motors, each indicating a logical direction. Participants had to navigate a 1.3 km route with 18 turning points. Performance was compared with that when using a visual map on a smartphone. Accuracy did not differ between conditions, but completion time was shorter and walking speeds were higher with the TactNav.

Flores et al. [39] created a belt with 8 vibration motors indicating directions. By activating and deactivating neighboring motors, participants were informed that they had to rotate. The belt was tested with 10 blind participants in a large lab space. The participants had to walk along 6 different paths, twice with the belt and twice with audio instructions. Path efficiency was higher and walking speed slower with audio instructions, but participants deviated less from the ideal path while using the belt. Participants were positive about the use of the belt, and more so than with the audio instructions.

Dura-Gil et al. [40] also tested a belt with 8 equally spaced vibration motors, but in the navigation test the three motors on the back side were not used. Blind and sighted participants had to walk 6 times 40 m along an athletic track guided by 3 different vibration patterns. There were no track deviation differences between the blind and sighted participants, nor between the results using the different patterns. Most participants indicated that they were guided normally or even well by the belt.

Gkonos et al. [41] compared navigation performance with a belt with 8 vibration motors indicating directions to 3 other types of guidance: use of a map, GazeNav, i.e. vibrotactile

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stimulation on the chest if a participant was looking in the correct direction, and VibroGaze, i.e. a combination of the belt and GazeNav. Each type of guidance was tested with 10 participants, who had to follow a route, partly inside a building and partly outside, which took about 6 to 8 minutes. All participants managed to successfully follow the route in all conditions. With the belt they were slower than with using the map, but faster than with VibroGaze; they also made more errors than with the map. The authors think that the worse performance with VibroGaze can be explained by the overwhelming effect of the stimulations (on chest and via belt).

Jimenez & Jimenez [42] tested a belt with 4 vibration motors: 1 on superior midline indicating 'stop', 1 on inferior midline indicating 'forward', and 1 each right and left of inferior midline indicating right and left, respectively. Performance in following a path in a lab space of 4 m by 6 m was compared to performance with audio guidance. With the belt, more errors were made and completion time was longer. However, interestingly, performance with the belt improved after a session with audio guidance.

Korn et al. [43] created a belt with 6 vibration motors. Directions were indicated with one motor or with two neighboring motors if a direction was in between. A checkpoint on the correct route was indicated by all motors vibrating together. Blindfolded participants had to follow a route of 23 m with 4 turning point and either or not 5 checkpoints. Contrary to the hypothesis of the authors, the participants were much slower on the route with checkpoints. Also confidence, level of control, transparency, guidance and future potential were all rated higher on the route without checkpoints.

Kayhan & Samur [44] tested a belt with a skin stretch device on each side. Their 3 blindfolded sighted and 1 visually impaired participants had to run on a standard athletic running track over a distance of 400 m while keeping their lane. When the lane curved right, both devices rotated counterclockwise, so that the skin on the left side was stretched forward and the skin on the right side backward, and vice versa. Performance with the belt was compared to that of 2 of the participants (1 blindfolded sighted and the one with the visual impairment) running also in a condition with verbal instructions. The numbers of directional warnings and lane violations were much smaller with the device than with verbal instructions. The user with visual impairments reached a speed of 7.4 km/h with the haptic device, which was only somewhat slower than the speed he managed with verbal guidance (8.1 km/h); the blindfolded user was even faster with haptic guidance (5.5 km/h versus 3.9 km/h).

VI. HEAD

Kerdegari et al. [45] designed a helmet that aimed at giving haptic feedback in low visibility conditions and compared this device with audio instructions. Inside the helmet 7 tactors were placed that could stimulate the forehead. Tactile patterns could indicate left, right or forward. The 10 blindfolded participants had to navigate 2 routes of about 20 m, once with the device and once with audio instructions. There were no differences in terms of travelled distance or total time, but with the haptic device the deviations were smaller. Moreover, participants showed a clear preference for the haptic device.

In the same experiment where they tested wrist and feet devices (see above), Dim & Ren [7] also tested an ear device. Vibrations to the right/left ear indicated turn right/left. Their 15 participants had to navigate a route with 18 turns on the university campus. With this ear device, 1.5% of the instructions were missed and only about 0.4% of the instructions resulted in an error. Although performance and intuitiveness were comparable to that using the wrist device and better than using the foot device, preference and comfortability clearly scored less.

Kuang et al. [46] designed a cutaneous device for forehead, hand and arm, but navigation performance was only tested when worn on the forehead since that was preferred by their participants. The device consisted of a small sphere at the end of a pin that could trace shapes on the forehead. For navigation purposes left- and rightward movements were used to indicate the direction and distance to the target path. Their 6 blindfolded participants had to navigate 3 curved paths within a room of 4×5 m. Their walking speeds were on average about 0.2 m/s, which is very slow (less than 1 km/hour). Their navigation errors were small and comparable to those achieved by [5] with two armbands.

VII. DISCUSSION AND CONCLUSION

Based on the fact that participants reached their destination and made just a few errors, most of the authors of the cited papers concluded that it was feasible to use the proposed device for navigation. However, it is also clear that the stages of development of the various devices vary immensely. This becomes especially clear by comparing the distances covered during actual walking; it may be assumed that if a device is promising and lacking just a few steps before being suitable to be brought to the market, testing should involve substantial distances. In some cases, however, participants were only required to navigate to targets a few meters away [5], [9], [13], [18], [26]–[28], [46], whereas in other cases, testing involved distances of several hundreds of meters [6], [11], [14], [15], [17], [20], [31]–[35], [44] or even up to more than a kilometer [16], [36]–[38]. Clearly, prototypes that were successfully tested over long distances are the most likely to reach the next stage of development.

