Time-Lag as Limiting Factor for Indoor Walking Navigation

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Abstract. Several navigation situations can be imagined where visual cueing is not practical or unfeasible, and where the hands are required exclusively for a certain task. The utilization of the sense of touch, as relatively new notification modality, should provide sufficient possibilites to cope with this issue.

The focus in this research work is on two questions (*i*) how the distance encoding schemas affects the overall navigation speed (or in more detail to what level the time lag contributes to the navigation precision) and (*ii*) if, beside the vibro-tactile stimulation, the transmission of the noise generated by the individual vibration elements influences the speed and/or precision of route guiding. To deal with these questions we have defined and conducted three waypoint following experiments with two different tactor activation methods, one without and the other two with the distance encoded in the vibration patterns. Additionally, we did studies where we masked the noise of the vibration elements and compared the results against the general setting where masking was not applied.

Our results shows that notification latency led to an increasing number of walking anomalies and consequently affects the walking precision and time to a high degree. Furthermore, we could not find evidence that multimodal stimulation with both vibration force and vibration "noise" tends to result in an increased system performance compared to the system with unimodal feedback using vibrations only.

Keywords: Time-lag, Indoor Navigation, Human Perception, Vibrotactile Notification, Space Awareness, Stimulation Patterns, Vibration Noise, Reaction Latency.

1 Introduction and Motivation

The sensory modalities *seeing* and *hearing* utilized in traditional human-computer interaction have limited information capacity [1], [2], [3, p. 44], [4, p. 242], [5] so that visually or auditory delivered navigation information (or more precarious alerts) tend to fail to raise the required user attention. The sense of touch which is a "private" medium and operates hands, eyes and ears-free is attributed to offer potential to assist the highly charged eyes and/or ears in information transmission.

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In special situations the visual and auditory channels are actually unfeasible to be used for notifications – mention for instance a fire figther in action, escaping from a loud, smoky factory building. A second issue which probably could be resolved by utilizing vibro-tactile feedback systems (or more general the sense of touch) is the difficulty of navigation for disabled (blind) people, particularly in unfamiliar places like public authority offices, on the university campus or on airports – they cannot just unfold the map of the region and orientate themselves.

1.1 Research Hypotheses

Under consideration of the above discussed visual and auditory limitations the following hypotheses have guided our work in order to improve vibro-tactile directed navigation.

(i) Encoding of distance information into vibro-tactile messages will allow persons to find waypoints faster. However, latency in the notification loop affects the speed of waypoint finding: a larger time lag results in a longer timespan to find a certain destination point. This is due to the drift between a person's actual position and the original position the notification is based on.

(ii) A navigation performance degradation is expected when removing the auditory sensory channel as information carrier (blanking the noise caused by the vibration elements). This is motivated from earlier work, e. g. [6, p. 225], where it has been found that the noise generated by vibration elements provided an additional information source.

2 Related Work

In recent years, researchers have investigated the potential of vibro-tactile displays in human-machine interfaces. Through the skin vibrations can be felt on the whole body, however, the focus in this work is on two-dimensional navigation in indoor walking scenarios, thus the center of interest is related work from experiments with tactile waistbelt or torso displays[1].

2.1 Vibro-Tactile Information Presentation

In order to enhance navigation in 2D spaces with vibro-tactile assistance systems it would be a good choice to place the system around the waist so to get a direct orientation mapping.

Jones *et al.* [8] tested a wirelessly controlled tactile display (built up from a 4 by 4 array of vibrating motors, and mounted on the lower back) for assisting navigational tasks. The evaluation of the vibro-tactile display regarding outdoor navigation confirmed, that the interpretation of presented vibration patterns for directional or instructional cues performs almost perfect. A further experiment

[1] A tactile torso display conveys information by presenting localized vibrations to the torso [7].

showed that the ability to recognize vibro-tactile stimulation on the back was superior as compared to the forearm.

