# Visual, Auditory and Tactile Navigational Information Presentation Modalities in Support of Soldier Wayfinding

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## ABSTRACT

*The Soldier Information Requirements Technology Demonstration (SIREQ TD) project was a human-factors-focused experimentation program to identify technologies that may significantly enhance the performance of future soldiers. SIREQ TD identified navigation as an important task, and further cognitive task analyses confirmed that wayfinding via compass and map is difficult, particularly at night. SIREQ TD developed the Future Infantry Navigation Device (FIND) as an experimentation test bed to enable detailed studies of the impact of various modes and levels of navigational information on soldier wayfinding performance. The FIND system used a GPS receiver and magnetic compass coupled to a laptop computer carried in a small backpack to track soldier position and movement. Comparison of position information against the stored map and pre-planned routes allowed the computer to provide navigational cues to the soldier via various sensory input means. Early studies in SIREQ TD comparing visual, auditory, and tactile display modalities against the in-service map/compass/pace-count method of navigation demonstrated the superiority of technology-assisted wayfinding and pointed to changes that could be made in the display systems to enhance their utility and usability. This paper summarizes the results of numerous studies that addressed alternative and improved displays.*

*For visual displays we compared rolling compass, cross-hair, magnitude arrow, egocentric fixed pointer, egocentric moving pointer, and exocentric moving displays. We also investigated head-mounted (occluded), heads-up (look-through virtual retinal) and weapon-mounted displays during wayfinding and target detection tasks. Occluded, see-through prism and larger tablet displays were compared against paper map and compass for effectiveness in displaying maps, navigating, mission planning and execution, platoon coordination, and battlefield awareness. Auditory display studies examined aspects such as sound dimension (1D or monaural, 2D or binaural/stereo, 3D or spatialized audio) and tone characteristics (such as pitch and rate of "beeping") in various combinations to provide directional and distance cues.*

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*Tactile display studies looked at aspects such as number of tactors (between 3 and 8) and location of the tactors on the body (abdomen, chest, neck/wrists, head).*

*Key findings were as follows:*

*Visual Displays:*

- *in-service compass, level indicator and rolling compass displays were inferior to all other visual displays regarding time to locate a waypoint*
- *an egocentric frame of reference is desirable to reduce misdirection*
- *directional information is vital*
- *both analog and digital information are desirable*
- *a forward point of view has merit*

*Auditory Displays:*

- *direction and angular distance to the bearing are important navigational cues*
- *direction (via left/right ear) and angular distance (via changing rate and/or pitch of tone) work well*
- *3D directional information may be difficult to discern at times; 2D is adequate*
- *bearing and distance information provided by voice might be very helpful*

*Tactile Displays:*

- *tactors performed better when placed on the chest or torso as opposed to on the neck and wrists*
- *chest and torso were the locations preferred by subjects*
- *8-tactor systems performed better than 3- or 2-tactor systems, and were preferred by subjects*
- *directional cuing and an indication of angular distance to the waypoint could be conveyed best with an 8-tactor system and were considered important information*

# 1.0 BACKGROUND AND INTRODUCTION

## 1.1 The Soldier Information Requirements Project and Navigation

Many nations around the world have embarked on soldier modernization programmes. The aims of these efforts are, in essence, to improve soldier performance through technology. Defence R&D Canada initiated the Soldier Information Requirements Technology Demonstration (SIREQ TD) project as a human-factors-focused experimentation program to identify technologies that may significantly enhance the performance of our future soldiers in the areas of command execution, target acquisition, and situational awareness.

SIREQ TD began with a Cognitive Task Analysis [1] to identify mission-critical tasks that could benefit significantly from technology insertion. Given the advances that have taken place in Global Positioning Systems (GPS) in recent years, it was no surprise that navigation and wayfinding were identified as key tasks where technology could potentially provide a significant improvement in performance. The current in-service method of navigation relies on a paper map, compass, and pace counting to reach designated waypoints. Pace counting is inaccurate and unreliable for distance measurement and is very demanding in terms of mental workload, especially when soldiers have to be watchful for route hazards and enemy threats. Navigation by this method is very prone to error, particularly at night, and is also highly dependent on individual skill and capability. A GPS receiver and digital compass connected to a wearable computer and display system should overcome these limitations and improve navigation accuracy considerably.

