Waypoint Navigation with a Vibrotactile Waist Belt

JAN B. F. VAN ERP, HENDRIK A. H. C. VAN VEEN, and CHRIS JANSEN
TNO Human Factors
and
TREVOR DOBBINS
Human Sciences and Engineering

Presenting waypoint navigation on a visual display is not suited for all situations. The present experiments investigate if it is feasible to present the navigation information on a tactile display. Important design issue of the display is how direction and distance information must be coded. Important usability issues are the resolution of the display and its usefulness in vibrating environments. In a pilot study with 12 pedestrians, different distance-coding schemes were compared. The schemes translated distance to vibration rhythm while the direction was translated into vibration location. The display consisted of eight tactors around the user's waist. The results show that mapping waypoint direction on the location of vibration is an effective coding scheme that requires no training, but that coding for distance does not improve performance compared to a control condition with no distance information. In Experiment 2, the usefulness of the tactile display was shown in two case studies with a helicopter and a fast boat.

Categories and Subject Descriptors: B.4.2 []: Input/Output Devices; H.5.2 []: Haptic I/O; H.1.2 []: User/Machine Systems; I.3.6 []: Ergonomics; J.3 []: Life and Medical Sciences

General Terms: Design, Experimentation, Human Factors, Performance

Additional Key Words and Phrases: Vehicle control, navigation, vibrotactile displays, visually handicapped

1. INTRODUCTION

Nowadays, GPS navigation tools are widely sold and becoming common in cars, outdoor sports, and many other applications. Although these tools may be of great value in many applications, displaying the information on a visual display makes them inaccessible or undesirable in specific situations. For example, car drivers and infantrymen could better focus their visual attention on the surroundings than on a visual navigation display. A visual display may even be useless for firemen working in dense smoke, divers in dark waters, or the visually disabled. Presenting the navigation information via the sense of touch might be an interesting alternative. In this paper we focus on two of those situations. The first is in the cockpit of an aircraft, a working environment in which high visual workload may compromise safety and performance. A possibility to counteract this threat is employing an alternative sensory channel. For example, the multiple resource model of human information processing (e.g., Wickens [1984] and Wickens and Liu [1988]) predicts no performance degradation when

Authors' addresses: J. B. F. Van Erp, H. A. H. C. Van Veen, and C. Jansen, TNO Human Factors, P. O. Box 25, NL-3769ZG, Soesterberg, The Netherlands; email: {vanerp,vanveen,c.jansen}@tm.tno.nl; T. Dobbins, Human Sciences & Engineering Ltd., 5 The Terrace, Mill Lane, Sidlesham, PO20 7NA, UK; email: trevor.dobbins@humansci-eng.com.

independent resources or sensory channels are used to present information, including touch (see Sklar and Sarter [1999]). The second situation is in a fast boat. Here, a visual display is of little use because of the (whole body) vibrations that make reading the display impossible unless the boat slows down.

In waypoint navigation, two parameters are important: direction of the next waypoint and the distance to this waypoint (e.g., Burnett and Porter [2002]). Although direction information alone would be sufficient, distance information may be beneficial if specific preparations are required just before reaching the waypoint (as in car driving [Van Erp and Van Veen 2004]). The design of a tactile waypoint navigation display requires finding an optimal translation of direction and distance into a tactile "picture." In principle, four display parameters are available with a vibrotactile display: *location* (where the vibration is presented), *timing* (when the vibration is on and when it is off), *frequency* of the vibration, and *amplitude* of the vibration.

1.1 Coding Direction on a Vibrotactile Display

The location of the vibration on a tactile display determines the spatial characteristics of a vibrotactile sensation [Cholewiak and Collins 2000]. Of the four display parameters, location might therefore be the first choice to code spatial information such as directions. There are numerous cases or best practices that use this coding principle. Relatively simple displays were used by Dobbins and Samways [2002] who used one tactor (i.e., a vibrotactile display element) on each wrist to display a virtual corridor in a maritime navigation setting, Bosman et al. [2003] who used tactors on the wrists to support way finding in buildings, and Van Erp and Van Veen [2004] who built tactors in a driver's seat to navigate a car through a town.