Lindeman *et al.* [9] used a vibro-tactile system built up from a matrix of 3 by 3 tactor elements mounted on the back to investigate visual and vibro-tactile stimulations. They reported that the performance increase was most significantly enhanced by visual cueing, however, haptic cues alone (unimodal feedback) provided a lower significant performance increase as well. Under consideration of these results, they suggested to use vibro-tactile cues in situations when visual cueing is not practical. Jan van Erp [10] investigated the direction in the horizontal plane using a linear tactor display with fifteen vibro-tactile elements (oscillating frequency fixed to 250Hz) placed on the torso of test persons. Results confirm that people have the ability to indicate a direction that matches a vibro-tactile point stimulus on the torso. Van Veen *et al.* [7] have investigated whether a tactile torso display can help to compensate for degraded visual information. A tactile display consisting of up to 128 vibrating elements (arranged in twelve columns and five rows) attached to a vest was developed. Their results showed an observable performance increase for tactile display variants compared to operation without tactile displays. Lindeman *et al.* have developed a body-worn garment to deliver haptic cues to the whole body. First evaluations regarding vibro-tactile navigation for collision avoidance or obstacle detection in real or virtual worlds have been presented, e. g. in [11] or [12], however, no qualitative statements about the usability and accuracy of the system, compared to "traditional navigation" approaches, have been given so far.

2.2 Hands- and Eyes-Free Walking Navigation

The guidance system proposed within this work is designed with the aim to relieve cognitive load from the eyes and ears, so it would be unfeasible to charge them with vibro-tactile information.

Elliott *et al.* [13] investigated tactile waistbelts for the transmission of navigational information in order to leave eyes and hands free for other tasks. The utilized tactile display was expected to reduce the high visual and cognitive workload of persons by reason of Wicken's Multiple Resource Theory (MRT) [14]. The results of their experiments showed that tactile navigation achieved best accuracy, followed by navigation with a GPS device, and by navigation with an ordinary compass. Duistermaat *et al.* [15] evaluated the performance of navigation and target detection tasks in night operation with a vibro-tactile waistbelt compared to a GPS device and a head-up navigation device. They found that the tactile system was rated higher than the GPS system in all test cases, and higher or as high as the head-up navigation system in many or most cases. Tsukada and Yasumara [16] developed a wearable tactile display called "ActiveBelt" for the transmission of directional cues and found that it is more desirable to activate the vibration elements only when users get lost in their navigation task rather than activating them constantly, and that the disposition of four tactors would be enough for accurate "walking navigation". Erp *et al.* [17] investigated the feasibility of navigation information presented on a tactile display instead of using a common visual display. Results of their studies using a vibro-tactile waistbelt indicated that both the vibro-tactile and the visual display perform with a similar reaction time.

2.3 A Basic Waistbelt Display

Ferscha *et al.* [18] presented a belt-like vibro-tactile notification system for assistance in raising users' attention, however they used simple activation patterns and the developed system featured a high latency between position detection and the corresponding notification. Riener and Ferscha described in [19] the results of a distance estimation experiment with different parameters of vibro-tactile stimulation.

2.4 Summary

Research on vibro-tactile stimulation, particularly for application in navigational scenarios, has increased considerably in the last years. Most of the reported work deals with outdoor navigation, often in combination with GPS position tracking. The reason for this is that (*i*) outdoor route-guiding operates acceptably accurate even with imprecise (tactile) feedback and (*ii*) a detected time lag has only little influence on the navigation quality and/or positioning precision due to the long distances to walk.

However, with technology advances in both position tracking (e. g. Ubisense 7000 series[2] or Intersense IS-900[3] Wireless Inertial Position and Orientation Tracking System for Real-time Location Sensing) and vibro-tactile feedback systems (for instance EAI C2-tactors[4] as used in this work), directed and accurate indoor route guiding might still come true.

Nevertheless, a number of issues still remain open and have to be considered, e. g. (*i*) the prevention or compensation of latency times or (*ii*) the definition of vibro-tactile notification patterns for precise route-guiding. The results of the authors' earlier work (as for example described in [18] or [19]) have provided a basis for determining an appropriate set of parameters for the investigations conducted in the frame of this work.

Outline

The rest of the paper is organized as follows. Section 3 describes the hardware setting used in the studies including placement and variation parameters of the vibro-tactile elements. Furthermore, definitions as well as a short characterization for the conducted experiments are given. In Section 4 the results

[2] Ubisense Platform Homepage, URL: `http://www.ubisense.net/content/8.html`, last retrieved March 20, 2009.

[3] Intersense Inc. IS-900 Systems, URL: `http://www.intersense.com/IS-900_Systems.aspx`, last retrieved March 20, 2009.

[4] Engineering Acoustics Inc., URL:`http://www.eaiinfo.com/TactorProducts.htm`, last retrieved March 21, 2009.

of evaluations regarding latency and stimulation parameters are presented and discussed. Section 5 concludes the work and gives some suggestions for future improvements.