### 1.2 Navigational Information Input Modalities

Navigational cues and information can be presented to the soldier using visual, auditory, or tactile displays. Early studies in SIREQ TD [2, 3] compared such displays against the in-service compass and pace count method for their effectiveness in supporting wayfinding. These studies also varied the amount of information provided to soldiers (direction, direction plus distance, etc) in an effort to further explore information needs. A companion paper in these proceedings [4] describes these initial studies in detail, while this paper describes the results of studies that explored the utility and usability of the different display modalities.

## 2.0 METHODOLOGY

### 2.1 Future Infantry Navigation Device (FIND)

The Future Infantry Navigation Device (FIND) was developed as a versatile test-bed for the SIREQ TD navigation and wayfinding studies. The system is described in more detail in the previous companion paper [4]. Briefly, it comprises a GPS and digital magnetic compass connected to a ruggedized laptop computer carried in a small backpack. An experimenter's remote control is used to control information presentation and data collection, and a soldier's display activation remote control button operates the user's display. Output signals are compatible with a range of visual, auditory or tactile displays. Pre-planned route waypoints are entered into the FIND software. The system continuously samples the wearer's position and direction of regard and displays information such as: current position and heading; direction and distance to the next waypoint; cardinal direction (N, S, E, W); other waypoint information such as waypoint number and grid reference; and even position of known friendly and enemy locations or hazards.

### 2.2 Static Tests of Navigational Information Presentation

Studies that focussed on alternative presentations of directional information such as bearing were conducted in a "static" manner. In these studies soldiers stood in a fixed location and rotated to face in the direction of a waypoint, but did not actually move to that waypoint. For each display system being investigated, soldiers were given 12 practice waypoints to become familiar with the system before undertaking the test session of locating 12 experimental waypoints. Waypoints were offset by 25º, 65º or 120º either left or right from the previous waypoint, with each offset and direction combination occurring twice during a session. Soldiers activated the FIND system to present a waypoint bearing by pressing a button on a remote control and then rotated to face the waypoint. When they felt they had successfully found the waypoint they pressed another button on the remote to stop the system. Actual facing direction was determined by an electronic compass that was updated at a rate of 10/s. Objective performance measures included time to find the correct bearing, accuracy of estimated bearing, frequency of misdirection errors, and number of head/body direction reversals. Subjective measures included ease of locating waypoint bearing, situational awareness and mental demand ratings, and a focus group discussion. Questionnaires also identified preferences, likes, dislikes, and possible improvements.

#### 2.2.1 Visual Displays for Static Navigation Studies

Seven different computer-generated visual displays were examined in this series of static studies. All were presented to the user on a TekGear M1 Personal Viewer Helmet Mounted Display (Figure 1).

**Figure 1: TekGear M1 Personal Viewer HMD used for static visual mode studies.**

*Display #1: Level Indicator (LI)*

The Level Indicator (LI) display resembled a level meter (Figure 2). The display presented successively more filled circles as the participant turned closer to the waypoint. Note that this display did not provide an explicit indication of which direction to turn to face the waypoint.

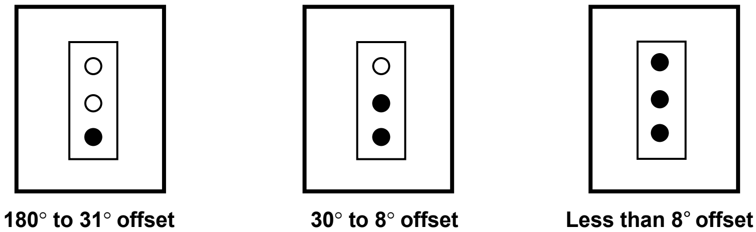



**Figure 2: Level Indicator display**

*Display #2: Magnitude Arrows (MA)*

The Magnitude Arrows (MA) display consisted of left and right arrows that showed the soldier which way to turn to face the waypoint (Figure 3). The filled arrows got progressively shorter as the soldier's facing direction neared the bearing to the waypoint. When the soldier was facing within 8º of the waypoint a marker appeared in the top centre of the display.

