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Field evaluation of a wearable multimodal soldier navigation system

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ABSTRACT

Challenging environments pose difficulties for terrain navigation, and therefore wearable and multimodal navigation systems have been proposed to overcome these difficulties. Few such navigation systems, however, have been evaluated in field conditions. We evaluated how a multimodal system can aid in navigating in a forest in the context of a military exercise. The system included a head-mounted display, headphones, and a tactile vibrating vest. Visual, auditory, and tactile modalities were tested and evaluated using unimodal, bimodal, and trimodal conditions. Questionnaires, interviews and observations were used to evaluate the advantages and disadvantages of each modality and their multimodal use. The guidance was considered easy to interpret and helpful in navigation. Simplicity of the displayed information was required, which was partially conflicting with the request for having both distance and directional information available.

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1. Introduction

In recent years, navigation systems have been developed for many user groups, such as those driving vehicles (Murata et al., 2013; Reagan and Baldwin, 2006; Szczerba et al., 2015), pedestrians (May et al., 2003; Münzer et al., 2006; Pielot et al., 2009; van Erp et al., 2005), and people with visual (Johnson and Higgins, 2006; Lewis et al., 2015; Wilson et al., 2007) or cognitive (Fickas et al., 2008) impairments. In addition, navigation systems for safety-critical domains have been suggested, for example, for firefighters (Streefkerk et al., 2012), first responders (Smets et al., 2008), and infantry soldiers (Elliott et al., 2010; Eriksson et al., 2008; Kumagai et al., 2005).

Challenging environments pose difficulties for navigation systems. A visual display may be useless in dense smoke or muddy water (van Erp et al., 2005). Similarly, terrain navigation is challenging when the environmental conditions are bad, for instance, when there is poor visibility due to darkness, heavy rain, snow, or thick vegetation, or when it is dangerous to walk there. In these conditions, the use of compass and map, or even a hand-held GPS (Global Positioning System) device, may be slow and cumbersome. Furthermore, the disadvantage of using traditional navigation means is that there is high mental workload required to pace count and detour around obstacles (Kumagai et al., 2005).

To cope with these challenges, the use of wearable systems have been suggested. For example, tactile displays, or vibrating tactors placed around the user's torso, have been studied on their own (Jones et al., 2006; Pielot et al., 2009; Srikulwong and O'Neill, 2010; van Erp et al., 2005), and in combination with electronic maps (Smets et al., 2008), head-mounted displays (HMDs) (Elliott et al., 2010; Kumagai et al., 2005; Streefkerk et al., 2012), and speakers or headphones (Calvo et al., 2014; Eriksson et al., 2008; Garcia et al., 2012; Kumagai et al., 2005). Many benefits of using wearable systems were found, including the selection of shorter routes and lower probability for disorienting (Pielot et al., 2009), faster performance (Srikulwong and O'Neill, 2010), less error in night-time navigation (Kumagai et al., 2005), and short familiarization time with the devices (van Erp et al., 2005). Additionally, in outdoor environments under high cognitive and visual workload, tactile displays were found useful (Elliott et al., 2010). Wearable devices can also improve users' situation awareness, i.e., perception and integration of surrounding information with respect to the situation at hand (Laarni et al., 2009).

1.1. Multimodal systems

In a multimodal system, as framed by Möller et al. (2009) and Dumas et al. (2009), human-machine interaction takes place via a number of media and utilizes different sensory and communication channels. Typically, the sensory channels refer to the visual (V), auditory (A) or tactile (T) senses. A common view in cognitive

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psychology is that humans process modalities partially independently, and human performance can be improved by multimodal interaction (see, e.g., Dumas et al., 2009). For example, multisensory integration may make the stimulus more salient, and thus improve performance in selective attention tasks (Van der Burg et al., 2008). Wickens' Multiple Resource Theory (Wickens, 2008) can be used for modelling the mental resources available: information coming from a single stimulus can be processed in parallel, if different sensory resources are required. It has been shown that multimodal cues can shorten response times in complex environments (Ferris and Sarter, 2008). Similarly, tactile and auditory cues can facilitate visual target search (Hancock et al., 2013).

1.2. *User evaluations in navigation and military contexts*

Challenging environments pose difficulties also for user evaluations. In many contexts researchers are unable to go near the activity, for example in firefighting and military tasks. Sometimes, the conditions may be so challenging that the researchers are be forced to take the tests to a laboratory (e.g., Andersson and Lundberg, 2004), where the context of intended use can be only partially simulated.

In order to get an overview of user evaluations of multimodal systems, a table was prepared listing methods used in the evaluation of multimodal systems especially in navigation tasks and in military contexts (Table 1). Most evaluations were performed in applied or laboratory conditions, with the exception of a study by Elliott et al. (2010). In most studies, performance measures (PMs, e.g., elapsed time), or observations and user comments are utilized. Statistical significance tests are often carried out with PMs, but also sometimes with questionnaires. Questionnaires typically cover user-related issues such as usability, suitability for task, acceptability, comfort, workload and situation awareness. Physiological measurements (electrocardiogram, ECG) have also been used (Mynttinen, 2010).

1.3. *Aim and scope of study*

We studied a wearable, multimodal navigation system with users in a controlled outdoors environment and in the context of a military exercise in demanding outdoor conditions. Our demonstrator system is capable of tri-modal output, i.e., feedback to user can be given via three different modalities (visual, auditory, and tactile). In the two studies we carried out, we used unimodal (one), bimodal (two) and trimodal (three modalities) output.

This paper addresses two research questions: Does the demonstrator system help in navigation? What are the advantages and disadvantages of each modality, and also of multimodal use? The research questions are contemplated mainly on the basis of data collected using questionnaires, interviews and observations.

Although the navigation system described in this study can be used for several purposes (e.g., within-group communication and warning signals), in this paper, only the navigation support provided by the system is considered. Participants were encouraged not to use a hand-held device (with GPS capability), which was a part of the navigation system. In the analysis, only the wearable devices of the system are considered. This paper focuses on the evaluation phase of the navigation system; phases such as task analysis and system design are not covered (see e.g., Laarni et al., 2009; Lemmelä et al., 2008).

In this paper, Section 2 reports two studies in which the system was tested in outdoor conditions. Section 3 discusses the study findings regarding unimodal and multimodal use of the navigation system and provides some considerations to support the future design and evaluation of wearable multimodal systems.