3 Experimental Design

For the studies conducted within this work a vibro-tactile waist belt – built up from eight high-precision C-2 tactor elements creating a strong, punctuated vibration force – has been used (see Fig. 1). Each of the tactor elements has a diameter of $30.48mm$, a height of $7.87mm$, and uses electromechanical voice-coils to generate vibrations with a resonance frequency in the range between 200 and $300Hz$. In order to allow precise delivery of orientation information the vibration elements have to be spaced equally. Considering this quality issue we used two differently sized belts, one with a length of $720mm$ and one with a measure of $850mm$, to be able to process the experiments with test participants with different waist girths (in the range of $75cm$ to $100cm$).

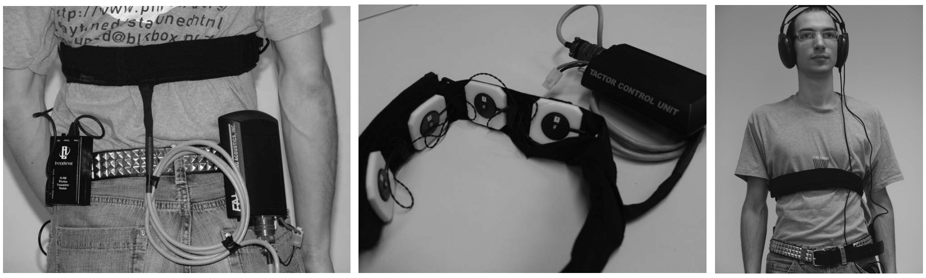

Fig. 1. The waist-belt system consisting of the vibro-tactile belt, the Intersense transceiver, and the belt controller, a detail view of the waist belt, a participant wearing the belt and the headphones in a two-dimensional indoor navigation experiment (from left to right)

3.1 Parameter Definition

Tactor Placement: As described by Cholewiak *et al.* [20] vibro-tactile perception is insusceptible to the vertical alignment of actuators on the body in the region from hip to chest, even if the underlying tissue (Epidermis) touched by a certain tactor varies widely and consists either of tendons, bones, muscles, etc. Instead, perception of vibrations is highly influenced by the position of tactor elements around the waist, for instance higher perception is reported for tactors positioned on the anatomical keypoints navel and spinal column, lower perception for vibration elements placed on the sides.

Position Tracking: For high-precise and accurate indoor position and orientation tracking of "navigating" test persons an Intersense IS-900 6-DOF[5] ultrasonic

[5] Degrees of Freedom.

positioning system was used. The wireless tracker, which had to be carried along by the candidates, was mounted on top of closed-back headphones (type AKG K55), worn throughout all experiments and playing "masking music" during the two experiments 1 and 3.

Vibro-Tactile Stimulation: In the different experiments, as described in Section 3.2 below, a combination of frequency and amplitude variation was used to notify test persons about distance and orientation.

(i) Frequency Range: We used frequency variation in the range from 200 to $300Hz$, since it is known to be perceived best by the Pacinian Corpuscles (PC) (see for instance Cholewiak *et al.* [20] or Riener [6, p. 115f]). Initial studies conducted on higher and lower frequencies confirmed that using frequencies below approximately $150Hz$ or above $350Hz$ are difficult to perceive and thus should not be used in Tactograms[6]

(ii) Amplitude/Gain Variation: For notifications using different vibration intensities the full range offered by the tactor system has been utilized. The overall range encompasses $24dB$, fragmented into 256 intensity levels. The linear mapping between distance and corresponding intensity level results in a logarithmic sensation.

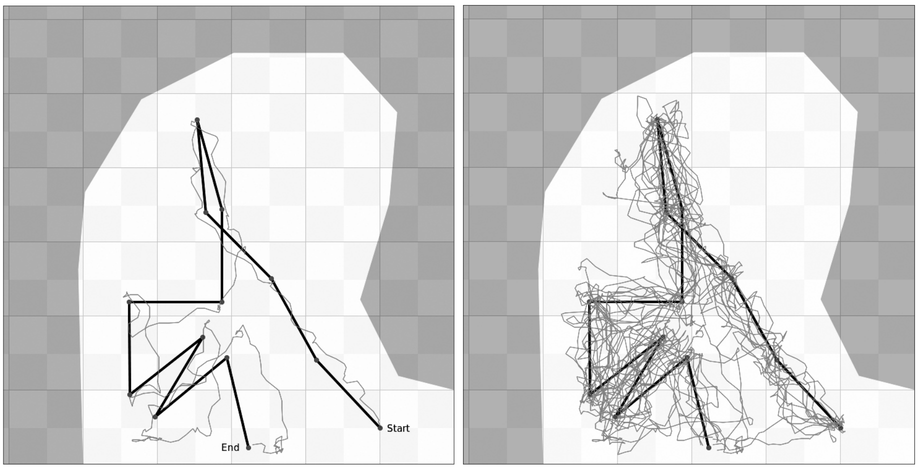

Fig. 2. The left image shows a navigation track (combination of thick, straight lines) with the overlayed trace of one test participant (thin solid line). Overlayed traces of all test persons on the same track indicate a rather good navigation precision, however, with several outliers (right image).