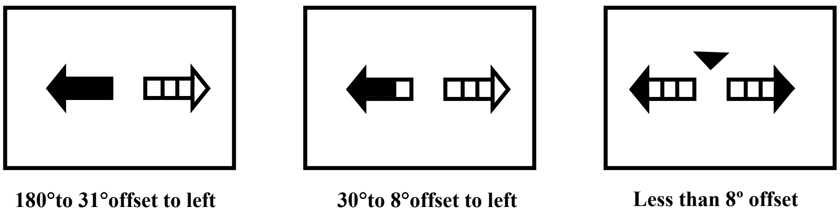



**Figure 3: Magnitude Arrows display**

*Display #3: Cross Hair (CH)*

The Cross Hair (CH) display consisted of arrows that indicated the direction the soldier needed to turn (Figure 4). A vertical line appeared when he was facing within 30º of the waypoint. Within 8º of the waypoint the arrows disappeared and a distinctive crosshair was produced to serve as a guide.

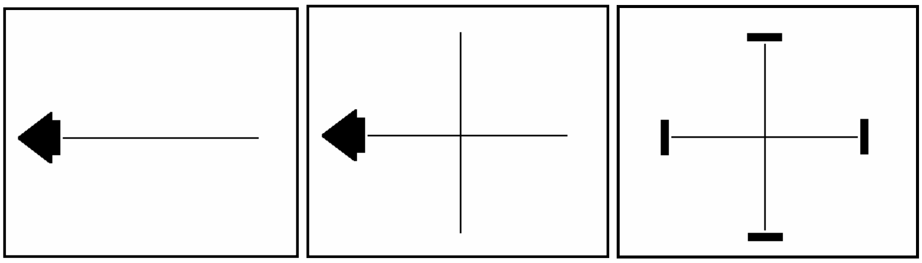



**Figure 4: Cross Hair display**

*Display #4: Egocentric - Moving Pointer Dial (Ego-MP)*

The Egocentric – Moving Pointer Dial (Ego-MP) display comprised a moving pointer that rotated within a stationary dial display to indicate the direction of the waypoint (Figure 5). The direction the user was facing was indicated by a small fixed triangle at the top of the display. As the participant turned to face the waypoint, the pointer moved toward the users' facing direction.

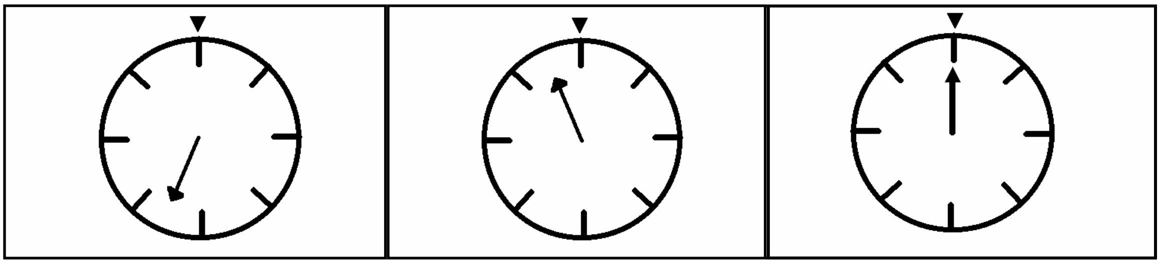
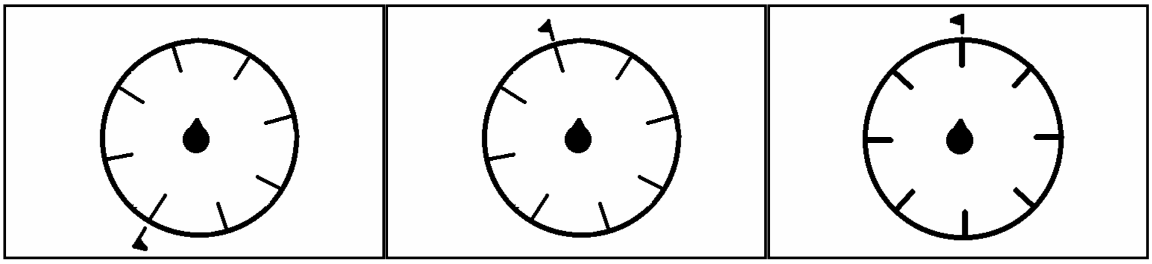



