Raising Awareness about Space via Vibro-Tactile Notifications

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Abstract. Human perception, in a world of continuous and seamless exposure to visual and auditory stimuli, is increasingly challenged to information overload. Among the primary human senses, vision, audition and tactation, particularly the sense of touch appears underemployed in todays designs of interfaces that deliver information to the user. While about more than 70% of the information perceived by humans is delivered via the sight and hearing channel, only about 21% is perceived via the haptic sense. In situations of work or engaged activity, where both the visual and auditory channel are occupied because of the involvement in the foreground task, notifications or alerts coming from the background, and delivered via these channels tend to fail to raise sufficient levels of attention.

With this paper we propose to involve the haptic channel for situations where important notifications tend to be ”overseen” or ”overheard”. We opt for a vibro-tactile notification system whenever eyes, ears and hands are in charge. A body worn, belt like vibration system is proposed, delivering tactile notifications to the user in a very subtle, unobtrusive, yet demanding style. Vibration elements seamlessly integrated into the fabric of an off-the-shelf waist belt, lets the system deliver patterns of vibration signals generated by modulating amplitude, frequency, duration and rhythm – so called tactograms – to eight well positioned vibra elements. A series of user tests has been conducted, investigating the perception of distance to physical objects, like walls or obstacles, in the vicinity of users. Results encourage for a whole new class of space awareness solutions.

Keywords: Human Perception, Vibro-tactile Interfaces, Information Overload, Space Awareness.

1 Raising Human Attention

Traditional interface design involving human perception has mainly focussed on two modalities: *vision* and *hearing*. In many situations, however, when the vision and audition channel of perception are highly in charge, alerting and notifying important information can suffer from inattentiveness due to information overload. In such situations, to raise human attention, the additional use of *haptic*

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sensation offers great potential for providing a supplementary level of awareness (about 21% of information is perceived with the haptic sense [1]; according to Mauter and Katzki [2] touch is used to a lower proportion, as 80% to 90% of all sensory input is received with the eyes). Steadily increasing information emergence directs to users oversaturation and distraction and encourages for new input and output modalities in human-centered computing. Other aspects which can generate added values in specific applications are the compensation of restrictions/limited awareness of visual and auditive sensations in noisy, dark or foggy environments.

Involving haptics in the design of user interfaces, particularly for the purpose of raising human attention in certain situations, or even to keep the user subtly informed about the environment has been addressed in the literature. Brewster and Brown [3] gives suggestions for using tactile output as display to enhance desktop interfaces and situations with limited or unavailable vision. Lindeman *et al.* [4], [5] states basic principles for haptic feedback systems and describes implementation-advances for their vibrotactile system ”TactoBox”. Additionally, the integration into a VR system (immersive simulator) of the U.S. Naval Research Laboratory has been depicted. Tsukada and Yasumara introduced in [6] a wearable tactile display called ”ActiveBelt” for transmitting directional cues – one application (”FeelNavi”) tries to map distance information to one of four pulse intervals. ”feelSpace”[1] is a research project with the aim to investigate the effects of long-time stimulation with orientation information. On their belt, the element pointing north is always vibrating slightly, so that the person wearing the belt gets permanent input about his/her orientation. Although these systems presents novel approaches, none of them give qualitative evidence regarding user perception of haptic distance awareness.

Erp *et al.* uses haptic directional information for navigational tasks [7]. They mentioned that direction information alone is sufficient for the considered application, but distance information may be beneficial. In their walking experiments with haptic distance notifications if a certain test person comes within a range of 20 meters to the end point they coded distance into the proportion between signal to pause times, while vibration intensity is fixed. Tscheligi *et al.* are studying navigation support for pedestrians [8], which are often occupied with one or more other tasks. Therefore, visual data presentation on a electronic device like a PDA is not appropriate, nor is it auditive feedback because of environmental noise or conversations. As result, they see great potential for future navigation devices in unobtrusive systems based on tactile feedback (like the one presented in [7]), even if they are still under development. ”Shoogle” [9] is a more recent approach for presenting eyes-free, single-handed interaction for mobile devices (data input with inertial sensors, realistic user feedback is given by stressing the two modalities vision and sound).