Route Design: For each of the three processed experiments a different course, as exemplarily shown in Fig. 2, was defined. The illustration shows a top view

[6] The notion of *Tactograms* for describing vibration patterns has been introduced in [6, p. 123f].

of our laboratory room with a tile size of 60 by 60cm and an overall room size of 730 by 745cm. The light-shaded area was accessible for test participants (and limited by the coverage area of the Intersense tracking system[7]).

To guarantee comparability between the different courses they have been designed according to the following properties, equal for any experiment.

(i) Entire walking distance: 18.0m
(ii) Waypoints: 13
(iii) Distance between waypoints: 1.50m
(iv) Track sections:
- (a) A nearly straight part consisting of 3 track sections (defined by 4 points), $+15°$ and $-15°$ angles.
- (b) One 170° U-turn.
- (c) Two consecutive angles of 90° each.
- (d) A zig-zag path, $+160°$ and $-160°$ angles.
- (e) The four remaining angles were 16°, 40°, 117°, and 127°.

3.2 Definition of Experiments

Before conducting the actual experiments, test participants had to perform a short familiarization experiment. It consisted of five waypoints and should help participants to get used to the system and the notification behavior of the tactor belt, particularly to the distance encoding scheme and its variation parameters vibration amplitude and frequency. They got no instructions at all on how the systems works or that distance is coded into vibrations – the only information they got was that (*i*) they had to walk along a route with several waypoints and (*ii*) a simultaneous pulsation of all vibration elements for one second means that a waypoint has been reached.

Experiment 1: Fixed Frequency/Gain with Auditory Masking

The results of this most trivial test case conducted at first for all test attendees were used as "baseline" for further investigations. The distance and direction mapping for this experiment was as follows. The two vibro-tactile elements on the waist belt closest to the destination (waypoint) were activated with the highest possible vibration amplitude and a fixed frequency of 250Hz, thus there was no notification about the actual distance to the next waypoint. If a participant was more than 1.9m away from the next Point of Interest (POI), the tactor element with shortest distance to this POI was activated in a 180ms pulse, 180ms pause pattern in order to guide the person to that waypoint. However, since the distance between waypoints was specified to be exactly 1.5m, this pattern was only used in very rare occasions, namely when a test person completely got lost.

[7] The routes for all the experiments have been defined with respect to fit into the Intersense coverage area.

Reaching a Waypoint: If a POI was reached, all tactor elements were activated in a 100ms pulse - 100ms pause pattern for 1 second, to clearly notify the walking person about its arrival at a waypoint. Immediately after this notification pattern the direction to the next waypoint was delivered. The covered path as well as the time required for approaching each waypoint were recorded and later used as reference values to evaluate the performance of the other two experiments featuring frequency and gain variation.

Masking Vibration Noise: For the purpose of auditory masking the noise generated by vibrating tactors a harmonic title of drone music [21] was played at such a person dependent volume, that the person could no longer hear the vibration source.