More complex displays consist of a matrix of vibrators. For example, Deguara et al. [1999], Ertan et al. [1998], and Traylor and Tan [2002] used a matrix display (3×3 or 4×4 tactors) on the back that translated the cardinal directions into moving patterns corresponding to the wanted direction. While this coding is based on perceiving the direction of motion on the back, using location also proved to be a powerful concept, called "tap-on-the-shoulder" principle by Van Erp and Verschoor [2004]. The basic idea of this concept is that the skin of the torso is actually a three-dimensional (3D) display and that a localized vibration on the torso can easily and accurately be interpreted as a direction. Employing this principle requires a display that covers large parts of the torso instead of only the dorsal side. For example, directions in the horizontal plane can be mapped to a linear array of tactors on the waist as investigated by Van Erp [2005] using 15 tactors, and Chiasson et al. [2002] using 4 tactors for waypoint navigation. Matrix displays that present 3D spatial information were used by, for instance, Raj et al. [1998] in a helicopter control task with a display consisting of four columns of three tactors each on the cardinal directions, by Rochlis and Newman [2000] in a simulated extra vehicular activity situation with a display consisting of six tactors (three vertical on the back and three on the other cardinal directions), by Van Erp et al. [2003] for a simulated helicopter hover task with a display consisting of 64 tactors covering the whole torso, by McGrath et al. [2004] and Rupert [2000] in a helicopter hover flight demonstration, and by Van Erp and Van Veen [2003] in a spatial orientation support tool for astronauts with a display consisting of 56 tactors on the torso.

The above-mentioned studies confirm the potential of the tap-on-the-shoulder principle in navigation or vehicle control tasks, that is, they translate direction into location on the display. The interesting questions then are how to make this translation, and what the display resolution should be. Navigation experiments with a 180° display resolution (one element to indicate right and one to indicate left) were already successful in navigating through a building or a town. However, based on a study done by Van Erp [2005], one can conclude that from a perception point of view, a 10° resolution in the horizontal plane is feasible, an 18 times higher resolution than of a two element display. The effect of display resolution on navigation or control performance has not been thoroughly investigated yet. Therefore, we choose to use a medium resolution display consisting of tactors on the four cardinal and the four oblique directions (i.e., a linear array around the waist consisting of eight tactors).

1.2 Coding Distance on a Vibrotactile Display

Since a vibrotactile display has to be in contact with the skin to be perceived, distance is not a parameter that can be manipulated directly. Also, the preferred display parameter to code distance is not a priori clear. Therefore, a "possibly arbitrary" parameter has to be chosen (e.g., intensity) and a scheme describing how this parameter should reflect distance has to be devised (e.g., the intensity increases when distance decreases). Of the three remaining display parameters, frequency and amplitude are not very well suited to code information. The number of perceptually distinguishable levels for these parameters is only in the order of 5–7, see Van Erp [2002] for an overview. However, the skin is very sensitive to temporal aspects of vibrotactile stimulation [Van Erp and Werkhoven 2004]. The choice for timing (or actually on-off rhythm) is also supported by examples of best practices. Chiasson et al. [2002] used three different rhythms to enlarge the 90° display resolution to indicate 30° segments, Van Erp et al. [2003] and McGrath et al [2004] used rhythm to indicate the amount of drift or the airspeed in their helicopter hover displays, and Bosman et al. [2003] found that length of pulse trains are a better coding than intensities.