Another important indication of the stage of development is the way the location of the user is determined. Several experiments used a Wizard of Oz approach, where an experimenter walking behind a participant gave directions to the device via a remote control. Although this is an appropriate way of testing the navigational guidance abilities of the device, such a system is not ready for autonomous use. In various outdoor experiments, especially those where the devices were tested along larger distances, localization was obtained via the GPS in a smartphone [6], [11], [14]–[16], [31]–[33], [35]–[38], thus ensuring autonomous navigation. Unfortunately, especially in a city environment, localization accuracy via GPS might not be sufficient. However, with the recent developments of dual-frequency GNSS (Global Navigation Satellite System) accuracy, also in cities, might improve substantially.

TABLE V
HEAD

Reference	Participants	Localization	Stimuli	Task	Metrics	Outcome
Kerdegari et al. (2016) [45]	25 (6f, 4m)	Vicon motion capture system	7 tactors around forehead, 2.5 cm apart	Navigate 4 routes of about 20 m	Time, distance, deviation, questionnaire	Time and distance not different in audio and haptic conditions; smaller deviations in and preference for haptic condition
Dim & Ren (2017) [7]	22–37 (4f, 11m)	By experimenter	1 vibration motor on each ear	Follow a route with 18 turns on campus	Errors, missed commands, Likert scale	1.5% errors; 0.4% missed commands; lower preference and comfort compared to vibrations on wrist or feet
Kuang et al. (2022) [46]	27–34 (2f, 4m)	Vicon motion capture system	Sphere moving to the right or left on forehead	Navigate 3 routes in 4×5 m room	Error in following target path; walking speed	Mean distance to target path: 0.26 m; walking speed: 0.2 m/s

Mean age or age range (if available) is given in years. Participants: f: female, m: male. Only the major metrics are mentioned.

For indoor experiments, the usage of GPS is not a real option. To create autonomous navigation devices, the building needs to be equiped with some system to localize the user. Several options were used in the cited papers, such as motion capture systems [5], [9], [18], [26], [27], [45], [46], an infrared system [21], or Hokuyo laser rangefinders [39]. Although these systems usually work well, their range is limited to just (a part of) a room. Clearly, such sytems cannot easily be extended to a larger part of the building. Alternatives could be RFID (radio-frequency identification) tags or BLE (Bluetooth Low Energy) beacons, but these were not proposed in the cited papers.

There are many other aspects that need to be considered before a device is suitable to enter the market. An obvious aspect is the price, but also weight, size, ease of use, power consumption and battery lifetime, learning time, workload and conspicuousness will be important in the decision to purchase or use one. If a device is too heavy or too bulky, or if there is need to also carry a laptop in a backpack, the attractiveness of a device is rapidly decreasing. Likewise, if the device is hard to use, if workload during use is high or if it takes substantial time to learn to use the device, this will have a negative impact on the potential success of a device. Although some users might enjoy a device attracting some attention, for example a device placed on the head, most users will prefer guidance that goes unnoticed by other people. Finally, a device needs to be reliable, so that users can trust its guidance.

Not all these aspects of the devices can be evaluated or compared easily as several aspects were not tested or mentioned in the cited papers. Apparently, most of tasks tested were easy to learn as practice time was usually short or not even necessary. So learning time was not a relevant aspect in the comparison here. In an attempt to make a comparison of some of the most important aspects possible, we created Table VI in which we rated these aspects. We made a distinction between indoor (I) and outdoor (O) devices. In the column 'Blindfold' we indicate whether the sighted participants were blindfolded '+' or not '–'; if only blind or visually impaired persons participated we left this open. If at least one blind or visually impaired person participated in the experiment, the device received a '+', otherwise a '–' in the column 'VI/B'. Wizard of Oz approaches received a '–' for 'autonomous', all devices that worked autonomously got a '+'. For distances our ratings could be objective: 1 – 10 m: '–', 10–100 m: '+', 100–1000 m: '++', $\geq$ 1000 m: '+++'. For compactness and inconspicuity it was harder to make an objective rating, especially since not all information needed was always available. We used the following criteria for compactness: '– –' if a device was quite bulky, like a backpack with wiring, or a big box on the belly; '–' for example, for a belt with a small box attached; '+' for just a belt, a smartwatch with a small processing device elsewhere on the body, small processing unit around lower leg, or a thin vest; '++' means very light and small, but this was not given to any of the hands-free devices (note that although in some of the experiments smartwatches were used, this was always in combination with other equipment on the body). For inconspicuity the criteria were: '– –' for devices that immediately attract attention, like something on the head or a bulky laptop with wiring; '–' for belts with a visible box containing the processing unit attached to it or armbands with clearly something attached to it; '+' for tight armbands, smartwatches with additional add-ons, small waist bands; '++' for devices you really do not see or that look normal, like smartwatches. Although ease of use, learning time, power consumption, battery lifetime, and price will eventually also be important aspects for the success of a device, we did not have sufficient information to include these aspects in the table. Note that we based the ratings on how the experiment was actually performed, not taking into account, for example, that a device could have been hidden by clothes.

The result of this analysis can be seen in Table VI. From this table we can make several observations. There is a very high correlation between compactness and inconspicuity. This might not be surprising as something bulky will also be conspicuous. What is also important to notice is that several of the devices scoring high on compactness and inconspicuity do not (yet) work autonomously. That means that if the step to autonomy were taken, the device might become less compact and possibly also more conspicuous.