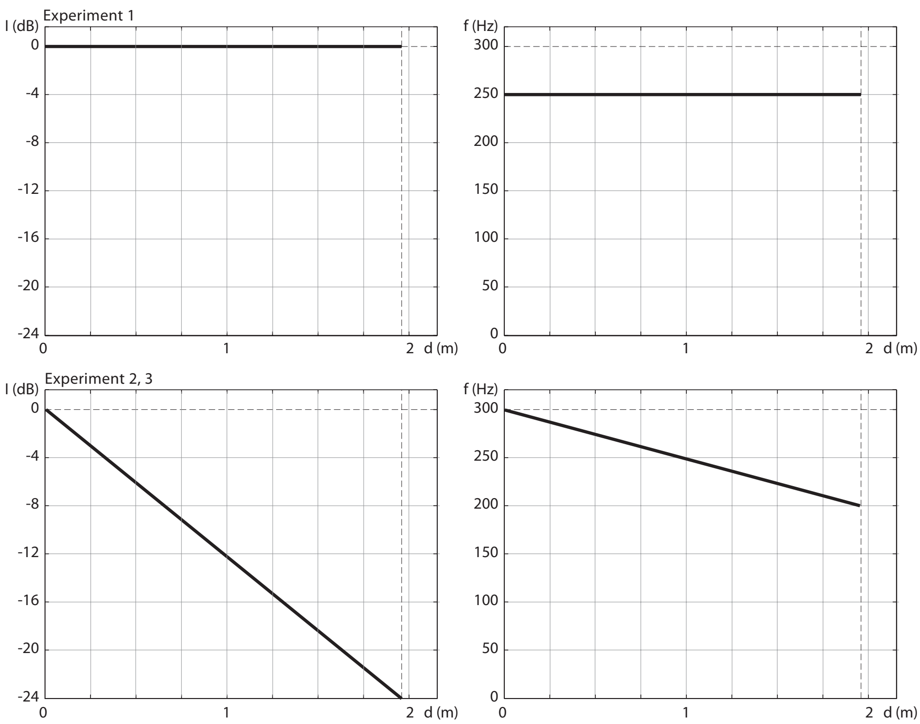

Fig. 3. Encoding schemes for the three experiments. Constant vibration intensity (peak value, 0dB attenuation) and frequency (250Hz) has been used in experiment 1, for the experiments 2, 3 a variation of vibration intensity (0dB to -24dB attenuation) and frequency (300Hz to 200Hz) depending on the distance (0.0m to 1.9m) has been utilized

Experiment 2: Frequency/Gain Variation without Auditory Masking

In this test case the distance of the test person to the next waypoint was encoded using vibration frequency and amplitude variation as follows. If a participant enters a freely configurable area around a Point of Interest (in all of the presented and discussed test sets a circle with a radius of $1.9m$ has been utilized) the parameters described in the paragraph "Vibro-tactile Stimulation" above were linearly mapped to the distance by increasing both frequency and amplitude with decreasing distance to the waypoint. Beyond the defined area directional notifications were given as described in the baseline test above.

Experiment 3: Frequency/Gain Variation with Auditory Masking

This experiment was similar to the previous one with the only difference that auditory vibration information was masked with music as described and used in the first experiment.

4 Evaluations

The experiments were conducted with 11 voluntary male test persons, aged between 23 and 32 years with an average age of 25.7 years, sized between 174 and $194cm$ with an average height of $181.7cm$, weighted from 65 to $104kg$ with an average weight of $78.5kg$, and with abdominal girths around the navel from 75 to $100cm$ with an average of $85.6cm$. Three of the participants were staff members, the remaining eight were computer science students.

As it has been evidenced that there is a strong gender dependent difference in reaction speed and navigation precision (e. g. in Kosinkski [22], Dane *et al.* [23], Der and Deary [24], Surnina *et al.* [25]), thus only male persons were allowed to take part in the experiments.

4.1 Notification Latency

The time lag from Intersense, sensing a person's movement, until the vibro-tactile waist belt emitted the corresponding tactile notification consisted of around $10ms$ for the acquisition of position data via the Intersense server (WLAN delay), added by another $180ms$ for sending one command to the tactor controller (more precisely, the tactor controller's microcontroller needs approximately $180ms$ to process a command, thus one command can be sent only once every $180ms$).

For the first experiment only one command was required for changing vibration patterns (Tactograms), the time lag is therefore $10ms$+$180ms$=$190ms$. However, for the second and third experiment three commands were needed, the latency calculates to $10ms + 3 \times 180ms = 550ms$.

4.2 Interviews and Observations

In general, the reaction from test attendees on the experiments and the vibro-tactile navigation was quite positive. Even though 73% of the participating persons had no experience with this kind of notification, they stated that (*i*) the belt-type navigation system was intuitively useable for navigation and (*ii*) they could imagine being guided by such a system in the real. More specifically, following conclusions can be drawn from observations and interviews following the user tests.

(i) Latency: Some of the test candidates quickly learnt how to compensate the indicated time lag. They seldomly turned around their own axis, but tended to step sidewards and backwards. 55% (6) of the test candidates explicitly complained about the latency of the system and that this made it particularly difficult to navigate efficiently when being close to a waypoint.

(ii) Tactor placement: Three test participants felt the strongest vibrations on the frontmost tactors, two persons had problems in feeling vibrations on the tactile element placed nearby the navel, one felt that the vibration elements placed left/right on his sides provides best vibration feedback. 45% (5) complained about a generally low vibration intensity on the back. Even if Cholewiak *et al.* [20] stated that belly and back are two anatomical reference points where vibrations are sensed better than on the sides, this did not hold true in our experimental setup, presumably caused by the fact that the tactor elements on the back were only pressed against the skin with low force.