2. Materials and methods

The multimodal navigation system used in this study has been developed in multiple phases, including scenario specification, cognitive task analysis, requirement specification, and concept design. The two studies described in this section concern the evaluation of a demonstrator, where various functionalities, including the multimodal outputs, have been integrated. In Study 1, the system was tested using unimodal and trimodal outputs in a controlled environment, and in Study 2, two bimodal conditions were used (visual + auditory (VA), tactile + auditory (TA)) in the context of a military exercise. The evaluation design was adapted from earlier work in the field, especially from (Elliott et al., 2010; Mynttinen, 2010).

2.1. *Navigation system and multimodal outputs*

The navigation system was built on Saab 9Land Soldier system. It included a hand-held unit with a 3.7″ display and computer, and terminals for voice and data. The display showed a non-rotating, north-up map with zooming possibility. Waypoints could be set to the route using the hand-held device. The navigation was based on GPS: The user's position was transmitted periodically and automatically, and the heading direction was inferred from preceding GPS readings. The system generated output for the visual and auditory modalities at 10 m intervals (corresponding to 7–12 s at walking speed). When the user stepped outside of the navigation corridor (corridor width 25 m, waypoint diameter 10 m), system output was generated for the auditory and tactile modalities. Table 2 summarizes the information presented for the participants.

Visual information was shown via an HMD (Penny C Wear Interactive Glasses (Fig. 1, left)). The glasses are see-through, and near-retina projection is used to display information to the right eye. The perceived image is hovering in front of the user (Fig. 2, right); the opacity of the image depends on the surrounding lighting conditions and its size and position on the physical facial characteristics of the user. In Study 1, left, right and forward arrows instructed the participant the correct direction to turn (Fig. 2, left). A researcher manually controlled the shown arrows from a remote location, because the system integration had not been completed at the time. In Study 2, the system showed the distance and direction to the waypoint in text format (Fig. 2, centre). When the waypoint was reached, a rectangle (Study 1) or an oval shape (Study 2) was shown.

Auditory instructions were speech-based and transmitted via headphones (Fig. 1, left). In TA condition in Study 2, a more robust set of headphones (Peltor™) with a volume knob was used. Examples of phrases spoken by the system were "Go North-West 120 m", "You are off track, turn left" (prompted when stepping outside of navigation corridor) and "You have reached the destination".

Tactile vibrations were transmitted using a vest made of stretch fabric. There were 36 tactors, or tactile vibrators, equally spaced in three rings around the torso (Fig. 1, right). The tactors vibrated at 120 Hz. The vibrations were either to the left or right side of the torso (Fig. 3), which indicated the direction where the user should turn to in order to get back to the navigation corridor, or a round-torso circling vibration when a waypoint was reached. The tactile vest was worn over a thin shirt in both studies.

2.2. *Study 1: preliminary navigation test*

Study 1 was a navigation test in a controlled outdoors environment.

Table 1
Studies evaluating multimodal systems in navigation and military tasks. The modalities (V = visual, A = auditory, T = tactile) listed pairwise (e.g., VA) mean bimodal stimuli, and a triplet (VAT) trimodal stimuli.

Ref.	Category/Setting	Description	Devices	Output modalities	Evaluation methods
(Elliott et al., 2010)	N, Mil, W F (wooded terrain)	A tactile land navigation system	Hand-held GPS (text or arrows), HMD (GPS map), tactile belt, map + compass	Vx3, T, VT	PM: waypoint completion and navigation time, deviation from route, timeliness of responses to radio, detected targets …; Q (pre and post) (scale 1–7): effectiveness of device; Q (scale 1–7): usability, usefulness, workload, situation awareness, moving, accuracy of guidance, rerouting …; Oral questions: best-liked properties, how to use each device.
(Streefkerk et al., 2012)	N, W A (simulated)	Firefighters' staged rescue task	HMD, tactile belt	VT	PM: completion time, walking speed, # victims found, situation awareness (as percentage of located items drawn on map); Q (scale 0–150): Rating Scale Mental Effort; Q (scale 1–7): preferences, ease of tasks; Q (scale 1–10): Added-value of components; Debriefing
(Smets et al., 2008)	N, W L (game environment)	First responder search-and-rescue task	Screen x2, tactile vest; game controller	VT	PM: time required for rescue; Q (pre): spatial ability test; Q (scale 1–5): situation (location) awareness; Q (scale 1–5): satisfaction: usability, usefulness, comfort.
(Garcia et al., 2012)	N, W L (game environment)	Navigating with multimodal interfaces	Screen, stereo headphones, tactile belt; thumb controls	Vx2, A, T, VA, AT, VT, VAT	PM: time to completion, accuracy of route; Q (pre): Sense Of Direction
(Mynttinen, 2010)	Mil, W A (practice firing range)	A close combat cued shooting task	See-through goggles (led lights), in-ear headphones, a tactile belt	V, A, T, VAT, mixed {V,A,T}	PM: reaction time and shooting accuracy; ECG measurement; Observations using video camera; I: first impressions (three positive and negative issues); Q: NASA-TLX; Q (scale 1–7, each modality separately): modality ranking, suitability, usability, obtrusiveness …; I: modality comparison, easiness …
(Andersson and Lundberg, 2004)	Mil, W L, A (mock-up)	A moving and weapon handling task	Wrist-mounted visual display, tactile vest	T, VT	PM: correct/false action; Video camera; Q (slider scale): comfort, utility, perceptivity of signals and their combinations, effect on movements …
(Oskarsson et al., 2012)	Mil, W, L (simulated vehicle)	Cueing of direction to threat	Head-down/up display, tactile belt, 3-D headphones	Exp.1: V, A, T, VAT Exp.2: VA, TA, VAT	PM: localization error, response time, correct radio calls Q (scale 1–7): mental workload, effort of driving, perception of threat direction, degree of using 3D audio sound for threat localization.
(Ferris and Sarter, 2008)	Mil, W L (game environment)	Cross-modal links between cues and targets	Screen, speakers, tactors on wrists; joystick	VA, AV, TA, AT, VT, TV (cue-target pairs)	PM: target detection, reaction time (variable factors: cue modality and spatial relationship); Video analysis.

Abbreviations: N = navigation, Mil = military, W = wearable, L = laboratory, F = field, A = applied; PM = performance measure, Q = questionnaire, I = interview, pre = prior to test, post = after test. Measures are post-test by default.