**Figure 5: Egocentric - Moving Pointer Dial display**

The display had a continuous scale and the user was given a visual indication of offsets every 2º. This differed from the categorical displays described above in which the presented information changed only at established offset thresholds. This display simulated a hand-held GPS screen.

*Display #5: Egocentric - Fixed Pointer Dial (Ego-FP)*

The major difference between the Egocentric – Fixed Pointer Dial (Ego-FP) display (Figure 6) and the previous moving pointer display is that the circular dial with its eight cardinal points turned as the subject rotated. The direction the user was facing was indicated by a central fixed pointer shaped like a head with a nose that always pointed to the top of the display, while the waypoint was a small flag on the rotating dial. This display had a continuous scale with visual indication of offsets every 2º.

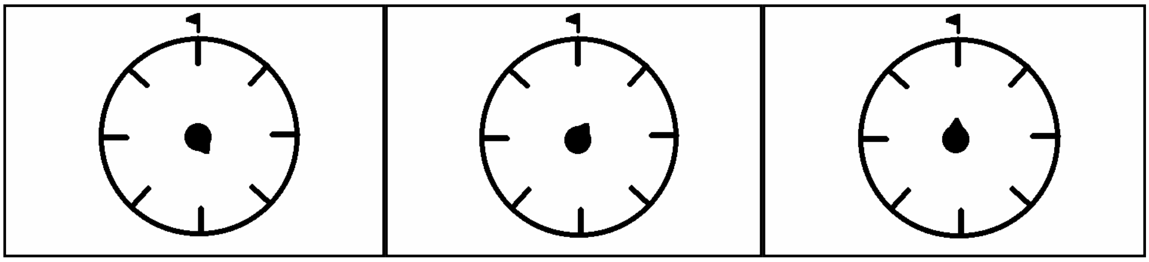


180° to 31°offset to left | 30° to 8°offset to left | Less than 8° offset

**Figure 6: Egocentric - Fixed Pointer Dial display**

*Display #6: Exocentric - Moving Pointer Dial (Exo-MP)*

Exocentric – Moving Pointer Dial (Exo-MP) display (Figure 7) comprised a moving pointer (head with nose) that rotated within a stationary dial to indicate the facing direction of user relative to the waypoint (i.e., the inverse of display # 4). A small flag icon representing the waypoint was always located at the top of the display. As the participant turned to face the waypoint the pointer representing the user rotated. This display had a continuous scale with visual updates every 2º.

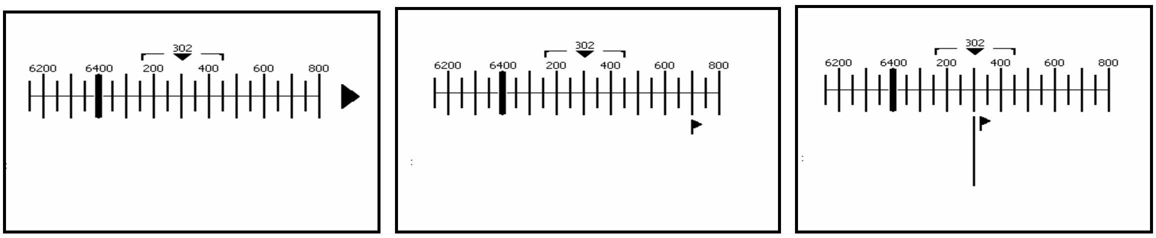


180° to 31° offset to left | 30° to 8° offset to left | Less than 8° offset

**Figure 7: Exocentric - Moving Pointer Dial display**

*Display #7: Rolling Compass (RC)*

The Rolling Compass (RC) display (Figure 8) featured an analog aspect with arrows and a moving flag similar to previous displays. In addition, bearing was displayed on a digital meter where the numbers indicated the current facing direction rounded to the nearest 50 mils (approximately 3º).