(iii) Masking vibration noise: A piece of music delivered via headphones was used to mask the vibration noise in two of the three experiments. This was regarded as a good option by four participants (36%) – they stated that the masking helped them to focus their attention on the vibro-tactile sensations. One person missed the noise and felt less capable of precise navigation, the other six participants felt indifferent to the music.

(iv) Vibration amplitude: 73% (8) test persons noted that in some cases the vibration signal was not strong enough, which was obviously caused by the applied distance coding scheme used in the experiments two and three. 64% (7) participants perceived the changed distance coding scheme between the first and the other two experiments, and furthermore found the distance dependent variation of frequency and gain a useful addition to the first experiment.

4.3 Walking Traces

All participants successfully accomplished the three navigation (or waypoint finding) experiments. The only briefing carried out just before conducting the tests was a a short training with five waypoints, in order to get familiar with the system. In the course of the experimental processing three “walking anomalies” recurred again and again, namely (*i*) extensive zig-zaging when approaching a waypoint, and then passing by, (*ii*) revolving around the waypoint, and (*iii*) make a fast beeline to a waypoint, missing it, and come back again, see Fig. 4 (from left to right).

Both the boxplots in Fig. 5 and Table 1 show that the performances of the second and third experiment were significantly worse compared to that of the first one, thus hypothesis 1 cannot be accepted. This result holds true for the number of occured anomalies as indicated in the righthand plot of Fig. 5. The number of anomalies was significantly lower for the first experiment (e. g. on average 2.18 compared to 4.73 for the second experiment), the result for the third experiment is slightly better than for experiment two.

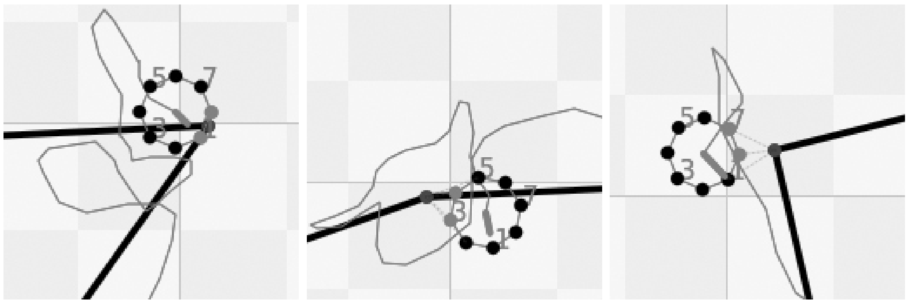

Fig. 4. Walking anomalies (from left to right). Zig-zaging before, revolving around, and passing by a waypoint. The bigger circle represents the vibration belt with eight tactors, the actual destination to be reached is the intersection point of the two straight lines.

Table 1. The walking distance is on average 27.64% (20.23%) higher for the second (third) experiment compared to the first one. This relationship holds true for the walking time and the counted anomalies ($p<0.05$).

	Walking Time (sec.)			Walking Distance (cm)			Anomalies (quantity)		
Attribute	Exp. 1	Exp. 2	Exp. 3	Exp. 1	Exp. 2	Exp. 3	Exp. 1	Exp. 2	Exp. 3
Min. (x_{min})	7.44	7.91	8.61	217.00	221.61	251.49	0	2	1
Median ($\widetilde{x}$)	8.81	12.31	10.75	264.50	357.56	305.92	2	5	4
Max. (x_{max})	10.31	13.69	13.27	301.81	399.16	410.11	6	7	7
Mean ($\overline{x}$)	9.64	12.43	11.74	285.00	363.77	342.65	2.18	4.73	4.27
SD (σ_x)	1.86	2.12	1.76	41.88	62.20	63.34	1.83	1.74	1.85

One of the main reasons for this performance degradation between the first experiment and experiments 2 and 3 originates from the increased time lag (550ms for the second and third, 190ms for the first experiment). However, this seems not to be the only cause as (i) the kind of notification (or vibro-tactile message) changed from experiment 1 to the experiments 2, 3 and (ii) 73% (8) of the test persons noted that the vibration intensity was partly too low for the experiments 2 and 3 (particularly at higher distances).