TABLE VI
SUMMARY TABLE OF THE MOST IMPORTANT FEATURES OF HANDS-FREE DEVICES

Paper	Year	Body part	In-/Out	Blindfold	VI/B	Autonomous	Distance	Compactness	Inconspicuity
Velázquez [13]	2012	foot	I & O	+	+	–	–	– –	– –
Kuang [46]	2022	forehead	I	+	–	+	–	– –	– –
Stratmann [28]	2018	shoulder	I	–	–	–	–	–	–
Liao [18]	2020	lower leg	I	–	–	+	–	–	–
Lobo [26], [27]	2017, 2018	abdomen	I	+	+	+	–	–	–
Aggravi [5]	2015	arm	I	–/+	–	+	–	+	+
Lisini Baldi [9]	2018	arm	I	–/+	–	+	–	+	+
Korn [43]	2020	waist	I	+	–	–	+	– –	– –
Gkonos [41]	2017	waist	I & O	–	–	–	+	– –	– –
Ertan [21]	1998	back	I	–	–	+	+	– –	– –
Kerdegari [45]	2016	forehead	I	+	–	+	+	– –	– –
Bosman [2]	2003	arm	I	–	–	–	+	–	–
Scheggi [4]	2014	arm	I		+	–	+	–	–
Flores [39]	2015	waist	I		+	+	+	–	–
Jimenez [42]	2017	waist	I	–	–	–	+	+	+
Jones [23]	2006	back	I	–	–	–	++	–	+
Barontini [12]	2021	arm	O		+	+	+	– –	– –
Ross [22]	2000	shoulder	O		+	+	+	– –	– –
Marston [3]	2007	arm	O		+	+	+	– –	– –
Liao [19]	2021	lower leg	O	+	–	+	+	–	–
Strasnick [8]	2017	arm	O	–	–	–	+	+	+
Dura-Gil [40]	2017	waist	O	+	+	–	+	+	+
Orso [25]	2016	shoulder, abdomen	O	–	–	–	++	– –	–
Van Veen [31], [32]	2004, 2005	waist	O	–	–	+	++	– –	–
Dim [7]	2017	arm	O	–	–	–	++	–	– –
Dim [7]	2017	ear	O	–	–	–	++	–	– –
Dim [7]	2017	foot	O	–	–	–	++	–	–
Petrausch [17]	2017	ankle	O	–	–	–	++	–	–
Tsukada [30]	2004	waist	O	–	–	–	++	–	–
Grierson [34]	2009	waist	O	–	–	–	++	–	–
Dobbelstein [6]	2016	arm	O	–	–	+	++	–	–
Von Jan [11]	2018	arm	O	–	–	+	++	–	–
Heuten [33]	2008	waist	O	–	–	+	++	–	–
Pielot [35]	2010	waist	O	–	–	+	++	–	–
Kayhan [44]	2022	waist	O	+	+	+	++	–	–
Pfeiffer [20]	2015	upper leg	O	–	–	–	++	–	++
Rector [10]	2018	arm	O		+	–	++	+	+
Schirmer [15]	2015	ankle	O	–	–	+	++	+	+
Prasad [24]	2014	shoulder, chest	O	–	–	+	++	+	+
Velázquez [14]	2018	foot	O		+	+	++	+	+
Elliott [36]	2010	waist	O	–	–	+	+++	–	–
Calvo [37]	2013	waist	O	–	–	+	+++	–	–
Srikulwong [38]	2013	waist	O	–	–	+	+++	–	–
Bertel [16]	2017	ankle	O	–	–	+	+++	–	+

Note that only the first author is listed. Distance: 1–10 m: –, 10–100 m: +, 100–1000 m: ++, $\geq$ 1000 m: +++. I: indoors, O: outdoors.

A. Indoors versus Outdoors

Not surprisingly, outdoors larger distances were covered than indoors. This is not necessarily a real issue, as in practice the distances that need to be covered indoors and outdoors will also differ. However, 7 of the indoor studies tested over distances less than 10 m and only 1 used a distance of more than 100 m (i.e. 110 m). Such distances are still far from being useful in a real setting, although these distances could possibly be extended using the same methods. In any case, this indicates that testing was quite limited. Outdoors, the majority of the studies tested their device over distances of at least 100 m, but often this involved several hundreds of meters. For a potentially useful device, satisfaction while using the device over such large distances is a requirement.

Another difference between the indoor and outdoor studies is the autonomy of the device. Indoors, 50% of the studies relied on the experimenter giving remote instructions, while the other 50% relied on some motion capture system. These systems tend to be optical or IR based and are not very suitable for general navigation. Outdoors, only 35% relied on the experimenter, whereas 65% of the studies relied on GPS (counting the device of [7] just once). As GPS is nowadays available via smartphones (at least outdoors), it requires a relatively small step to make all the outdoor devices autonomous.

There does not seem to be a clear difference in terms of compactness and inconspicuity of the indoor and outdoor devices. Based on the distances and the autonomy, it can be concluded that outdoor devices are much closer to reaching the market than the indoor devices.

B. Suitability of Body Parts

The suitability of several body parts has been tested, and in most of the studies the conclusion was that the device was feasible for navigation. However, arm and waist are the most frequently tested locations. It can not be concluded from this survey whether these locations were relatively easy to address or whether they were more successful and thus more publishable than any other body parts.

Interestingly, the way the arm and waist devices give guidance was in general quite different. Vibrations on the waist mostly indicated a specific direction in which the user had to go and these were clearly body-relative signals. For the arm, several solutions were tested. Often both arms had a device and stimulation on the right meant ‘go right’ and on the left ‘go left’. In other cases, vibration could mean on- or off-course, but there were also arm devices where vibrations indicated relative directions.

In terms of practical use, both arm devices and waist devices can be easy to put on, arm devices like bracelets and waist devices like a belt. They can also be relatively compact and inconspicuous. These latter observations are not directly obvious from Table VI as some of the devices were still worn over other clothes and were therefore unnecessary conspicuous. Putting on a vest for a back or belly device usually requires more effort. Moreover, such vests incorporate often many actuators and are also more likely to be bulky. Since directions on the torso can be displayed adequately via a belt, a vest does not seem to be the best way to go. Clearly, head devices are more conspicuous.

The largest distances covered (more than a kilometer) were done with waist devices and an ankle device. However, these waist devices scored low on compactness and inconspicuity as a somewhat bulky processing unit was connected to the belt. It seems, however, doable to minituarize such units. The ankle device was tested over 1.4 km, and this device scored relatively high on inconspicuity, as the whole device could be hidden under a trouser leg. In the experimental setting, the user also had to carry a laptop and a mobile eye tracker making the device less compact. However, as these latter add-ons were only relevant for the supplemental tasks and not for navigation, so far this device seems to have the best potential for further development.