Table 2
Summary of information presented for the participants with each modality in each of the two studies (V = visual, A = auditory, T = tactile). Information was automatically updated at 10 m intervals and/or when stepping outside the navigation corridor. In Study 1, the visual instructions were manually controlled.

Mod.	On the move	Waypoint reached
V	Study 1: A left, right, or forward arrow Study 2: Distance and cardinal directions to waypoint in text format inside a rectangle	Study 1: A blank rectangle Study 2: An oval shape
A	Verbal commands:Distance and cardinal directions; Outside corridor: Turn right/left	“You have reached the destination”
T	[No stimulus within corridor]; Outside corridor: Vibrations to the left or right side of the torso	A round-torso circling vibration

Fig. 1. Wearable devices. Left: HMD for presenting visual modality. The light-weight headphones were used in Study 1 and in the bimodal VA condition in Study 2. Right: Tactile vest showing three rings of tactors.

2.2.1. Participants

Four civilian volunteers, aged 20–35 (2 male, 2 female), participated in the study. One participant reported having very good orienteering skills. All participants had experience with smart phones, tablets, and navigators, and one had some prior experience with a wearable device, but not with HMDs.

2.2.2. Task

The study took place in a sports field (length appr. 100 m) surrounded by wooden area and a passing road. The weather was cloudy and cool, and the participants wore coats over the tactile vest. Each route consisted of three waypoints located on different sides of the sports field. The visually unidentifiable waypoints (GPS coordinates) were set in seven different positions and numbered consecutively: three on each side of the field, one starting/ending point (waypoint 1) at the end of the field. The triangular routes were the same for all participants, but different for each condition. The waypoints for the routes were as follows: auditory condition waypoints 1-4-7-1, tactile 1-3-5-1, visual 1-2-6-1, and trimodal 1-3-6-1. Unimodal outputs were first tested individually in the order A-T-V, followed by trimodal output (Fig. 4). Each participant performed the study in the same order with the same pre-set routes.

The participant was instructed to find three waypoints with the help of the system. They were told to turn about 45°, when a vibration (T) or an arrow (V) was perceived. For example, a vibration on the left side of the torso or an arrow pointing left indicated the participant should change the course leftward. The participant could use a compass for the cardinal directions (A), but prior the task, they were also told and indicated by hand gestures that the passing road was almost parallel to north-south direction. Otherwise the participants relied only on the guidance from the wearable devices. They were not shown the map or the waypoints pre-set in the hand-held device. No special training was given besides testing each signal and ensuring the participant could follow the instructions.

2.2.3. Data collection procedure

Prior to test, the participant filled a consent and background information form, which included demographics, orienteering skills and experience with different technologies. During the test, researchers observed the participant from a short distance away.

After testing each modality, a researcher used a first impressions interview: self-evaluated performance (“In your opinion, how well did you perform in the navigation task with the help of the device?”, scale 1–5, min-max) and attention to surroundings (“How well were you able to pay attention to the surroundings while you moved?”, scale 1–5, min-max), and three pros and cons (“Please mention three plusses and three minuses of the device(s) you used”). After testing all modalities, the participant was interviewed again. The interview considered the participants’ opinion on the whole (multimodal) system, their preferred choice of devices/modalities for navigating in terrain, and suggestions for improvement.

2.2.4. Results

All participants completed all routes successfully. The self-evaluated performance was best for the visual modality (manually controlled) and worst for the tactile modality (A 3.5 ± 0.6, T 2.8 ± 0.5, V 4.5 ± 0.6, VAT 3.5 ± 0.6, mean and standard deviation, scale 1–5). On the other hand, the participants’ attention for surroundings was best for tactile and worst for the trimodal condition (A 3.0 ± 0.8, T 4.0 ± 0.8, V 2.3 ± 0.5, VAT 1.5 ± 0.6).

For navigating in terrain, the participants were asked about their

Fig. 2. Left: Visual instructions used in Study 1. Centre: Visual instructions in Study 2, according to which the distance to the waypoint is 80 m south-west. Right: A hovering arrow as seen via the HMD—an illustration only. [span 1.5–2 columns, colour in print].

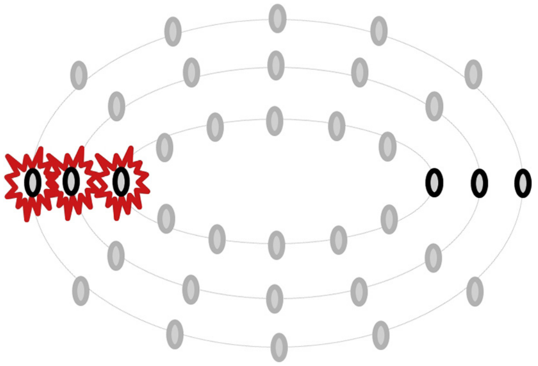

Fig. 3. Tactor configuration of the tactile vest. Only the left- and rightmost tactors were used. When the participant was instructed to turn left to return to the navigation corridor, the three tactors located on the left side of the vest vibrated.

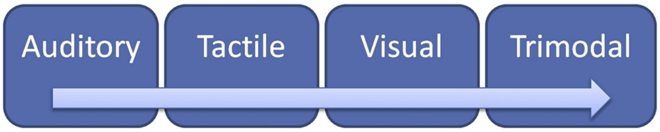

Fig. 4. Modalities tested in Study 1. Each participant used the system four times: first using individual modalities, and finally with all modalities.

preferred modalities. One participant preferred tactile as the primary choice. Another participant answered auditory or visual. The last two participants chose the visual modality as the most preferred one, but they spontaneously added secondary choices, one of them selecting the bimodal VA and the other participant the trimodal VAT. Most of the comments given concerned individual modalities and devices, and there were relatively few comments on trimodal use (Table 3). The comments regarding the slowness of the GPS and consequent buffering of auditory instructions are not included.

2.2.4.1. Technical and other challenges. The slow GPS signal caused several difficulties. The researchers needed to verbally instruct the participants to change direction if they walked too much outside of the sports field, and tell the participant when a waypoint had been reached if the destination reached signal was not delivered due to GPS delays. The visual modality was controlled manually and remotely by a researcher and it was not affected by the slow GPS. This resulted in information conflicts between different sensory channels in the multimodal condition. The interviews revealed that the conflicting information was interpreted in different ways: The participants used either the most reliable or the last perceived output, or an average of tactile and visual modalities (auditory was mentioned to require too much processing; the instructions required processing cardinal directions in a foreign language).