Hypothesis 2, which states that a test person will perform faster and/or better in experiment 2 than in experiment 3 by reason of multimodal instead of unimodal feedback have to be rejected, the results even show that it is rather the other way round (see Table 1). All individual results, the walked distance, the duration required for completing a trace and the number of anomalies are lower for the third experiment than for the second (however, statistically not significant). This result can be explained by the fact that the multimodal stimulation (vibration noise from a tactor element and the vibration itself) confuses and distracts a test person – 36% of the test participants noted that using a masking music during the experiment helped them to improve their concentration on the

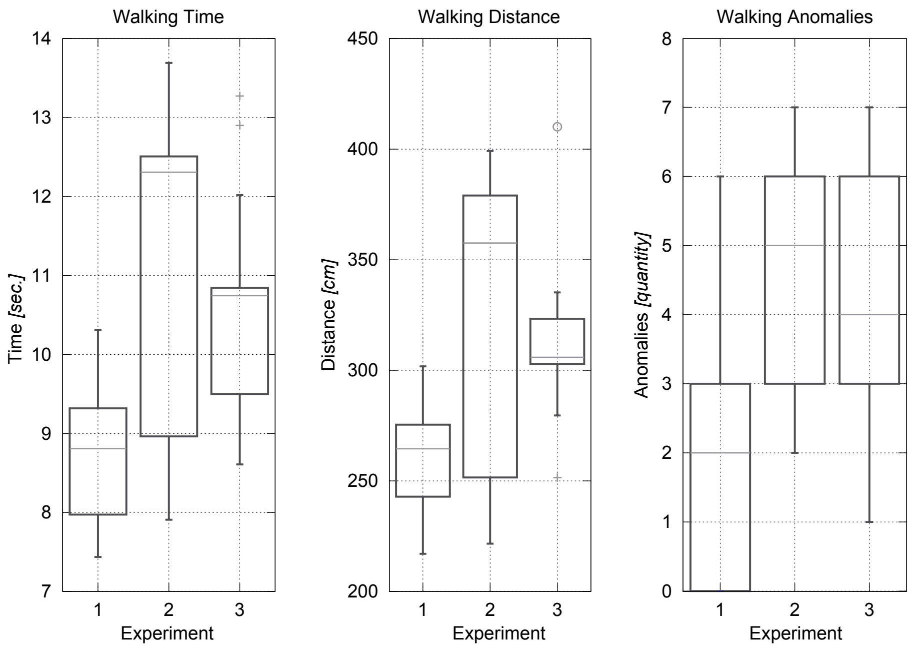

Fig. 5. Boxplots indicating the overall walking time, walking distance, and the number of anomalies (from left to right)

main task. Additionally, a learning effect from experiment 2 to experiment 3, although different route traces have been used, cannot be ruled out definitively.

5 Conclusions and Further Work

In this paper we have described a belt-type body-worn indoor navigation system. Both the findings from the questionnaires and the empirical results confirmed that latency (or time lag) negatively affect precise and fast route guiding.

The proposed distance encoding scheme (varying both vibration frequency and amplitude) missed its expected performance. This result can at least be partly explained by observations from several test participants, who noted that sometimes vibrations were very difficult to sense. From combining these statements with our observations while conducting the experiments it became clear that the occurence of this problem correlates with high waypoint distances – and therefore low vibration amplitudes – during experiment 2 and 3. On the other hand, the positive feedback from other test persons with respect to the distance depending encoding model motivates further research on distance encoding.

The hypothesis on a noticeable performance degradation when blanking the noise generated by the vibration elements, and thus reducing the feedback dimensionality from bimodal to unimodal, has to be rejected. Test persons reported that the masking of vibration sound leads to a higher focus on the vibration force, the empirical results also showed an improvement in navigation speed and/or precision.

Further research questions relate to the interrelationship of performance degradation and (*i*) notification latency or (*ii*) distance depending variation of vibration intensity.