C. Guidance Methods

An overview of the guidance methods used by the haptic devices in this overview can be seen in Table VII. A simple, but effective way of guidance is to stimulate the right/left side of the body if the user has to turn right/left. This is mostly used with bracelets, but occasionally also on the shoulder, the ears or the waist. Instead of stimulation relative to the body, several devices stimulate relative to a body part, like on the right or left side of an ankle or wrist. This latter type of stimulation has the advantage that only one device is needed instead of two (one on each side), but especially in the case of the wrist, this might be somewhat less intuitive due to the movement of the arm. Several of the devices give more specific directional information, the majority of these being devices for the waist. A few of the devices only gave correction feedback when users deviated from the intended path. In addition to giving directions, some of the devices also gave distance information.

As in all experiments the users reached their target location, it it hard to conclude anything on the ‘optimal’ guidance method. As indicating right and left seems already quite effective, the question arises whether the more sophisticated methods giving more detailed directional information are better or even necessary. It will depend on the exact aim of the device. When hiking in a park or in the woods, or when sightseeing, just a global direction indication might be preferred, but when the aim is to reach a target location via the shortest route or when walking in a city environment, right/left instructions might be more efficient.

D. Devices Possibly Suitable for Users With Visual Impairments

Most of the devices tested had the intention to make navigation guidance easier for sighted users and such devices are not necessarily also useful for visually impaired or blind users. In some of the studies users actually had to rely on their vision. Although blindfolded sighted users are not a good representation of how users with visual impairments navigate, in studies with blindfolded users it is at least guaranteed that vision is not essential for navigation. Of the few indoor devices actually tested with blindfolded, visually impaired

TABLE VII
OVERVIEW OF GUIDANCE METHODS

Stimulation	Reference
Stimulation on right or left body side indicates turn right or left	[2], [4], [5], [7], [9], [24], [25], [28], [42], [45]
Movement to right or left on body indicates turn right or left	[21], [23], [44], [46]
Stimulation on right or left side of body part indicates right or left	[12], [15]–[17]
Indication of forward, backward, right and left relative to body	[34]
Indication of forward, backward, right and left relative to body part	[13], [47]
Egocentric direction indication on body	[26], [27], [30]–[33], [35]–[41], [43]
Egocentric direction indication on body part	[6], [8], [11], [18], [19]
Stimulation on right or left body side indicates veering to right or left	[10], [22]
Stimulation when on or off course	[3]
Muscle stimulation	[20]

or blind users, only two devices worked autonomously and were tested over distances of more that 10 m. The helmet tested with blindfolded participants by Kerdegari et al. [45] worked reasonably well, but is probably more suitable for fire-fighters in low-visibility circumstances than for visually impaired users. The waist band of Flores et al. [39] worked well in a small room and their blind participants were positive about the provided guidance. However, it remains to be seen how hard or easy it will be to extend the use of such a device to a larger and more diverse environment.

Also outdoors only few autonomous devices were tested with visually impaired, blind or blindfolded participants. The device tested by Marston et al. [3] required users to wear a hat, a backpack with computer and a wristband. So although this device worked autonomously and was tested over distances of about 80 m, it was quite bulky and thus not very attractive. The device created by Liao et al. [19] was tested over shorter distances and involved a bulky processing unit and vibration motors around their lower leg. They also had to wear a helmet, and elbow, hand and knee pads, but that was for safety. The device of Velázquez et al. [14] was tested by two blind users. They used their cane as they were used to and only received navigational instructions on their foot sole if they had to change direction. The processing unit was fastened around their lower leg and could be hidden under one of their trouser legs. The two users found the guidance intuitive and demanding just a low cognitive load. The most impressive performance, both of blindfolded sighted and the visually impaired participants, was obtained with the waist device of [44]. The users had to run along a standard atlethic running track. Via stretching units on their waist, they received guidance if they had to change direction. Compared to running with verbal instructions, they made much less lane violations and received fewer directional warnings. Although the visually impaired participant (but not the blindfolded sighted participant) was somewhat slower with the haptic device, he still reached a speed of 7.4 km/h. These two latter devices seem closest to being of use for visually impaired users. Hopefully, the researchers will further extend and test their device with more participants, larger distances and longer durations.

Of course, some of the devices that were not tested with blindfolded or visually impaired users might also be valuable for users with visual impairments. In a study about the requirements of a robot guide for blind people, Hersh and Johnson [48] mentioned the following requirements: “discreet and inconspicuous, small, light weight and portable, easy to use, robust to damage, require minimal maintenance, have a long life and a long battery life”. For navigation purposes we would add ‘sufficient location accuracy’.

None of the devices were tested with deafblind users. Haptic devices suitable for visually impaired users that do not rely on additional auditory instructions, would probably also work for deafblind users. Devices that provide explicit instructions like ‘go right’ or ‘go left’ seem most suitable. An essential requirement for all users with visual impairments is that a device should be reliable at all times. 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.

E. Comparison with Hand-Held Devices

To compare performance of these hands-free devices with the hand-held devices discussed in our previous survey [1], we created a similar overview in Table VIII. The criteria were basically the same, with a few adaptations. For compactness we used the following criteria: ‘– –’ for relatively large objects in the hand (larger than a smartphone; ‘–’ for holding a smartphone with additional add-ons, like bands on fingers; ‘+’ for small hand-held devices like a smartphone. For inconspicuity we use: ‘– –’ if bulky or with backpack and visible wiring; ‘–’ for holding a smartphone with clearly visual add-ons or if clear scanning movements have to made while using the device; ‘+ for smartphone in hand (although this is clearly visible, this is usually not considered conspicuous); ‘++’ for invisible devices, not applicable to hand-held devices.

Also the hand-held devices reported high success rates with most participants reaching their destination [1]. However, it was noted that especially indoors walking speeds were much slower than normal walking speeds. This was usually not due to the device being slow, but due to the participant. As there were hardly any practice trials before the actual experiments, it was assumed that training would substantially improve performance.