2.3. Study 2: navigation test in a forest

Study 2 lasted for three days and took place in the context of a military exercise in a forest.

2.3.1. Participants

Nine military conscripts (all male, aged 19–20, time served one year or less) participated in the study. All had normal or corrected to normal (contact lenses) vision. Eight participants had right eye dominance, one reported “undetermined”. One participant was left-handed. The participants were very familiar with hand-held and GPS devices, but most had little or no experience with wearable and virtual technologies. They had not used the wearable navigation system before. In addition, all participants self-reported having good orienteering skills, serving as a baseline for the navigation task.

2.3.2. Task

The study took place in a forest in daylight conditions. The weather was sunny and the temperature varied from −5 °C to 0 °C, which felt chilly due to the wind. A thin layer of snow covered the ground. The participants used the system for navigating while they performed a reconnaissance task in the context of a larger military exercise including two opponent sides. The objective was to visit each waypoint (a selection of GPS coordinates supporting the exercise) and return to the starting point after the reconnaissance task was finished. The route for each participant was different, and the participants had the freedom to change the waypoints or step outside of the route if the situation demanded.

The system was tested bimodally (Fig. 5). Five participants were included in the TA condition only, one participant in the VA, and three were included in both conditions separately starting with the TA. In the TA condition, the users wore the tactile vest and a robust set of headphones with a volume knob. In the VA condition, the users wore the HMD and light-weight headphones (Fig. 1, left). In both conditions, the participants carried the hand-held device in a pocket or integrated to a tactical vest. The participants were allowed to use a compass, but in daylight it was not necessary for determining the cardinal directions. The map on the hand-held device could be used as support, but otherwise the participants relied only on the guidance from the wearable devices.

Before starting the test, the participants were shown a short introductory video of the different wearable devices and a slide show on setting up a route using the hand-held device. The participants were informed that the system is a demonstration system

Table 3
Comments on different modalities derived from first impressions interviews in Study 1 (V = visual, A = auditory, T = tactile, VAT = trimodal). The number of participants is given in parentheses if a comment was given by more than one.

Mod.	Pros	Cons	Suggestions
V	Accurate (3) Simple	Arrow disappeared from field of view (3) Non-ergonomic fit (3) Limited visual field due to glasses	Slanted arrow A compass shown on display
A	Distance information provided (3) Clear voice	Not in users' native language (2) Cardinal directions (2)	Message needs to be shorter and simpler to interpret (e.g. left-right) (3)
T	Clear vibrations (3) Easy to follow (2) Surroundings can be monitored (2)	Difficulty in knowing how much to turn (3) The vibrations came too rarely	Support for confirmation on right direction (2) Forward, backward, stop -signals are needed
VAT	Many information sources gives certainty (2) Navigation was smoother than with unimodal	Easier to focus on one device at a time Unsuitable for moving in terrain	–

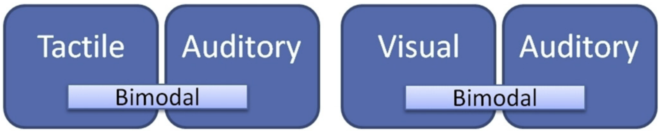

Fig. 5. Tested modality combinations in Study 2.

and that there could be a lag in the GPS signal. All signals were tested before starting, and researchers ensured the participants could perceive them.

2.3.3. Data collection procedure

Prior to test, each participant filled a consent form. A researcher helped each participant to insert waypoints into the hand-held device. The route selection was based on the participant's task in the military exercise. During the task, the participant navigated the route on his own or accompanied by other draftees and, when the task allowed, a researcher. When in the vicinity, the researchers observed and took notes either in writing or using hand-held videocameras. In the TA condition, the participant also wore a head-mounted video camera (manufacturer V.I.O., model POV.1.5 or POV. HD). A separate Android smartphone GPS application was used for tracking the navigated route; this device was placed in the participant's pocket by the researchers. Immediately after the task, the participant was briefly interviewed on their first impressions (self-rated performance and three pros and cons, as in Study 1). In addition to audio-recording the interviews, a pre-filled form was used for notes.

Then each participant was given a multipage questionnaire (Likert scale 1–7, disagree-agree). It included demographics and prior experience with technology (Part 1 of questionnaire), and statements concerning individual modalities (Parts 2–4, 10–12 statements for each modality) and the hand-held device (Part 5) and the whole system (Part 6, 31 statements). The statements in Parts 2–4 regarded the format and interpretability of information, and wearability, usability and usefulness of the device. In Part 6, there were statements regarding the functioning of the whole system, usability and learning aspects, wearability and physical strain, information display, situation awareness, and suitability for field tasks and navigation. There were also open field questions after each part. The three participants who tried both bimodal conditions answered the whole questionnaire (with the exception of the visual modality) after the TA condition, and filled only the part concerning visual modality after the VA condition.

The questionnaire items were mostly adapted from System Usability Scale (SUS) (Brooke, 1996), Questionnaire for User Interface Satisfaction (QUIS) (Chin et al., 1988), systems usability framework (Savioja et al., 2014; Savioja and Norros, 2013), and Situational awareness rating technique (SART) (Taylor, 1989). NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988) was not included in its original format, but the questionnaire contained items regarding mental workload related to each modality and the experienced stress in general. After all participants had completed the task, the following themes were discussed in a focus group: usefulness and autonomous adaptation of different modalities, situation awareness, ergonomics and suitability for military use.

All interview data was transcribed from audio-recordings and analysed. Data from head-mounted and other video cameras were watched and analysed by systematically coding findings and themes that emerged from the data; these included any comments regarding the usability of the devices (mostly the hand-held device), problems in reading instructions from the wearables, and finding the exact location of the waypoint. Questionnaire data was analysed in a spreadsheet program by descriptive statistics and qualitative analysis.

2.3.4. Results

All participants were able to get a feel of how the system worked and use it in navigating in the terrain. Based on the Android phone tracking (separate from the hand-held device containing the waypoints), the routes traversed by the participants were approximately 300 m–1.5 km long and lasted 20–40 min. The routes were not followed directly from waypoint to waypoint, because of terrain features or the enemy situation and reconnaissance needs in the military exercise. Fig. 6 shows two examples of pre-planned waypoints that could be retrieved from the system and the actual routes traversed.