180° to 31°offset to right | 30° to 9°offset to right | Less than 8° offset to right

**Figure 8: Rolling Compass display**

As the soldier turned closer to the waypoint, the arrow became a small flag icon within the field of view. The field of view was 1050 mils, or 60º, consistent with the convention of ±30º. As the flag or waypoint direction entered a bracketed area of ±8º (300 mils), an additional reference line or guide was provided. This reference line could be used like the crosshair guide to select a landmark.

*In-service Compass (IC)*

The Canadian Forces currently use a lensatic magnetic compass as the In-service Compass (IC) (Figure 9) in conjunction with paper maps. This was the baseline visual display for all tests.

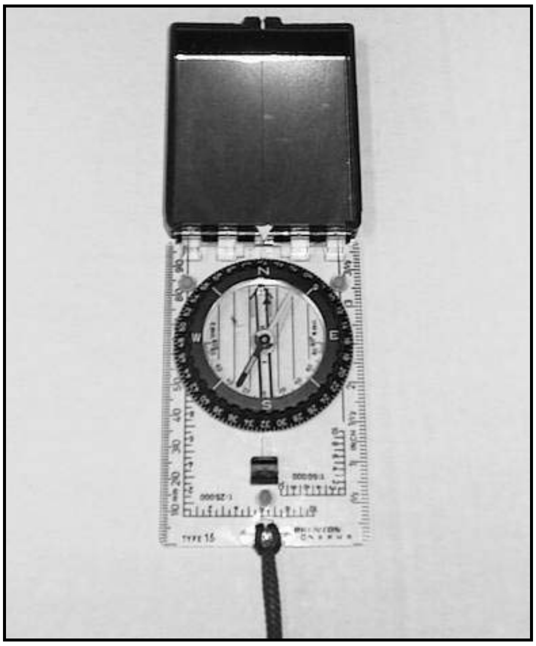


**Figure 9: In-service Compass**

### 2.2.2 Auditory Displays for Static Navigation Studies

Infantrymen operating in hostile environments are required to maintain high levels of vigilance, which places extraordinary strain on the visual channel. An alternative means of information transfer is the auditory channel. Some of the benefits of an auditory display over a visual display are the ability to receive information in a 360$^o$ range, and the ability to be used at night or in low visibility conditions [5]. As well, an auditory display can be used effectively to display beyond-the-horizon information, and it works well in environments featuring multiple visual obstacles (i.e., urban location, mountains, or forest) [5]. The auditory channel may offer an advantage during infantry navigation tasks by employing an attentional pathway that is not likely to conflict with other high attentional demand tasks, such as visually searching for an enemy.

Seven auditory display designs involving three dimensions of sound (1D, 2D, and 3D) and four combinations of tonal characteristics (constant rate and constant pitch [C], changing rate and constant pitch [R], constant rate and changing pitch [P], and changing rate and changing pitch [RP]) were studied.

1D sound was considered mono sound, which presented the same sound in both the left and right ear. 2D sound was considered binaural sound, which presented the sound in either the left or right ear. 3D sound used a head-related transfer function to virtually place the sound around the soldier. The dimension of sound was used to present directional information about the waypoint while the changing rate and pitch presented information about the angular distances from the bearing. The seven auditory displays investigated were 1D-RP, 2D-C, 2D-R, 2D-P, 2D-RP, 3D-C, and 3D-RP, as shown in Table 1.