1.3 Research Goals and Issues

The main goal was to demonstrate the "proof-of-concept" of a vibrotactile waypoint navigation display as alternative to a visual display in demanding (military) environments. Relevant questions were the following: What is the preferred scheme to translate waypoint distance into vibration rhythm? Is waypoint navigation possible using only a tactile aide with a 45° resolution? And, are operators able to use vibrotactile information in demanding operational environments that include whole body vibration? To gain more insight in these issues, we performed two experiments. Experiment 1 was a study with pedestrians to investigate four schemes to code for distance. Experiment 2 was a proof-of-concept study and consisted of two case studies to test the display in a helicopter and in a fast boat.

2. EXPERIMENT 1, DISTANCE-CODING SCHEMES

2.1 Methods

Twelve participants were tested: Six females and Six males, ranging in age between 18 and 24. All were in good condition. They were paid for their participation and had signed an informed-consent agreement after extensive written and verbal instructions of the procedures. The experiment was run with a wearable stand-alone system consisting of minicomputer (486 DX Tiqit matchbox PC), a digital compass (Honeywell HMR2300), batteries, a GPS receiver (Garmin GPS 35-HVS), and the tactile display. The system, except for the display, was placed inside a backpack. Information about current position and compass angle were sampled with 1 Hz. The system calculated the direction and distance of the waypoint and translated them into a tactile picture. This picture was displayed using eight tactors, placed at adjustable distances on an elastic band worn around the waist over the participant's own T-shirt. The elastic band was adjustable to enable a tight but comfortable fit. The location of the eight tactors was adjusted to the participant's body size so that they covered the cardinal and oblique directions, see Figure 1. The tactors were based on pager motors (JinLong Industries), such as those used in mobile phones, which were housed in PVC boxes. The tactors had a contact area of 1.5 by 2 cm and vibrated at 160 Hz. They were activated in 1-s pulses; the pause between subsequent pulses depended on the distance to the next waypoint and the coding scheme, see below. Reaching a waypoint (i.e., being within 15 m) was communicated to the user by making all eight tactors vibrate for 1 s.

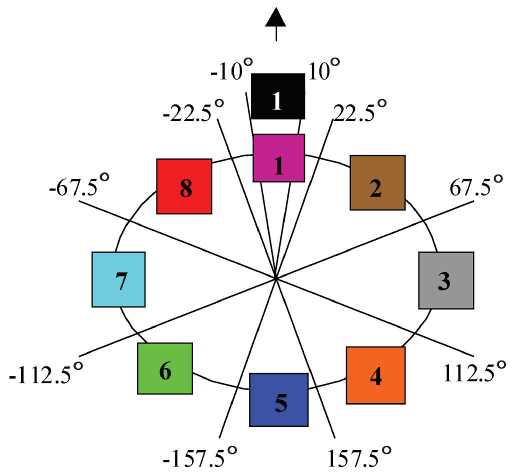

Fig. 1. Schematic picture of the vibrator positions and numbering. The arrow indicates the forward direction. A vibrator is active when the waypoint direction is within its range as indicated by the lines and angles. The color coding will also be used in the results section. In Experiment 2, vibrator 1 vibrates in a higher rhythm when the course error is smaller than 10°.

We used a within-subjects approach with 10 different routes and 5 different distance-coding schemes, and created random sequences of the schemes to balance any learning effect. Each participant walked the 10 routes in the same sequence, while combinations of routes and schemes differed between participants. The same sequence of conditions was used within each participant for the first five routes (training) and the last five routes (test). All routes were between 360 and 390 m in length, and all used the same two locations as first two waypoints. Each route consisted of six waypoints (imaginary circles with a 15 m diameter) located on an open field of grass of about 110 × 90 m, surrounded by bushes. The waypoints could not be identified visually.