2.3.4.1. First impressions interview and questionnaire results. In the first impressions interview, the participants self-evaluated their performance with the help of the system slightly better in the TA condition (TA 3.5 ± 0.5, n = 8; VA 3.2 ± 0.8, n = 3; mean and standard deviation, scale 1–5). Fig. 7 shows the questionnaire

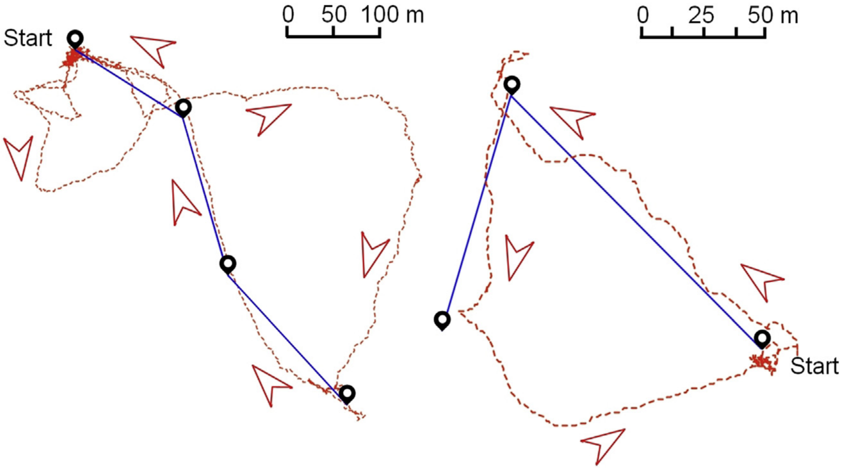

Fig. 6. Two examples of traversed routes. The straight lines indicate the planned route with black waypoints. The dashes indicate the actually traversed and tracked routes. Arrowheads show the direction of walking; in the left figure the preplanned route was navigated "backwards" toward the starting point. The loops near the waypoints indicate that the participants walked in circles searching for the exact location. Note the different distance scales.

results for individual modalities regarding statements common for all modalities (Parts 2–4 of the questionnaire). The data on the auditory modality are from the TA condition (see Section 2.3.3).

All modalities helped in navigating (“The [device] helped me to navigate in the test”, Fig. 7), which was supported by comments to the open questions and the first impressions interview. Table 4 summarizes the comments given in the interviews, questionnaires and the focus group. It was frequently mentioned that the system would support navigation especially in the dark. On the negative side, several comments were made on the attachment of the cables.

The questionnaire results and comments regarding the visual modality reflect the problem with the physical fit of the HMD, which limited the visual field (Table 4) and affected the visibility of the presented information (Fig. 7, top-most chart; see also Fig. 2, right). The researchers’ observations during the signal testing also support this finding. Although the ease of interpretation of the auditory information was estimated to be at about the same level as the other modalities, there were several comments that the guidance needs to be made clearer. Comments were also made on the slowness of the GPS and resulting buffering of audio messages. The tactile vest was rated least distracting of the wearable devices, and many positive comments were given regarding its use especially while moving, and in the dark. The vibrations were, however, hoped to indicate the correct direction more accurately.

The mental workload when navigating in terrain was asked in the context of each modality and was evaluated low (V 1.3 ± 0.5, n = 4; A 1.8 ± 1.4, n = 8; T 1.4 ± 0.5, n = 8; scale 1–7). Kruskal-Wallis (KW) test was used to test differences between modalities. The KW analysis was not significant ($p > 0.05$). According to questionnaire results (TA 5.3 ± 1.9, n = 8; VA 6.0 ± 0.0, n = 1; average of four learning statements concerning the whole system) and written comments, the system was considered easy to learn, and sufficient information on how the system works was given (5.9 ± 1.5; all participants).

2.3.4.2. Focus group. The focus group discussion considered the potential of the whole wearable system. Although all participants did not try all modalities, they had seen the initial introduction video and seen others put on and take off the devices. In general, the system was thought to be more useful in dark conditions (see also Table 4). The concept of multimodality was not covered in the discussions per se. Because the participants had different preferences on the individual modalities, there was no consensus on an optimal setup. The system should, however, be easily put on because the clothing worn depends on the mission. Additionally, all cables should be securely attached and hidden to support moving in all postures.

The effect of the system on situation awareness was also discussed in the focus group. The HMD was thought to force the users to divide their attention among multiple things. The auditory instructions should not come too often, because environmental sounds would be blocked, which is undesired in reconnaissance missions. Additionally, the optimal frequency of repeating the auditory instructions would depend on the speed of traverse and the length of route.

2.3.4.3. Technical and other challenges. The testing conditions were challenging. In addition to coping with the demands of the military