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References

1. van der Heijden, A.H.C., Bem, S.: Eye movements and attention. Consciousness and Cognition 6(2-3), 437–440 (1997), Article No. CC970308
2. Broadbent, D.E.: Perception and communication. Pergamon, London (1958)
3. Mayer, R.E., Moreno, R.: Nine Ways to Reduce Cognitive Load in Multimedia Learning. Educational Psychologist 38(1), 43–52 (Winter 2003)
4. van der Heijden, A.H.C.: Selective Attention in Vision, illustrated edn. Routledge, New York (1992)
5. Hsia, H.: The information processing capacity of modality and channel performance. Educ. Technology Research and Development 19(1), 51–75 (1971)
6. Riener, A.: Sensor-Actuator Supported Implicit Interaction in Driver Assistance Systems. PhD thesis, Johannes Kepler University, Linz, Austria (January 2009)
7. Veen, H.A.V., Erp, J.B.V.: Providing Directional Information with Tactile Torso Displays. In: Proceedings of EuroHaptics 2003, TNO Human Factors Soesterberg, The Netherlands. LNCS, pp. 471–474. Springer, Heidelberg (2003)
8. Jones, L.A., Lockyer, B., Piateski, E.: Tactile display and vibrotactile pattern recognition on the torso. Advanced Robotics 20(12), 1359–1374 (2006)
9. Lindeman, R.W., Yanagida, Y., Sibert, J.L., Lavine, R.: Effective vibrotactile cueing in a visual search task. In: Rauterberg, M., Menozzi, M., Wesson, J. (eds.) Proceedings of 13th International Human-Computer Interaction (INTERACT 2003), pp. 89–96. IOS Press, Amsterdam (2003)
10. van Erp, J.B.: Presenting directions with a vibrotactile torso display. Ergonomics, Taylor and Francis Ltd. 48(3), 302–313 (2005)
11. Lindeman, R.W., Page, R., Yanagida, Y., Sibert, J.L.: Towards full-body haptic feedback: the design and deployment of a spatialized vibrotactile feedback system. In: VRST 2004: Proceedings of the ACM symposium on Virtual reality software and technology, pp. 146–149. ACM, New York (2004)
12. Lindeman, W., Yanagida, Y., Noma, H., Hosaka, K.: Wearable vibrotactile systems for virtual contact and information display. Virtual Real. 9(2), 203–213 (2006)
13. Elliott, L.R., Redden, E.S., Pettitt, R.A., Carstens, C.B., van Erp, J., Duistermaat, M.: Tactile Guidance for Land Navigation. Technical Report ARL-TR-3814, Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5425 (2006)
14. Wickens, C.D.: Processing resources in attention. In: Parasuraman, R. (ed.) Varieties of Attention, pp. 63–97. Academic Press, New York (1984)
15. Duistermaat, M.: Tactile Land Navigation in Night Operations. Technical report, TNO Defence, Security and Safety Kampweg 5 3769 ZG Soesterberg, The Netherlands, R&D No. 9954-AN-01 (December 2005)

16. Tsukada, K., Yasumura, M.: ActiveBelt: Belt-Type Wearable Tactile Display for Directional Navigation. In: Davies, N., Mynatt, E.D., Siio, I. (eds.) UbiComp 2004. LNCS, vol. 3205, pp. 384–399. Springer, Heidelberg (2004)
17. van Erp, J.B., van Veen, H.A., Jansen, C., Dobbins, T.: Waypoint navigation with a vibrotactile waist belt. ACM Trans. Appl. Percept. 2(2), 106–117 (2005)
18. Ferscha, A., Emsenhuber, B., Riener, A., Holzmann, C., Hechinger, M., Hochreiter, D., Franz, M., Zeidler, A., dos Santos Rocha, M., Klein, C.: Vibro-Tactile Space-Awareness. In: Adjunct Proceedings of the 10th International Conference on Ubiquitous Computing (Ubicomp 2008), Seoul, South Korea, September 2008, pp. 117–120 (2008), Video paper
19. Riener, A., Ferscha, A.: Raising awareness about space via vibro-tactile notifications. In: Roggen, D., Lombriser, C., Tröster, G., Kortuem, G., Havinga, P. (eds.) EuroSSC 2008. LNCS, vol. 5279, pp. 235–245. Springer, Heidelberg (2008)
20. Cholewiak, R.W., Brill, C.J., Schwab, A.: Vibrotactile localization on the abdomen: Effects of place and space. In: Perception and Psychophysics, vol. 66, pp. 970–987 (2004)
21. Krebs, K.M.: Illumination and division (2009), `http://www.restingbell.net/releases/rb009-symmetries` (last retrieved March 20, 2009)
22. Kosinski, R.J.: A Literature Review on Reaction Time. Clemson University, Department of Biological Sciences (September 2009), `http://biology.clemson.edu/bpc/bp/Lab/110/reaction.htm` (last retrieved January 15, 2009)
23. Dane, S., Erzurumluoglu, A.: Sex and handedness differences in eye-hand visual reaction times in handball players. International Journal of Neuroscience 113, 923–929 (2003)
24. Der, G., Deary, I.J.: Age and Sex Differences in Reaction Time in Adulthood: Results From the United Kingdom Health and Lifestyle Survey. Psychology and Aging 21(1), 62–73 (2006)
25. Surnina, O.E., Lebedeva, E.V.: Sex- and Age-Related Differences in the Time of Reaction to Moving Object in Children and Adults. Human Physiology 27(4), 436–440 (2001)