Waypoint direction was coded by the location of the vibration; each of the eight vibrators covered a 45° cone with borders as depicted in Figure 1. For example, tactor 5 would indicate that the waypoint is right behind. Two approaches were used to design the distance-coding schemes. The first is to use a monotonic relation between distance and rhythm, in general the smaller the distance, the faster the rhythm. In this approach, the rhythm has a fixed relation to the remaining distance, in which remaining distance could be either absolute (i.e., the number of meters) or relative with total leg length as reference (a leg is the stretch between two consecutive waypoints). The second is to apply a three-phase model. Navigating a leg consists of (1) setting the desired course, (2) cover the distance (roughly) maintaining the desired direction, and (3) accurately homing-in on the waypoint. During phase 1, the new heading must be set, which requires frequent feedback from the system. In the second phase, the user requires less feedback, and possibly merely needs a confirmation that he/she is still on track. Finally, when the user closes in on the waypoint (phase 3), again information is needed frequently. In the three-phase approach, the temporal density of the information depends on the navigation phase, and not monotonously on the remaining distance. Based on the above considerations, the following distance to coding schemes were used (see also Figure 2):

1. *Three-phase model in absolute mode*. The pause between the 1-s pulses was as follows: phase 1 (within 15 m of the start point): pause 2 s. Phase 2: pause 6 s. Phase 3 (within 20 m of the endpoint): pause 1 s.
2. *Three-phase model in relative mode*. Phase 1 (within 10% of the leg length from the start point): pause 2 s. Phase 2: pause 6 s. Phase 3 (within 10% of the leg length from the endpoint): pause 1 s.

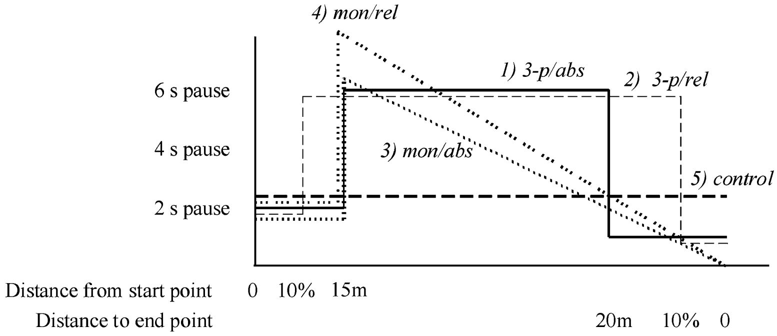

Fig. 2. Schematic depiction of the five distance-coding schemes for a leg length of 80 m. The conditions are abbreviated: 3p/abs and 3p/rel denoted three-phase model in absolute and relative mode, respectively (dashed lines); mon/abs, en, and mon/rel denote monotonic model in absolute and relative mode, respectively (dotted lines).

3. *Monotonic model in absolute mode*. The pause was 1/10th of the number of meters left to the next waypoint (i.e., every second of pause signaled 10 m of distance). However, within 15 m of the starting point, a signal was given every 2 s, otherwise the pause would have been too long to pick up the new heading. Formally this could be considered a two-phase model.
4. *Monotonic model in relative mode*. The pause started at 10 s and was reduced with 1 s for every 10% closer to the waypoint. However, within 15 m of the starting point, a signal was given every 2 s,
5. *Control condition*. Pause duration was fixed at 2 s.

The procedures were as follows. After reading the written instructions, the participant and experimenter walked to an open field of grass. During this walk and during the training, participants were told which condition was coming next and what they could expect (e.g., "the vibration-rate will increase as you come nearer to your target waypoint"). Participants were instructed to finish the experiment as fast as possible, while maintaining a normal walking speed. The participants had unrestricted vision, but the waypoints could not be visually identified. During the training, the experimenter was allowed to correct unwanted behavior such as walking in the bushes. After the last condition, the experimenter interviewed the participant on issues such as usability and points for improvement using an open interview protocol.

2.2 Results

Based on the logged data, we calculated the effective walking speed as the leg distance (distance along a straight line between two waypoints) divided by the walking time. All participants were able to complete all routes without problems; the mean effective walking speed for the distance-coding conditions is presented in Figure 3, averaged over legs and subjects. An analysis of variance with coding scheme as independent and effective walking speed as dependent variable did not reach significance ($F(4, 44) = 1.55$, $p > .20$).