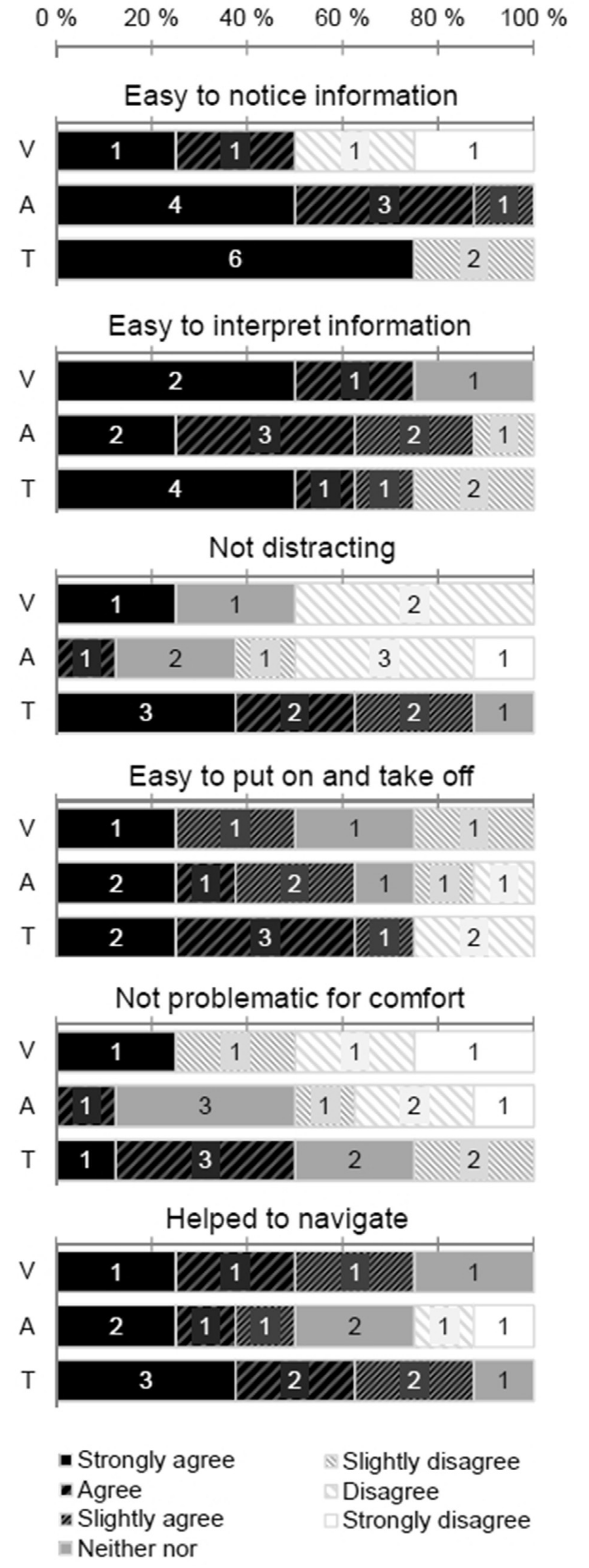

Fig. 7. Participants' responses to questionnaire statements in Study 2 depicted relatively to each modality. Darker colours indicate stronger agreement with the statements whereas lighter colours indicate disagreement. The data labels show the number of respondents. (V = visual, A = auditory, T = tactile. Total number of participants $n_V = 4$, $n_A = 8$, $n_T = 8$. Auditory modality data is reported only in TA condition. The statements in the questionnaire were formulated in more detail, and the formulations of the statements “Not distracting” and ”Not problematic for comfort” were reversed.)

exercise and therefore lack of experimental control, the researchers had to troubleshoot disconnected cables and drained batteries, which was partly due to cold weather. Further, during the study, the GPS was slow and it caused buffering of the auditory instructions.

The participants were instructed to select a few waypoints (GPS coordinates) suitable for their reconnaissance task. They were very adept in using the hand-held device, and even with very little training, able to modify their routes by themselves. They initially inserted 2–4 waypoints, but changed or skipped some of them when the situation in the military exercise required them to do so. This resulted in a drawback: most of the inserted waypoint coordinates were not saved in the system or were overridden by new waypoints. Therefore, we cannot state an exact number for the waypoints found.

The head-mounted cameras were used to estimate if the waypoints were reached with the help of the tactile vest and auditory instructions in the TA condition. Two participants found all the waypoints they sought (one and two waypoints, other waypoints were skipped manually due to non-system related reasons), confirmed by their comments on feeling the round-torso circling vibration. One participant verbally commented that the instructions were making him go in circles (similar to loops in Fig. 6); all three waypoints were found in this manner. For one participant the GPS was so slow that the waypoints could not be found, and for another, based on the video material, it was not possible to say for certain if the waypoints were found. Three participants were noticed to frequently check on the map shown on the hand-held device, and therefore the contribution of the wearable devices on their navigation was undetermined. In the VA condition, only one participant could be followed by researchers, and based on the hand-held camera footage and the participant verbally observing the instructions were guiding him in circles, both two waypoints were found.

3. Discussion

Next we will summarize the findings regarding the navigation with the system. Because the evaluated system was a demonstrator, the results need to be interpreted in how the users foresee its potentials and challenges. Table 5 shows a literature overview regarding the results found in the use of multiple modalities in field navigation and offers a reference for further discussion.

3.1. Navigation with the system

The demonstrator system helped in navigation with all tested modality combinations although there were technical issues with the slow GPS. The wearable navigation system was considered easy to learn with minimal training, which has been also noted by others (Elliott et al., 2010; Eriksson et al., 2008; Kumagai et al., 2005; van Erp et al., 2005). In Study 2, the mental workload was considered low for all modalities evaluated individually, which is typical for wearable devices in the navigation context (see Table 5). In the study by Elliott et al. (2010), the workload was found lower for a multimodal (VT) condition than for individual modalities.

3.2. Unimodal use

In the literature, diverse preferences for individual modalities have been mentioned (Table 5). In a study by Kumagai et al. (2005), the auditory was found preferable over visual for target detection, whereas tactile was liked while moving because it enabled simultaneous tasks using other senses. Another study found tactile the best, followed by visual (Eriksson et al., 2008). Our findings in Study 1 differ from these as there was a preference for visual for terrain travel and self-evaluated performance. However, the visual modality was manually input and therefore very accurate, and the

Table 4
Summary of comments given by participants regarding the system and individual modalities in Study 2 (V = visual, A = auditory, T = tactile). The source of each comment is mentioned in the column on the right, including the number of participants supporting the comment and the related bimodal condition. The comments are from the first impressions interviews (I), questionnaire (Q) and focus group (FG). E.g., “5 in TA I; FG” means that five participants in TA condition gave the comment during their interviews and the issue was also brought up in the focus group.

Mod.	Comments	Source
System	Supports navigation,	6 in TA I, 2 in VA I
System	Supports navigation esp. in the dark	2 in TA I; FG
System	Guides to the right place	3 in TA I
System	Makes navigation easier	2 in TA I; 1 in VA I
System	No need to read paper map	2 in TA I; 1 in TA Q
System	Easy to learn	3 in TA Q
System	Distance information provided	2 in TA I; 2 in VA I
System	Should be easily put on and taken off	100. FG
System	Should be functional also when it's snowing or raining	103. FG
System	Attachment of the cables (e.g., due to vegetation and crawling)	5 in TA I; FG
V	HMD was too big	2 in VA I
V	Limited visual field due to glasses	1 in VA I, 1 in VA Q
V	It should be possible to flip away the see-through HMD	FG
V	HMD forces users to divide attention among multiple things	FG
V	Abundance of information can hamper environment monitoring	1 in VA I
V	Difficulties with moving while wearing the HMD	1 in VA Q
A	Guidance should be simpler	1 in TA I
A	Cardinal directions were confusing	2 in TA Q
A	Auditory instructions need clarification	1 in TA Q
A	Environmental sounds should not be blocked	1 in TA I; FG
A	Guidance should be audible over the sound of running steps	1 in TA I
T	Useful	2 in TA I
T	Convenient, also in the dark	2 in TA Q
T	Light-weight	1 in TA Q
T	Easy-to-use	11 in TA Q
T	Vibration should indicate the correct direction more accurately	1 in TA Q
T	Suitable when moving	1 in TA Q
T	Cables should be attached firmly to support moving in all terrain	1 in TA Q

Table 5

Summary of findings from field navigation studies with multiple modalities reported in literature. Both unimodal and multimodal studies in field and applied conditions are included. The modalities (V = visual, A = auditory, T = tactile) listed pairwise (e.g., VA) mean bimodal stimuli.