TABLE VIII
SUMMARY TABLE OF THE MOST IMPORTANT FEATURES OF HAND-HELD DEVICES

Paper	Year	Body part	In-/Out	Blindfold	VI/B	Autonomous	Distance	Compactness	Inconspicuity
Amemiya [49]	2009	hand	I		+	+	–	– –	– –
Sokoler [50]	2022	thumb	I	–	–	–	–	–	–
Robinson [51]	2009	hand	I	–	–	+	+	– –	– –
Amemiya [52], [53]	2009, 2010	hand	I		+	+	+	–	– –
Choinière [54]	2017	hand	I	+	–	+	+	–	–
Ghiani [55]	2008	fingers	I		+	+	+	–	–
Spiers [56]–[59]	2015–2018	hand	I	–	+	+	+	–	–
Lim [60]	2015	hand	I	–	–	–	+	+	+
Jacob [61]	2012	hand	O	–	–	+	+	+	–
Spiers [62]	2016	hand	O	–	–	+	+	–	–
Orso [25]	2016	fingers	O	–	–	–	+	+	–
Lin [63]	2008	hand	O	–	–	–	+	+	+
Dim [7]	2017	finger	O	–	–	–	++	– –	– –
Gallo [64]	2020	hand	O	–	–	+	++	– –	– –
Nasser [65]	2020	hand	O		+	+	++	– –	– –
Kawaguchi [66]	2012	hand	O	–	–	+	++	–	–
Yasui [67]	2019	hand	O	–	–	+	++	–	–
Williamson [68]	2010	hand	O	–	–	+	++	–	–
Robinson [69]	2010	hand	O	–	–	+	++	–	–
Pielot [70]	2011	hand	O	–	–	+	++	+	–
Azenkot [71]	2011	hand	O		+	+	++	+	–
Rümelin [72]	2011	hand	O	–	–	+	++	+	+

Note that only the first author is listed. Distance: 1–10 m: –, 10–100 m: +, 100–1000 m: ++, $\geq$ 1000 m: +++. I: indoors, O: outdoors. A '+' in the column 'VI/B' indicates that at least one visually impaired (VI) or blind (B) participant tested the device.

Compared to the hands-free devices, the hand-held devices worked autonomously in a larger percentage of the studies, namely in 75% of the indoor studies and in 79% of the outdoor studies. This needs not be surprising as in all the autonomous devices tested outdoors, a smartphone was used as hand-held device in which GPS is directly available. Moreover, smartphones are already widely in use for visual navigation guidance; haptic signals can then be designed as an add-on to an existing system, as smartphones are also able to generate vibrations. For hands-free devices that use a smartphone, in general another way of stimulation is needed; a smartphone could be strapped to an arm or leg, but stimulation of other body parts with a smartphone seems less feasible.

Only few of the hand-held devices were tested with visually impaired, blind or blindfolded participants. Clearly these studies focused on other aspects such as improving sightseeing experiences, increasing safety when navigating in a busy city, or being able to talk to a friend without having to attend to a map on the smartphone. Interestingly, the smartphone device created by Azenkot et al. [71] was tested with visually impaired participants who made only a few navigation errors in a busy city environment. Compared to the hands-free devices, this possibly is the best option so far for visually impaired persons.

F. Concluding Remarks

Many of the studies in this overview were already 5 or more years old, and apparently, these were not followed up by a more recent study. Lack of continuation might be due to various reasons. One obvious reason is that the researchers did not find the outcome of their test with the device promising enough. Another quite common reason seems to be that the study was a student(s) project, which stopped after the student(s) graduated. Finally, funding is probably also an issue. Grants are usually given for a limited period and when this period is over, research necessarily stopped. Some of the more recent studies were just small lab studies, with only minimal distances covered, but some of the other devices were tested extensively. In this respect, the studies of [10], [11], [14], [16], [44] look the most promising. It remains to be seen whether these studies will indeed be followed-up.

In this overview, we presented, discussed and compared hands-free haptic devices for pedestrians. It became clear that there are large differences in the stages of development of the

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various devices. In general, devices intended for use outdoors were at a higher technology readiness level than the indoor devices. This was mainly due to the availability of GPS, which allows autonomous navigation via a smartphone. Currently, the accuracy of GPS is not always sufficient, but with the development of dual frequency GNSS this might improve in the near future. Moreover, for sighted persons high accuracy is much less of an issue than for persons with visual impairments. Compactness of a device seems an important requirement for eventual success, but the most compact devices were not (yet) autonomous. The majority of the devices were designed for the arm or waist and such devices seem to have more potential than devices for shoulder, back, belly or head. Finally, although the need for hands-free navigation devices is clear for users with a visual disability, none of these devices are at a readiness level where they could be useful, the major issues being the lack of reliability of outdoor devices and the very limited range of indoor devices.

REFERENCES

[1] A. M. L. Kappers, M. Fa Si Oen, T. J. W. Junggeburth, and M. A. Plaisier, "Hand-held haptic navigation devices for actual walking," *IEEE Transactions on Haptics*, vol. 15, no. 4, pp. 655–666, 2022.

[2] S. Bosman, B. Groenendaal, J. W. Findlater, T. Visser, M. de Graaf, and P. Markopoulos, "GentleGuide: An exploration of haptic output for indoors pedestrian guidance," in *Human-Computer Interaction with Mobile Devices and Services*, L. Chittaro, Ed. Berlin, Heidelberg: Springer, 2003, pp. 358–362.

[3] J. R. Marston, J. M. Loomis, R. L. Klatzky, and R. G. Golledge, "Nonvisual route following with guidance from a simple haptic or auditory display," *Journal of Visual Impairment & Blindness*, vol. 101, no. 4, pp. 203–211, 2007.

[4] S. Scheggi, A. Talarico, and D. Prattichizzo, "A remote guidance system for blind and visually impaired people via vibrotactile haptic feedback," in *22nd Mediterranean Conference on Control and Automation*, 2014, pp. 20–23.