**Table 1: Auditory Display Designs**

| | Auditory Dimension | | |
|---|---|---|---|
| **Tone Characteristics** | **1D (mono sound - both left and right ears)** | **2D (binaural sound - left, right or both ears)** | **3D (HRTF sound – virtually spaced)** |
| ***Constant*** **Rate & Pitch** | | 2D-C | 3D-C |
| ***Changing Rate*** **& Constant Pitch** | | 2D-R | |
| **Constant Rate &** ***Changing Pitch*** | | 2D-P | |
| ***Changing Rate*** **&** ***Changing Pitch*** | 1D-RP | 2D-RP | 3D-RP |

### 2.2.3 Tactile/Haptic Displays for Static Navigation Studies

Conventional means of information transfer via the visual and auditory pathways may be nearing their respective saturation points. Alternative means of getting information to the soldier through the haptic or tactile sensory pathway could be highly desirable, particularly in environments that demand high levels of information transfer and situational awareness [6].

Seven tactile display designs were used as described in Table 2. The displays differed in their location on the body, the number of vibrotactile transducers (or tactors) they utilized, and the location of the electronic compass. The four locations on the body were the torso (waist), chest, neck, and wrists. Three-tactor systems were tested on the torso, chest and neck. A two-tactor system was used on the wrists, while an eight-tactor system was used on both the torso and chest locations. The electronic compass was located either on the head or on the body.

**Table 2: Tactile Display Conditions**

| | Tactor Layout | |
|---|---|---|
| **Tactor Location** | **Bilateral** | **Distributed** |
| **Torso** (lower abdomen) | **Condition 1 and 2** 3 tactors Left, Right, Front | **Condition 6** 8 tactors Front, Back, Left, Right, Front-Left, Front-Right, Back-Left, Back-Right |
| **Chest** (below nipple line) | **Condition 3** 3 tactors Left, Right, Front | **Condition 7** 8 tactors Front, Back, Left, Right, Front-Left, Front-Right, Back-Left, Back-Right |
| **Neck** | **Condition 4** 3 tactors Left, Right, Front | |
| **Wrists** | **Condition 5** 2 tactors Left and Right | |

## 2.3 Dynamic Tests of Navigational Information Presentation

The major limitation of the static tests is that the participants did not actually move to the waypoint. As a consequence, factors such as ease of manoeuvrability and interference with the conduct of concurrent tasks such as searching for enemy, terrain traverse, avoiding obstacles, communications, etc, could not be assessed. Therefore, a series of dynamic tests was undertaken to examine some of these issues in a more realistic test situation.

For dynamic studies, soldiers performed waypoint-to-waypoint navigation through pre-planned routes in wooded terrain using the FIND system and visual or tactile displays. Routes were typically 1-2 km in length, with 4-5 legs in each route. Multiple routes of similar complexity were prepared for each experiment so that no soldier navigated the same route more than once and to minimize the development of “beaten paths” as cues for navigation. In addition to the navigation task, soldiers were required to detect and simulate engagement of static enemy targets en-route, as well as avoid obstacles such as simulated minefields.

As in the static studies, the electronic compass was updated at a rate of 10/s, and GPS position was updated at a rate of 1/s. Objective measures collected for analyses in the dynamic studies included: time to complete route; extra distance traveled; root mean square error deviation; waypoint estimation error; route tracking and obstacle avoidance accuracy; speed of navigation and terrain traverse; target detection and engagement performance; and the frequency and duration of consults of the FIND system. Subjective assessments included standardized measures of mental workload (NASA-TLX, [7]) and situation awareness (SAGAT, [8]), along with customized scales and acceptability ratings for factors such as: ease of use; quality, quantity and type of information; workload demands; ability of the aid to support situation awareness; task-relevant and overall effectiveness; and many other questionnaire items. Additional subjective data were collected via observation by human factors specialists and during in-depth focus group discussions with participants.

### 2.3.1 Visual Displays for Dynamic Navigation Studies

Navigational information was presented using either the Tekgear M1 Personal Viewer (occluded display), the Microvision Nomad Virtual Retinal Display (VRD; see through display), or a Garmin e-trex Summit GPS strapped onto the weapon and set to the “navigate/big compass” page (Figure 10).