Ref.	Category/ Setting	Description	Devices	Output modalities	Results
(Elliott et al., 2010)	N, Mil, W, F (wooded terrain)	Waypoint navigation + secondary tasks	Hand-held GPS (text or arrows), HMD (GPS map), tactile belt, map + compass	Vx3, T, VT	Waypoints were found. Navigation times were significantly lower for V than for T or the multimodal VT (hand-held V with arrows) for speeded traverse. The mean workload was lower for VT than either device used alone. With wearables (T and V-HMD), rerouting obstacles and situation awareness were rated better than with a hand-held GPS. Tactile requires less training and visual attention, and is easy to use. Hands-free was appreciated. Tactile was preferred for travel and visual map/GPS for confirming location.
(Streefkerk et al., 2012)	N, W, A (simulated)	Firefighters' staged rescue task	HMD, tactile belt	VT	The search task took longer to perform and the workload was slightly higher with the multimodal system compared with baseline (difference not significant). 75% of users preferred the tested system over the baseline. The users commented on information overload, and the interface presented inaccurate or irrelevant information for the task.
(Kumagai et al., 2005)	N, Mil, W, F (wooded terrain)	Waypoint navigation + secondary tasks	Helmet-mounted display, mono sound speakers, tactile belt	V, A, T (unimodal)	Waypoints were found; no significant differences between modalities for distance travelled or performance. The devices were easy to learn. Low overall mental workload for the wearables. High acceptance rate for all modalities for terrain traverse. For object detection, A was more acceptable than V. Tactile was liked while moving because visual search and listening were possible. Otherwise no overall preference of any one modality. Visual display needed position adjustment, and users stopped their movement to use it. Tactile was uncomfortable (esp. thermal) and restricted mobility. Direction of A was difficult to determine.
(Eriksson et al., 2008)	N, Mil, W, F (semi-open terrain)	Waypoint navigation + secondary tasks	Hand-held GPS, stereo headphones, tactile belt	Vx2, A, T (unimodal)	Waypoints were reached. With visual (arrows + distance), navigation speed was higher than with T or A (continuous pulsating ringing). Self-rated mental workload was higher for A than T. Two thirds of users preferred T and the rest V. Auditory was not liked due to blocked sounds and the delimiting effect on attention. Tactile directed attention away from terrain less than A or V. Tactile could be improved on usability and integration to equipment.
(Calvo et al., 2014)	N, W, F (open field)	Waypoint navigation	Hand-held mobile phone, stereo headphones, tactile belt	Vx3, A, T (unimodal)	Waypoints were found in all conditions. Egocentric map condition (V) was rated most usable. Comparing V (arrows), A (audio tones), and T conditions, A was faster than V, but A was considered less usable than V or T conditions. Usability of the eyes-free conditions (i.e., A and T) was considered high and perceived mental workload low, supporting the intuitiveness of these displays. Tactors suffered from misalignment.

Abbreviations: N = navigation, Mil = military, W = wearable, F = field, A = applied.

study was done in civilian context. The participants self-reported their attention for surroundings was lowest in the visual condition, which could be a significant factor in military activities, such as in target detection mentioned by Kumagai et al. (2005)). Findings on individual modalities were similar in both studies, and they are elaborated in the following subsections.

3.2.1. *Visual modality*

The visual modality easily suffers from the size and problematic fit of the display, its delimiting effect on the visual field and the difficulty moving while wearing the HMD (Studies 1 & 2; Kumagai et al., 2005). In our system, interpreting distance information and cardinal directions was considered too demanding to focus on. Although providing distance information is important, the advantage of the simplicity of using arrows has been noted (Study 1; Elliott et al., 2010; Eriksson et al., 2008). Future improvements such as slanted arrows or displaying a compass were suggested the participants. Additionally, the (see-through) eye piece could be mounted to a helmet and flipped down (Kumagai et al., 2005) or otherwise flipped away from visual field (Study 2).

3.2.2. *Auditory modality*

Auditory information was evaluated to be easily noticed. The participants requested for the auditory message to be shorter and simpler (instead of spoken distance and cardinal directions), which might be difficult to attain while preserving the well-liked distance information. Kumagai et al. (2005) have tested stereo sounds, but some users had difficulties in detecting from which side the sound was coming from. In general, the volume level should be adjustable to accommodate different individuals (Kumagai et al., 2005) and to match the environmental sounds (Study 2) as the environmental sounds are easily blocked (Study 2; Eriksson et al., 2008). In addition, the optimal repetition frequency of the instructions would depend on the speed of traverse and the length of route.

3.2.3. *Tactile modality*

The tactile modality was liked on many accounts: it is easy to follow, and convenient while moving and observing the environment, also in the dark (similar to Kumagai et al., 2005). The tactile modality has been also praised on its hands-free and “eyes-free” operation (Calvo et al., 2014; Elliott et al., 2010). Although Elliott et al. (2010) reported tactile cues were not perceived as strongly when running uphill, our participants thought the information was easy to notice also in the field conditions. In our studies, the coding scheme was very simple (left and right vibrations), and the participants wished for more accurate directions. Kumagai et al. (2005) and Jones et al. (2006) have used a directional coding scheme successfully. However, distance coding has been found more difficult to interpret and it did not improve performance compared to a control condition (van Erp et al., 2005).

3.3. *Multimodal use*

There was a smaller number of findings on the multimodal use, partially because of the participants’ tendency to elaborate on the modalities separately and the format of the questionnaire used in Study 2. In Study 1, the participants had a chance to compare both unimodal and trimodal use, and they had a better basis for commenting on multimodal use against a “unimodal baseline”. In both studies, there were individual preferences on modality combinations.