2.3 Discussion

The tactile waist belt proved to be an effective navigation display. After approximately 30 min (five routes), the participants demonstrated acceptable effective walking speeds (4.2–4.4 km/h) which are somewhat below normal walking speeds (please note that effective walking speeds do not compensate for "zigzagging," meaning that a detour reduces the effective walking speed). The display is thus quickly learned.

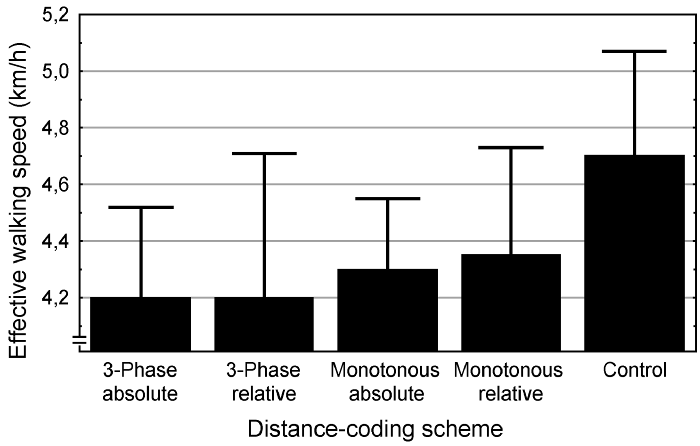

Fig. 3. Results of Experiment 1. Effective walking speed does not depend on the distance-coding scheme.

In general, the differences between the coding alternatives were small, and were not significant. Highest effective walking speeds were reached with the coding scheme in which participants received feedback unrelated to the distance to next waypoint. The small differences could be caused by the fact that distance information (as presented in this experiment) is simply not needed in waypoint navigation on foot, that the experiment had not enough statistical power to reveal an effect, or that the participants were not able to interpret the information. The first may be related to the fact that the waypoints were not actual landmarks that could be identified when approximated close enough. In other words, since the waypoints were just GPS coordinates, the benefit of knowing the distance is reduced compared to a landmark as waypoint that could be identified when direction and distance are known. The latter can be due to the fact that subjects were not able to perceive the rhythm changes at all, which is not very likely since the Weber fraction for tactile intervals is about 20% [Van Erp and Werkhoven 2004], or were not able to translate the rhythm in required behavior leading to performance improvements. This may be because the subjects received too little training in translating the distance coding.

Drawback of the present coding schemes is that they affect the direction information as well. By manipulating the pause between pulses, the temporal resolution of the direction information is also manipulated. In the distance-related feedback schemes, direction updates came with intervals up to 8 s while the latency in the control condition was relatively short: always 2 s. This explanation may or may not be proven justified after future research, but partly based on participants' verbal reports we would advice to keep the frequency of feedback at or above a minimum of 1 vibration every 4 s.

The post experiment debriefing furthermore confirmed that the direction indication was directly clear and very useful, but that the distance indication was more difficult to interpret. Subjects also indicated that distance information was not critical to come to a higher walking speed, but that a prewarning a short distance before reaching the next waypoint would be convenient to focus attention and to prepare for a course change.

3. EXPERIMENT 2, CASE STUDIES

Experiment 2 consisted of two case studies in which the navigation display of Experiment 1 was tested in two operational environments. Based on the results of Experiment 1, we decided not to code for distance but only to indicate when a waypoint was reached by a 1 s pulse on all eight tactors. Furthermore, the