TekGear M1 Personal Viewer — Microvision Nomad VRD — Garmin e-trex Summit

**Figure 10: Visual displays used for dynamic navigation studies.**

The FIND software generated information for the two HMDs that emulated the Garmin “big compass” display. For the occluded display the image was black-on-white, while with the Nomad VRD red writing appeared over the foreground environment being viewed through the prism.

### 2.3.2 Tactile Displays for Dynamic Navigation Studies

In this study soldiers were asked to navigate a short route (733 m) with one of three tactor displays. The designs comprised an eight-tactor system on either the head or the chest, as well as a four-tactor system on the head. The electronic compass was positioned on the back for all three tactile display conditions in this study.

### 2.3.3 Visual Displays for Navigation, Mission Planning and Execution, Platoon Coordination, and Battlefield Awareness

In addition to the individual soldier navigation performance studies described above, SIREQ TD also compared the effectiveness of occluded, see-through prism and larger tablet displays against paper map and compass for effectiveness in displaying maps, navigating, mission planning and execution, platoon coordination, and battlefield awareness. These displays are shown in Figure 11.

**Olympus M2 Monocular HMD** **MicroOptical CO-3 Prism Display** **Larissa Daylight Readable Display**

**Figure 11: Visual displays used for studies of platoon mission tasks.**

These missions required a platoon of dismounted infantry to navigate wooded terrain to an objective rendezvous, plan and brief an assault on an objective building in a mock village, maneuver to assault positions, and then execute the urban assault.

## 3.0 RESULTS

### 3.1 Static Navigational Information Presentation Results

### 3.1.1 Visual Displays in Static Navigation Tests

Results showed that for time to identify waypoint bearing the level indicator display, the rolling compass and the in-service compass were inferior to all other displays. The time to identify the bearing also increased with increasing bearing offset. For accuracy, all displays were significantly more accurate than the in-service compass. In terms of frequency of misdirection, the level indicator and the exocentric moving pointer display showed more frequent misdirections than did the other displays. Subjective measures of performance included ratings of ease of use, acceptance for land navigation, and mental demand; on these measures the level indicator was found to be significantly more difficult to use than other displays. There was no difference in mental workload among displays, but the level indicator display was rated as significantly less acceptable for land navigation and for situational awareness. Not surprisingly, the level indicator display was also rated as the least preferred display. Comments were collected to identify likes, dislikes, and possible improvements required for HMDs.

### 3.1.2 Auditory Displays in Static Navigation Tests

Based on the results of the auditory tests, soldiers require two things to be present in the design of an auditory wayfinding display: 1) indication of the direction of the bearing [e.g., tone presented in either the right/left ear as 2-dimensional or 3-dimensional sound]; and 2) indication of the angular distance of the bearing [e.g., changing rate and/or pitch].

The least preferred auditory displays were the 1D-RP and 3D-C displays. The main reason for dislike of the 1D-RP display was the lack of direction information it provided for the waypoint, while with the 3D-C display soldiers found it very difficult to determine when they were facing in the direction of the waypoint. On the questionnaire, the 3D-RP was rated the most preferred, but when asked during the focus group, all of the soldiers preferred the 2D-RP display. Soldiers commented that when facing closer to the bearing it was more difficult to determine directionality with the 3D-RP display than with the 2D-RP display.

Both experimental design and auditory display improvements were recommended for future studies. These included having soldiers use the auditory displays to determine bearings and advance to the waypoints, adding additional information in the display such as distance to waypoint in metres and bearing to waypoint in mils, having both presented in voice form, and integrating a volume control. Also, future experiments should investigate the effect of combining two or more modalities for wayfinding.

### 3.1.3 Tactile Displays in Static Navigation Tests

The results of this trial indicated that not only did the designs for the torso and chest perform better than the neck and wrist designs, but these were also preferred by the soldiers. Performance data showed that the eight-tactor systems were better than three- or two-tactor systems, and were also more favoured by the soldiers. Eight tactors provided a directional cue and an indication of the angular distance to the waypoint, which was identified by participants as an important feature. The optimal location for the electronic compass was uncertain and indicated that further study was needed so that this issue could be investigated under more realistic conditions. Several interface design issues were also identified, including user ability to control the vibrational characteristics of the tactors (particularly intesity), as well as the need to integrate coded information such as location or distance to waypoint.