As possible platform for a vibro-tactile belt display, the QBIC-platform, presented in [10], could serve. Prewett *et al.* [11] presents a vibro-tactile display

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[1] The study project feelSpace, URL:`http://feelspace.cogsci.uos.de` (April 12, 2008).

system to support the perception of the presence of the target interaction object in a 3D VR environment.

This experiment is the first in a larger series of studies considering haptic interaction, with the overall aim to investigate on the correlation between various haptic stimulations and corresponding user perception. We are interested in (*i*) distance- and position awareness, (*ii*) orientation awareness, (*iii*) awareness of danger objects or zones, (*iv*) mapping of important activities and (*v*) awareness about size and shape of objects. Here, only the aspect of *distance awareness* was considered, evaluations regarding quality, accuracy, reliability and users' personal opinions were given.

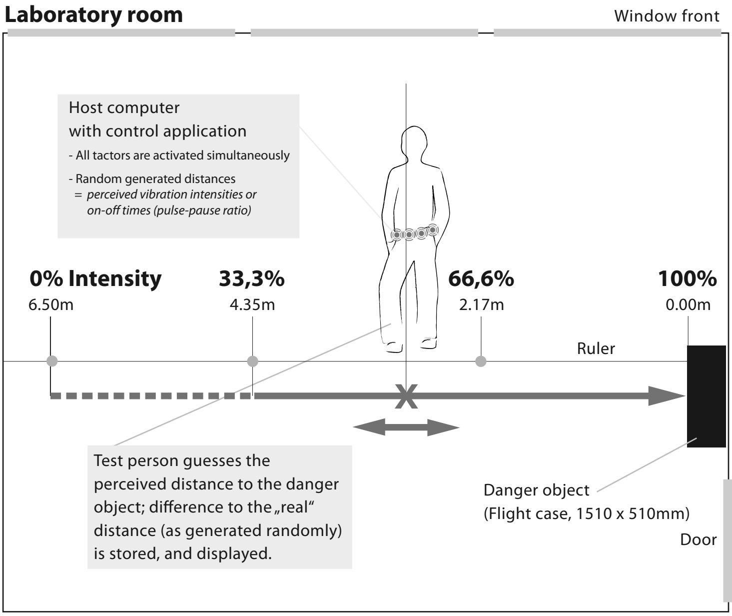

Fig. 1. Experimental setting for studying vibro-tactile distance-awareness

2 Space Awareness

For transmitting haptic stimulations to persons, a vibro-tactile belt system has been developed. It has the capability of generating intuitive room or space awareness by individually activating 8 tactor-elements around the waist (uniformly distributed), and, by variation of vibration intensity or frequency, allows for indicating object distances. The mapping between an object in space, and the corresponding activated tactors on the waist belt, is performed by a combination of software and hardware components, which are described briefly in the next section.

2.1 A Vibro-Tactile Waist Belt

The vibro-tactile waist system consists of the belt itself (with embedded tactor elements), the communication/control hardware, and a battery pack for mobile operation. On the host side, the framework is responsible for mapping information like distance, orientation, etc. to tactor control commands and for triggering the *haptic events*. Communication between the 130 x 90 x 45mm-sized belt hardware (board-size without housing is 74 x 93 x 33mm) and the host is established via Bluetooth connection. The weight of the entire system (including power supply and belt) is 680g, which is rather heavy but could be downsized by factor 2–3 when using a miniaturized, optimized setting (reference design for technical feasibility is given e.g. in [10] – the mainboard for the QBIC-platform is 44 by 55mm in dimension). Essential components of the system are an Atmel AVR Mega 32 Microcontroller for controlling the tactor elements, a ULN2803AG high-current darlington transistor array (8 pairs of NPN darlington transistors) for driving the vibration motors, a OEMSPA441 connectBlue industrial Bluetooth 2.0 serial port adapter (SPA), and 8 pieces of standard, low-cost Nokia 7210 cell-phone vibramotors, housed in a PVD-contactor with a contact area of approximately 3 by 2cm. The wireless system is completed by a PM85-22 universal rechargeable 22Wh Li-ion battery pack. The software part for generating random values, translating them into appropriate control commands and delivering them wirelessly to the vibro-tactile belt has been implemented as a combination of JAVA/C++ applications, exchanging information with the Atmel microcontroller via Bluetooth communication.