[5] M. Aggravi, S. Scheggi, and D. Prattichizzo, "Evaluation of a predictive approach in steering the human locomotion via haptic feedback," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 597–602.

[6] D. Dobbelstein, P. Henzler, and E. Rukzio, "Unconstrained pedestrian navigation based on vibro-tactile feedback around the wristband of a smartwatch," in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, ser. CHI '16. New York, NY, USA: Association for Computing Machinery, 2016, pp. 2439–2445.

[7] N. K. Dim and X. Ren, "Investigation of suitable body parts for wearable vibration feedback in walking navigation," *International Journal of Human-Computer Studies*, vol. 97, pp. 34–44, 2017.

[8] E. Strasnick, J. R. Cauchard, and J. A. Landay, "BrushTouch: Exploring an alternative tactile method for wearable haptics," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, ser. CHI '17. ACM Press, New York, 2017, pp. 3120–3125.

[9] T. Lisini Baldi, S. Scheggi, M. Aggravi, and D. Prattichizzo, "Haptic guidance in dynamic environments using optimal reciprocal collision avoidance," *IEEE Robotics and Automation Letters*, vol. 3, no. 1, pp. 265–272, 2018.

[10] K. Rector, R. Bartlett, and S. Mullan, "Exploring aural and haptic feedback for visually impaired people on a track: A wizard of oz study," in *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility*, ser. ASSETS '18. New York, NY, USA: Association for Computing Machinery, 2018, pp. 295–306.

[11] V. von Jan, S. Bertel, and E. Hornecker, "Information push and pull in tactile pedestrian navigation support," in *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct*, ser. MobileHCI '18. New York, NY, USA: Association for Computing Machinery, 2018, pp. 55–62.

[12] F. Barontini, M. G. Catalano, L. Pallottino, B. Leporini, and M. Bianchi, "Integrating wearable haptics and obstacle avoidance for the visually impaired in indoor navigation: A user-centered approach," *IEEE Transactions on Haptics*, vol. 14, no. 1, pp. 109–122, 2021.

[13] R. Velázquez, O. Bazán, J. Varona, C. Delgado-Mata, and C. A. Gutiérrez, "Insights into the capabilities of tactile-foot perception," *International Journal of Advanced Robotic Systems*, vol. 9, no. 179, pp. 1–11, 2012.

[14] R. Velázquez, E. Pissaloux, P. Rodrigo, M. Carrasco, N. I. Giannoccaro, and A. Lay-Ekuakille, "An outdoor navigation system for blind pedestrians using GPS and tactile-foot feedback," *Applied Sciences*, vol. 8, no. 578, 2018.

[15] M. Schirmer, J. Hartmann, S. Bertel, and F. Echtler, "Shoe me the way: A shoe-based tactile interface for eyes-free urban navigation," in *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, ser. MobileHCI '15. New York, NY, USA: Association for Computing Machinery, 2015, pp. 327—336.

[16] S. Bertel, T. Dressel, T. Kohlberg, and V. von Jan, "Spatial knowledge acquired from pedestrian urban navigation systems," in *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services*, ser. MobileHCI '17. New York, NY, USA: Association for Computing Machinery, 2017.

[17] V. Petrausch, T. Schwarz, and R. Stiefelhagen, "Prototype development of a low-cost vibro-tactile navigation aid for the visually impaired," in *Computers Helping People with Special Needs*, K. Miesenberger and G. Kouroupetroglou, Eds. Cham: Springer International Publishing, 2018, pp. 63–69.

[18] Z. Liao, J. V. Salazar Luces, and Y. Hirata, "Human navigation using phantom tactile sensation based vibrotactile feedback," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 5732–5739, 2020.

[19] Z. Liao, J. Salazar, and Y. Hirata, "Robotic guidance system for visually impaired users running outdoors using haptic feedback," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2021, pp. 8325–8331.

[20] M. Pfeiffer, T. Dünte, S. Schneegass, F. Alt, and M. Rohs, "Cruise control for pedestrians: Controlling walking direction using electrical muscle stimulation," in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, ser. CHI '15. New York, NY, USA: Association for Computing Machinery, 2015, pp. 2505–2514.

[21] S. Ertan, C. Lee, A. Willets, H. Tan, and A. Pentland, "A wearable haptic navigation guidance system," in *Digest of the Second International Symposium on Wearable Computers*, 1998, pp. 164–165.

[22] D. Ross and B. Blasch, "Wearable interfaces for orientation and wayfinding," in *Proceedings of the Fourth International ACM Conference on Assistive Technologies*, 2000, pp. 193–200.

[23] L. A. Jones, B. Lockyer, and E. Piatesk, "Tactile display and vibrotactile pattern recognition on the torso," *Advanced Robotics*, vol. 20, no. 12, pp. 1359–1374, 2006.

[24] M. Prasad, P. Taele, A. Olubeko, and T. A. Hammond, "HaptiGo: A navigational 'tap on the shoulder'," in *2014 IEEE Haptics Symposium (HAPTICS)*, 2014, pp. 339–345.

[25] V. Orso, L. Gamberini, R. Mazza, Y.-T. Hsieh, W. Jensen, G. Jacucci, and A. Morrison, "Follow the vibes: A comparison between two tactile displays in a navigation task in the field," *PsychNology Journal*, vol. 14, no. 1, pp. 61–79, 2016.

[26] L. Lobo, A. Higueras-Herbada, D. Travieso, D. Jacobs, M. Rodger, and C. Craig, "Sensory substitution and walking toward targets: An experiment with blind participants," in *Studies in Perception and Action XIV*, J. Weast-Knapp and G. Pepping, Eds. Routledge, Taylor & Francis, 2017, pp. 34–38.

[27] L. Lobo, D. Travieso, D. M. Jacobs, M. Rodger, and C. M. Craig, "Sensory substitution: Using a vibrotactile device to orient and walk to targets," *Journal of Experimental Psychology: Applied*, vol. 24, no. 1, pp. 108–124, 2018.