For wearable navigation systems, the direction of and the distance to the next waypoint, and the simplicity of interpreting the displayed information, have been noted as important (Elliott et al., 2010; Kumagai et al., 2005; van Erp et al., 2005), which was also supported by our findings. Added to that, in the military context, there is a need to be able to observe the environment and act (e.g., run, crawl, aim, shoot) without interference from the devices.

This raises an interesting question of whether to use one device with multiple functionalities, or several devices with simple—and possibly redundant—information. Redundancy may diminish user's concern about not noticing the information and against the breakage of devices. Issues that require consideration include battery life, cabling, wearability (see guidelines by Gemperle et al., 1998; Knight et al., 2006), learning, and ease-of-use. Wearability is especially important with tactile displays, because continuous contact with the skin needs to be maintained (Calvo et al., 2014; Jones and Sarter, 2008). Furthermore, the time of day affects the experienced mental effort (Kumagai et al., 2005). Multisensory cues can be advantageous under perceptual load (Spence and Santangelo, 2009). An example of a successful modality combination was suggested by Elliott et al. (2010), who concluded that a visual display supports where the user is with respect to waypoints and a tactile display supports staying on course. Alternatively, automatic modality adaptation (i.e., adapting a multimodal interface to different interaction contexts) could be considered (Kong et al., 2011).

3.4. *Methodological considerations*

The data collection methods used in our study gave us quite a comprehensive understanding of the various user aspects of the system. Feedback on individual modalities, as well as on the combination of them, was received. A limitation of this study was the lack of objective performance measures (e.g., completion time and deviation from the route, see Tables 1 and 5). Objective measures were not calculated because the system was a demonstrator and, in Study 2, the navigation speed and accuracy were of secondary priority to complying with the objectives of the military exercise. In this respect, the qualitative approach used in this study offers more valuable insights to the use of the wearable multimodal system.

Additionally, we realized that more attention needs to be given to *how* the modalities were used by the participants in the multimodal conditions, e.g., reliance on one or more modalities, conflict handling between information sources, and dependence on task and context. To facilitate the analysis of multimodal interaction, we drafted a suggestion for viewing multimodal data collected in the field (Fig. 8). This kind of presentation of the data could work as a post-trial video analysis tool for researchers, or act as material for “think aloud” interviews or as stimulus for workshops with potential users and system developers (cf. Buur et al., 2010).

In general, a controlled study (cf. Study 1) is useful for comparing individual modalities and their combinations and for determining whether a user can succeed in navigation using that modality alone. Field trials (cf. Study 2) can concentrate more on performance, workload, situation awareness, preferences, and strategies of how different modalities were used in certain tasks (see also context of use by Bristow et al. (2004)) and whether this strategy changed during the study. In addition to measuring the usability of individual modalities, the usability of the system as a whole (e.g., Savioja and Norros, 2013) and the use of multiple modalities simultaneously (see Beringer et al., 2002; Kühnel et al., 2010; Ramsay et al., 2010; Turunen et al., 2009; Wechsung, 2014) should be covered.

3.5. *Conclusions*

All three modalities evaluated in these two studies were found helpful in navigation and were very easy to learn. Although each modality has its weaknesses, in a multimodal system their

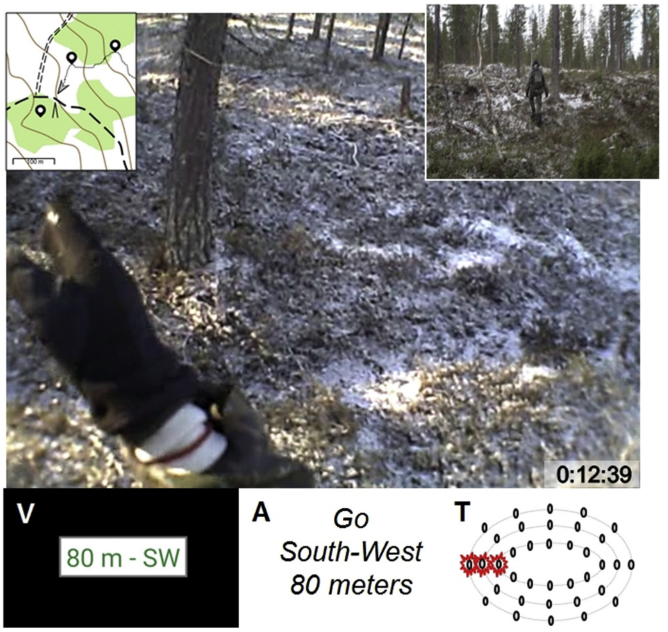

Fig. 8. Suggested data analysis station for post-trial replay of data collected using cameras and log data. In the main screen, video from the head-mounted camera shows what the user was looking at. Multimodal system output is replayed under the main screen, and insets show—on secondary screen if available—a map of the traversed route and video stream from a general-view (e.g., hand-held by a researcher) or a 360-degree camera. Gaze tracking data and physiological measurements (e.g., pulse) could also be shown.

strengths can be employed and built on. A simple visual arrow can integrate seamlessly to the constantly monitored surrounding view while traversing in terrain in daylight conditions. Additionally, visual information can be constantly displayed (vs. sequential data presentation). The auditory modality, i.e., speech, is an intuitive way for presenting distance information to a target. The tactile modality is especially convenient for supporting navigation in the dark, because it does not strain other perceptual modalities, and also very intuitive for immediate reactions (cf. a person tapping another on the shoulder). Multimodal use is complicated to evaluate because both the devices themselves and the type of information relayed affect the user experience, and it is easier for users to elaborate on individual modalities. Redundant information through multimodal systems, however, can increase users' confidence in the correctness of the information.

However, while acknowledging the benefits of the modalities, we could identify some general user requirements for wearable multimodal systems for field conditions; each of these requirements are critical in that if some of them are not met, the users may be reluctant to use the system:

- The user has to be able to use the system in all weather and lighting conditions
- The devices should not block the user from ambient events
- The tactile patterns should be detectable in different postures
- The wearable system should fit well and offer mobility
- The system should be easily put on and taken off
- The system should not transfer heat to the user
- The user should be periodically informed of the status of the system and its modalities
- The relayed messages should be simple to interpret.

These results can guide the future design and evaluation of multimodal systems in the field. In addition to finding an optimal modality combination for each task and context, there are several open possibilities left for future research: what type of information is displayed through each modality, how to construct a simple but efficient stimulus coding for both distance and direction, how do the individual modalities contribute to the perception of the whole in field conditions, and how do users deal with conflicting information.

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