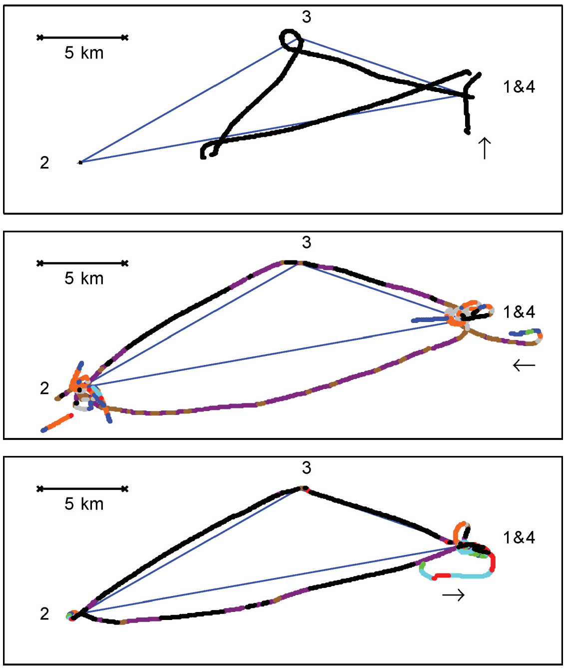

Fig. 4. The flight paths for the three helicopter trials. In trial 1 (upper panel), the pilot flew on instructions of the navigator, in trials 2 (middle panel) and 3 (lower panel) with the tactile display only. The color coding corresponds to the active vibrator (see also Figure 1). The arrow indicates the flying direction. Gaps in the data are caused by GPS loss.

directional resolution in the frontal direction was enlarged by using a faster rhythm of the front tactor when the waypoint was within a 20° cone (see also Figure 1).

3.1 Methods

In each case study we tested one operator. They were both very experienced in waypoint navigation and controlling their vehicles. The helicopter pilot had some experience with tactile displays. They both participated voluntarily and were not paid. We used the same navigation equipment as in Experiment 1, except for the mini computer that was replaced by a laptop. We used two platforms: a UK Royal Army Gazelle helicopter and a 500 BHP rigid inflatable boat of the UK Royal Marines. The platforms were not modified in anyway. Both vehicles resulted in whole body vibrations with main components in the range up to 15 Hz. The exact profile is dependent on the vehicle maneuvers, posture of the participant, and contact points between the participant and vehicle (e.g., seat, feet, and hands; see also ANSI S3.18-1979 (R1999)).

The pilot flew a triangular course clockwise (see also Figure 4). He started by flying toward waypoint 1, the starting point. Thereafter, about 22 km to waypoint 2, 15 km to waypoint 3, and 10 km to waypoint 1. The boat operator drove a triangular course counter clockwise at open sea. Starting close to waypoint 3, he drove about 6 km to waypoint 1, 7 km to waypoint 2, and 4.5 km to waypoint 3. The radius of the waypoints in the helicopter trials was 50 m, in the boat trials 100 m. Both environments were chosen such that there were no landmarks or reference points and the waypoints could not be visually identified.

The instruction for both operators was the same: Follow the direction indicated by the vibration. When reaching the waypoint, all tactors will vibrate, directly followed by the direction to the next waypoint.

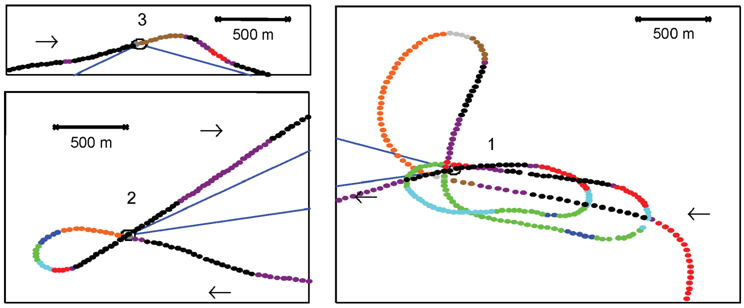

Fig. 5. Details of flight trial 3 (with tactile display). The arrow indicates the flying direction, the numbers the waypoints, and the color coding the active tactor; see Figure 1.

The pilot received additional instructions after the second trial, explaining that the transition from vibrator 2 to vibrator 1 indicated a course error of 22.5° and not 0°. The participants knew that they should follow a triangular course. The speed was fixed beforehand in consultation with the drivers: 100 mph for the pilot (≈160 km/h), 35 mph (≈56 km/h) for the boat driver. After the experiment the participants were interviewed using an open interview protocol.