[28] T. C. Stratmann, S. Sadeghian Borojeni, W. Heuten, and S. C. Boll, "Shouldertap - Pneumatic on-body cues to encode directions," in *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, ser. CHI EA '18. New York, NY, USA: Association for Computing Machinery, 2018, pp. 1—6.

[29] M. Pielot, B. Poppinga, W. Heuten, and S. Boll, "Pocketnavigator: Studying tactile navigation systems in-situ," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2012, pp. 3131–3140.

[30] K. Tsukada and M. Yasumura, "Activebelt: Belt-type wearable tactile display for directional navigation," in *UbiComp 2004: Ubiquitous Com-*

puting, N. Davies, E. D. Mynatt, and I. Siio, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004, pp. 384–399.

[31] H.-J. van Veen, M. Spapé, and J. van Erp, "Waypoint navigation on land: Different ways of coding distance to the next waypoint," in *Proceedings of EuroHaptics 2004*, 2004, pp. 160–165.

[32] J. B. F. van Erp, H. A. H. C. van Veen, and C. Jansen, "Waypoint navigation with a vibrotactile waist belt," *ACM Transactions on Applied Perception*, vol. 2, no. 2, pp. 106–117, 2005.

[33] W. Heuten, N. Henze, S. Boll, and M. Pielot, "Tactile wayfinder: A non-visual support system for wayfinding," in *NordiCHI '08 Proceedings of the 5th Nordic conference on Human-computer interaction: building bridges*, 2008, pp. 172–181.

[34] L. Grierson, J. Zelek, and H. Carnahan, "The application of a tactile way-finding belt to facilitate navigation in older persons," *Ageing International*, vol. 34, pp. 203–215, 2009.

[35] M. Pielot and S. C. Boll, "Tactile wayfinder: Comparison of tactile waypoint navigation with commercial pedestrian navigation systems," in *Pervasive*, ser. LNCS 6030, P. Floréen, A. Krüger, and M. Spasojevic, Eds. Berlin Heidelberg: Springer-Verlag, 2010, pp. 76–93.

[36] L. R. Elliott, J. van Erp, E. S. Redden, and M. Duistermaat, "Field-based validation of a tactile navigation device," *IEEE Transactions on Haptics*, vol. 3, no. 2, pp. 78–87, 2010.

[37] A. A. Calvo, V. S. Finomore, G. M. Burnett, and T. C. McNitt, "Evaluation of a mobile application for multimodal land navigation," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 57, no. 1, pp. 1997–2001, 2013.

[38] M. Srikulwong and E. O'Neill, "Wearable tactile display of directions for pedestrian navigation: Comparative lab and field evaluations," in *2013 World Haptics Conference (WHC)*, 2013, pp. 503–508.

[39] G. Flores, S. Kurniawan, R. Manduchi, E. Martinson, L. M. Morales, and E. A. Sisbot, "Vibrotactile guidance for wayfinding of blind walkers," *IEEE Transactions on Haptics*, vol. 8, no. 3, pp. 306–317, 2015.

[40] J. V. Durá-Gil, B. Bazuelo-Ruiz, D. Moro-Pérez, and F. Mollà-Domenech, "Analysis of different vibration patterns to guide blind people," *PeerJ*, vol. 5, p. e3082, 2017.

[41] C. Gkonos, I. Giannopoulos, and M. Raubal, "Maps, vibration or gaze? Comparison of novel navigation assistance in indoor and outdoor environments," *Journal of Location Based Services*, vol. 11, no. 1, pp. 29–49, 2017.

[42] R. Jimenez and A. M. Jimenez, "Blind waypoint navigation using a computer controlled vibrotactile belt," I. L. Nunes, Ed. Cham: Springer International Publishing, 2017, pp. 3–13.

[43] O. Korn, J. Gay, R. Gouveia, L. Buchweitz, A. S. Schulz, and M. Umfahrer, "Tactile navigation with checkpoints as progress indicators? Only when walking longer straight paths," in *Proceedings of the 13th ACM International Conference on PErvasive Technologies Related to Assistive Environments*, ser. PETRA '20. New York, NY, USA: Association for Computing Machinery, 2020.

[44] O. Kayhan and E. Samur, "A wearable haptic guidance system based on skin stretch around the waist for visually-impaired runners," in *2022 IEEE Haptics Symposium (HAPTICS)*, 2022, pp. 1–6.

[45] H. Kerdegari, Y. Kim, and T. J. Prescott, "Head-mounted sensory augmentation device: Comparing haptic and audio modality," in *Biomimetic and Biohybrid Systems*, N. F. Lepora, A. Mura, M. Mangan, P. F. Verschure, M. Desmulliez, and T. J. Prescott, Eds. Cham: Springer International Publishing, 2016, pp. 107–118.

[46] L. Kuang, M. Aggravi, P. R. Giordano, and C. Pacchierotti, "Wearable cutaneous device for applying position/location haptic feedback in navigation applications," in *2022 IEEE Haptics Symposium (HAPTICS)*, 2022, pp. 1–6.

[47] R. Velázquez and E. Pissaloux, "On human performance in tactile language learning and tactile memory," in *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*, 2014, pp. 96–101.

[48] M. A. Hersh and M. A. Johnson, "A robotic guide for blind people. Part 1. A multi-national survey of the attitudes, requirements and preferences of potential end-users," *Applied Bionics and Biomechanics*, vol. 7, pp. 252–609, 2010.

[49] T. Amemiya and H. Sugiyama, "Navigation in eight cardinal directions with pseudo-attraction force for the visually impaired," in *2009 IEEE International Conference on Systems, Man and Cybernetics*, 2009, pp. 27–32.

[50] T. Sokoler, L. Nelson, and E. R. Pedersen, "Low-resolution supplementary tactile cues for navigational assistance," in *Human Computer Interaction with Mobile Devices*, F. Paternò, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2002, pp. 369–372.