## 3.2 Dynamic Navigational Information Presentation Results

### 3.2.1 Visual Displays in Dynamic Navigation Tests

There were no significant differences between display configurations for the time participants took to complete their wayfinding routes. However, soldiers travelled 60% further (232 m vs 142 m further on a 1200 m route) with the occluded display compared to the other visual displays. Navigational accuracy, calculated as the root mean squared error deviation from a straight line path between waypoints, did not differ significantly between displays. While accuracy of waypoint estimation was significantly worse with the weapon-mounted GPS device, the absolute distance error was quite small operationally (about 12 m vs 6 m). There were no differences between systems in the number of targets engaged en route

Subjective assessments of usability indicated that the occluded display was rated unacceptable by more than 20% of the participants in almost all categories, while the weapon mounted display was rated generally more acceptable than the VRD display. The weapon mounted display was rated highly with regard to target detection. The results of a vote for overall preference were: Occluded 0, VRD 1, Weapon 15. The general conclusion was that a hand-held GPS would serve soldiers very well for dynamic navigation.

### 3.2.2 Tactile Displays in Dynamic Navigation Tests

The objective performance results of this trial indicated that an eight-tactor system located on the chest provides an optimal number of tactors and site of stimulation. The majority of participants also preferred the chest location and expressed reservations about integrating the head-mounted tactile system into a helmet. Eight tactors provided an indication of both direction and angular distance to the waypoint bearing, which were deemed important by the soldiers. The optimal location of the compass was discussed during the focus group. All soldiers preferred the compass on the body when the tactors were around the chest as it allowed them to watch their arcs without changing the incoming navigational information. If the tactors were to be located on the head, then eleven out of eighteen (61%) participants felt the compass should also be positioned on the head.

Soldiers felt that distance, bearing, and grid location are important while navigating with the tactile system. Such information might best be provided visually or verbally when requested by the user, since coding using tactor amplitude or pulsing might lead to confusion. This latter finding points to the potential benefits of multi-modal displays wherein the tactile display might provide directional cues while the visual or auditory displays can be interrogated when the user has the capacity and desire to do so. Further research is required to determine the optimal method(s) of providing information using tactile or multi-modal displays.

### 3.2.3 Visual Displays for Platoon Mission Operations

The results of this experiment indicate that digital map information is useful and desirable for many infantry soldier tasks. Participants noted that the digital map display enabled all sections to obtain a comprehensive, common operating picture of the battle while maintaining stealth and unit separation. Situation awareness was also improved with the digital map conditions, specifically for knowing the location and status of the other platoon elements. Participants rated the see-through prism and the tablet displays as most preferred, with the occluded display being judged unacceptable overall. While participants considered both the prism and tablet displays as being acceptable overall for digital map information, they tended to view the role assignment of these displays differently.

## 4.0 SUMMARY

Technological advances in GPS, portable computing capability and miniature high resolution displays are coming together to make powerful portable navigation systems possible. These will change forever the way humans find their way around. The studies reported above demonstrate that modern technology can significantly improve soldier performance in the areas of navigation, wayfinding, situation awareness, mission planning and mission execution. However, the studies also show that the systems must be designed with the user and the task in mind. A solid human-factors-based approach will ensure that novel technologies provided to the soldier will actually be used to optimize performance, rather than being just a novelty that takes up precious space, weight and power on the backs of our already overburdened infantrymen.

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## 6.0 SIREQ TD PROJECT REFERENCES

The results presented in this paper represent a small subset of the extensive body of work conducted in the SIREQ TD project. Over 70 technical reports detailing the results of six years of effort into soldier information requirements are available from the Canadian Defence Information Database (CANDID) at the following website:

http://pubs.drdc.gc.ca/pubdocs/sireq_e.html

The following SIREQ TD reports are the sources of the information presented in this paper.

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