The procedures were as follows. The first test was done with the helicopter. After a verbal explanation of the goals of the experiment, the operation of the tactile display and the interpretation of the signals, the pilot tried the display driving around in a normal passenger car. The pilot drove along a number of waypoints without knowing their location. This familiarization run clarified the operation of the display, but also showed that training was not really necessary. In the helicopter, the first run was without the tactile display but on commands of the navigator on board. Directly thereafter, the pilot flew two runs with the tactile display and no instructions from the navigator. The waypoints were originally in British National Grid coordinates and were translated into Garmin GPS coordinates for the tactile trials only. As can be seen from the data plots, the coordinates of waypoint 2 were translated incorrectly. The pilot was instructed not to use any reference points on the ground. For the boat trial, the driver also received instructions on the goals of the experiment and the operation of the display, but not the familiarization run with the passenger car. Two trials with the tactile display were run. To familiarize the driver with the tactile signals, he was instructed to sway the vehicle at the start of the first run.

3.2 Results

Figure 4 presents the helicopter flight paths in combination with the activation pattern of the tactile display for the three helicopter trials. The mean and standard deviation of the heading error were −2.9 (4.6), 16.7 (10.0), and 4.8 (5.3)°, for the three trials, respectively.

Inspection of Figure 4 shows that

1. the pilot had no trouble with perceiving the displayed information in the helicopter environment;
2. the pilot could easily fly into the direction of the waypoints;
3. performance in the third trial is better than in the second trial. Larger parts of each leg are colored black, indicating a course deviation smaller than 10°. The figure shows that in the second trial, the pilot corrects the heading error till the transition to the middle vibrator and not till 0°. In the third trial, performance was as good as the first trial with instructions from the navigator;
4. contrary to the second trial, waypoint 3 is passed adequately in the third trial (see details in Figure 5). Noteworthy is the fact that the strategy to pass the waypoint is different from the earlier attempts: the pilot chooses for a more efficient path when supported by the tactile display;

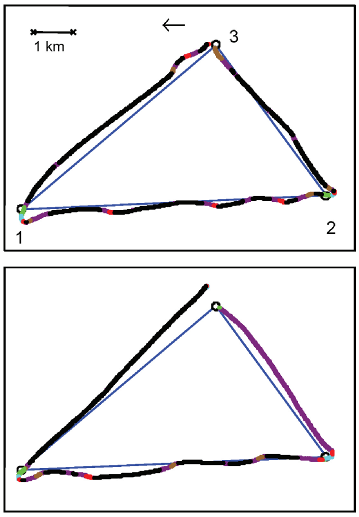

Fig. 6. The first (upper panel) and second (lower panel) boat trial, both with support of the tactile display. The arrow indicates the direction. The colors code the active vibrator according to Figure 1.

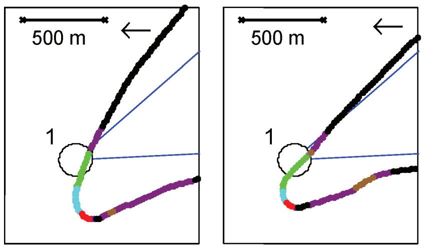

Fig. 7. Details of the passage of waypoint 1 for boat trial 1 (left panel) and 2 (right panel). The arrow indicates the direction, the colors code the active vibrator according to Figure 1.

5. the noisy behavior near waypoints 1 and 2 in the second trial and near waypoint 1 in the third trial had two causes. First, the rotor blades resulted in a loss of GPS reception, and second, the radius of the waypoints appeared too small in relation to the airspeed and turning rate of the helicopter. The right panel of Figure 5 shows that the waypoint could only be reached by first flying away from it.