[51] S. Robinson, P. Eslambolchilar, and M. Jones, "Evaluating haptics for information discovery while walking," in *Proceedings of the 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology*, ser. BCS-HCI '09. Swindon, GBR: BCS Learning & Development Ltd., 2009, pp. 93–102.

[52] T. Amemiya and H. Sugiyama, "Haptic handheld wayfinder with pseudo-attraction force for pedestrians with visual impairments," in *Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility*, ser. Assets '09. New York, NY, USA: Association for Computing Machinery, 2009, pp. 107—114.

[53] ——, "Orienting kinesthetically: A haptic handheld wayfinder for people with visual impairments," *ACM Transactions on Accessible Computing*, vol. 3, no. 2, 2010.

[54] J.-P. Choinière and C. Gosselin, "Development and experimental validation of a haptic compass based on asymmetric torque stimuli," *IEEE Transactions on Haptics*, vol. 10, no. 1, pp. 29–39, 2017.

[55] G. Ghiani, B. Leporini, and F. Paternò, "Vibrotactile feedback as an orientation aid for blind users of mobile guides," in *Proceedings of the 10th International Conference on Human Computer Interaction with Mobile Devices and Services*, ser. MobileHCI '08. New York, NY, USA: Association for Computing Machinery, 2008, pp. 431–434.

[56] A. Spiers, A. Dollar, J. van der Linden, and M. Oshodi, "First validation of the haptic sandwich: A shape changing handheld haptic navigation aid," in *2015 International Conference on Advanced Robotics (ICAR)*, 2015, pp. 144–151.

[57] A. J. Spiers, J. van Der Linden, M. Oshodi, and A. M. Dollar, "Development and experimental validation of a minimalistic shape-changing haptic navigation device," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016, pp. 2688–2695.

[58] A. J. Spiers and A. M. Dollar, "Design and evaluation of shape-changing haptic interfaces for pedestrian navigation assistance," *IEEE Transactions on Haptics*, vol. 10, no. 1, pp. 17–28, 2017.

[59] A. J. Spiers, J. van der Linden, S. Wiseman, and M. Oshodi, "Testing a shape-changing haptic navigation device with vision-impaired and sighted audiences in an immersive theater setting," *IEEE Transactions on Human-Machine Systems*, vol. 48, no. 6, pp. 614–625, 2018.

[60] H. Lim, Y. Cho, W. Rhee, and B. Suh, "Vi-Bros: Tactile feedback for indoor navigation with a smartphone and a smartwatch," in *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, ser. CHI EA '15. New York, NY, USA: Association for Computing Machinery, 2015, pp. 2115–2120.

[61] R. Jacob, A. C. Winstanley, N. Togher, and R. Roche, "Pedestrian navigation using haptic feedback: Results from a field study to test spatial abilities and memory recall," in *Proceedings of the 20^th Annual GIS Research UK (GISRUK) Conference*, 2012, pp. 1–8.

[62] A. J. Spiers and A. M. Dollar, "Outdoor pedestrian navigation assistance with a shape-changing haptic interface and comparison with a vibrotactile device," in *2016 IEEE Haptics Symposium (HAPTICS)*, 2016, pp. 34–40.

[63] M.-W. Lin, Y.-M. Cheng, and W. Yu, "Using tactons to provide navigation cues in pedestrian situations," in *Proceedings of the 5th Nordic Conference on Human-Computer Interaction: Building Bridges*, ser. NordiCHI '08. New York, NY, USA: Association for Computing Machinery, 2008, pp. 507–510.

[64] D. Gallo, S. Shreepriya, and J. Willamowski, "Runahead: Exploring head scanning based navigation for runners," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, ser. CHI '20. New York, NY, USA: Association for Computing Machinery, 2020, pp. 1–13.

[65] A. Nasser, K.-N. Keng, and K. Zhu, "ThermalCane: Exploring thermotactile directional cues on cane-grip for non-visual navigation," in *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility*, ser. ASSETS '20. New York, NY, USA: Association for Computing Machinery, 2020.

[66] H. Kawaguchi and T. Nojima, "STRAVIGATION: A vibrotactile mobile navigation for exploration-like sightseeing," in *Advances in Computer Entertainment*, A. Nijholt, T. Romão, and D. Reidsma, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 517–520.

[67] T. Yasui, T. Kitamura, T. Izumi, and Y. Nakatani, "Evaluation of a vibration-based route indication for children who are not familiar with maps," in *2019 IEEE 8th Global Conference on Consumer Electronics (GCCE)*, 2019, pp. 40–44.

[68] J. Williamson, S. Robinson, C. Stewart, R. Murray-Smith, M. Jones, and S. Brewster, "Social gravity: A virtual elastic tether for casual, privacy-preserving pedestrian rendezvous," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '10. New

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York, NY, USA: Association for Computing Machinery, 2010, pp. 1485–1494.

[69] S. Robinson, M. Jones, P. Eslambolchilar, R. Murray-Smith, and M. Lindborg, ““I did it my way”: Moving away from the tyranny of turn-by-turn pedestrian navigation,” in *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services*, ser. MobileHCI ’10. New York, NY, USA: Association for Computing Machinery, 2010, pp. 341–344.

[70] M. Pielot, B. Poppinga, W. Heuten, and S. Boll, “6th Senses for everyone! The value of multimodal feedback in handheld navigation aids,” in *Proceedings of the 13th International Conference on Multimodal Interfaces*, ser. ICMI ’11. New York, NY, USA: Association for Computing Machinery, 2011, pp. 65–72.

[71] S. Azenkot, R. E. Ladner, and J. O. Wobbrock, “Smartphone haptic feedback for nonvisual wayfinding,” in *The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility*, ser. ASSETS ’11. New York, NY, USA: Association for Computing Machinery, 2011, pp. 281—282.

[72] S. Rümelin, E. Rukzio, and R. Hardy, “Naviradar: A novel tactile information display for pedestrian navigation,” in *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, ser. UIST ’11. New York, NY, USA: Association for Computing Machinery, 2011, pp. 293–302.

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