Figure 6 depicts the paths of the boat trials. Details of the passage of the first waypoint are depicted in Figure 7. The mean and standard deviation of the heading error were 0.7 (9.8), and −1.3 (6.3)° for the first and second trial, respectively.

The following can be seen

1. after a short familiarization (as can be seen by the sway on command of the experimenter at the start of the first leg of the first trial), the driver could well drive toward the waypoints by tactile cues only;
2. passing the waypoints is adequate. In trial two, the changing colors illustrate the increased sensitivity when homing in on the waypoint: The driver went straight but the display indicates that the deviation increases.

Besides the objective data, we gathered subjective remarks of the operators. We also explicitly asked them whether they had used any visual landmarks to navigate, which they both answered in the negative. For the helicopter pilot, this is confirmed by the fact that he followed the tactile navigation display in the second trial, despite the fact that the second waypoint was “mislocated.” The boat driver added that there were no landmarks in sight, even if he would have wanted to use any. Both operators were enthusiastic about the display afterwards, despite initial doubts of the boat driver. They experienced no problems in perceiving the vibrations. Both indicated that they would like to have a warning when they came close to the waypoint. This is a very simple way of coding distance. The boat driver explicitly mentioned that the display allowed him to better concentrate on the waves ahead and would make him less dependent on the (problematic) communication with a navigator.

3.3 Discussion of Experiment 2

The results show that the tactile navigation display is also successful in an operational environment. This is not trivial: vibrating environments could make the perception of the vibrotactile signals difficult or even impossible as reported in other research projects [Castle and Dobbins 2004]. This indicates that there is a need for general knowledge about perceiving vibrotactile signals in a vibrating environment. A second conclusion is that the results support the conclusion of Experiment 1 that the display can be used for waypoint navigation. Apparently, the display is intuitive and can be used without extensive practice. The operators’ reactions to the vibrating signals were direct and adequate. The performance of the helicopter pilot showed a fast learning effect, that of the boat driver showed no room for improvement.

4. GENERAL DISCUSSION

The main goal of the present studies was to come to a proof-of-concept for displaying waypoint navigation on a tactile display. Employing the sense of touch may be advantageous in situations in which visual displays are inconvenient or less appropriate. The results indicate the usefulness of the tactile display: pedestrians, the helicopter pilot, and the boat driver all showed adequate performance with the display after a short familiarization only. This confirms the result of earlier studies in which spatial information was translated into a direction on the torso. The spatial resolution of the display (45°) seems sufficient for waypoint navigation in different situations. Future studies may explore a coding scheme for direction that has a higher resolution for the frontal cone. Compared to the coding in Experiment 1, we used such a scheme in Experiment 2 by changing the rhythm of the front tactor. However, we did not compare behavior between the two schemes.

The distance-coding schemes investigated in Experiment 1 did not result in performance improvements compared to the control condition. This may partly be caused by the confounding of distance information with the temporal resolution of the direction information that was present in the distance-coding schemes only. This confounding should be solved in future designs, for example, by displaying distance information in the tactile picture without changing the refresh rate (i.e., by manipulating frequency, amplitude, or temporal composition when the direction tactor is on), or by using an additional tactor that is controlled independently of the tactors that present the direction information. On the other hand, high quality distance information may not be critical for performance. In all three settings, the users indicated that a prewarning before reaching the waypoint would be adequate.

The third issue we were interested in was whether the operators would experience problems with receiving the vibrotactile display in vibrating environments as reported by Castle and Dobbins [2004]. Both the performance and the results of the debriefing of the helicopter pilot and the boat driver indicate that this was not the case. Both detection and localization seem to be unaffected. There is no clear-cut explanation why the vibrating environment did not have any negative effects in the present case studies. Fundamental knowledge on the effect of whole body vibration on vibrotactile perception is needed.

After this proof of concept, performance with the tactile display should be directly compared to map and compass, and visual GPS performance, possibly in situations of high (visual) workload, stress, and degraded visibility.

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Received October 2004; revised January 2005; accepted January 2005