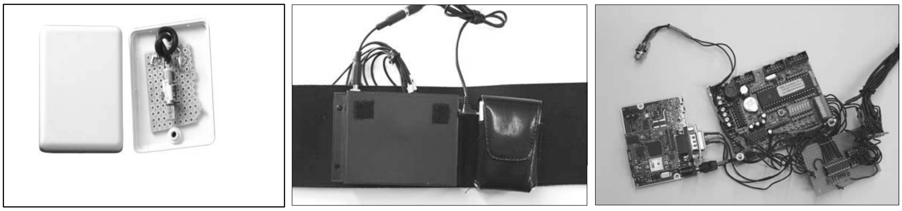

Fig. 2. Vibration elements, belt hardware with battery pack, and control hardware, dismantled from the housing (from left to right)

Tactor Placement: A good starting point for considerations about the where to place tactors can be found in [4, p.147f]. For the experiment, only the region of waist is significant. Weinstein [12] investigated the spatial resolution of receptors in humans' skin. He found that the threshold distance in the region of the abdomen is approximately $30mm$. The calculation of the minimum number of tactor elements around the waist can be derived from the waist-circumference of average males and females, which is between 86 and $89cm$ for men, and between 74 and $81cm$ for woman (with an overall mean of $82.5cm$).

$$\frac{825mm \text{ [mean waist-circumference]}}{2 * 30mm \text{ [threshold diameter]}} = 13.75 \text{ [tactors]}$$

According to this estimation, the maximum accuracy for (orientation) awareness on a vibro-tactile belt system should be achieved when placing 14 tactor elements around the waist. As we only consider distances in the present experiment, the utilized 8-tactor belt system should be sufficient to provide complete sensations around the waist.

2.2 Tactor Actuation

Our vibro-tactile belt system is responsible for haptic feedback based on 4 parameters: (*i*) vibration intensity (pulse-width modulation, PWM), (*ii*) activation frequency, (*iii*) duration (relationship between pulse- and pause-times), and (*iv*) rhythm. The dynamic behaviour of all vibro-tactile elements (*tactors*) in a system is specified by vibro-tactile patterns or "*tactograms*". For the current studies, all parameters except the fourth (*rhythm*) had been utilized and diversified.

Vibration intensity: The intensity of vibro-tactile transducers is controlled with pulse-width modulation (PWM) in time-per-unit. The implementation of the hardware controllers used in the present experiment allows only one shared PWM-value for all tactor elements (which is sufficient because of equal actuation of all tactors). Individual intensities per vibration element would be possible by variation of the stimulation frequency, which would be perceived in a similar manner than changes in the amplitude.

Activation frequency: In our setting, vibration frequency is individually adjustable for a certain tactor. For the current experiments all tactors are switched on and off simultaneously. As we didn't evaluate orientation information, the activation all around the waist was used to get a higher perception of vibro-tactile distance information. Vibration intensity and frequency were choosen according to the functional features of pacinian corpuscles or mechanoreceptors (they are embedded in almost the entire body and adapt rapidly to intensity changes; furthermore they are sensitive in the frequency range from 10 to $500hz$, with highest perception at $\approx 250hz$ [13], [14], [15]).

Pulse-pause time (duration): The variation parameter *interval length* was used as another alternative to notify about changing distances between a person and an obstacle. The maximum interval length was selected according to several investigations on response times for HCI-systems, which recommends a maximum response time of two seconds or less (see Testa *et al.* [16, p.63], Miller [17], or Shneiderman *et al.* [18, Chap.11]).

3 Experimental Design

The vibro-tactile waist belt, which is adjustable in length to enable a tight fit, was attached and adjusted to each of the test participants (ranging from 23 to 32 years in age). All of them had been informed before the test, to wear only a thin shirt for better vibration perception. Prior the recording of real measurements we did a *calibration task* by transmitting a number of given distances (variation of the parameters *vibration intensity* and *interval length*) to the test candidates (0% or 650.00cm, 33% or 435.00cm, 66% or 217.00cm, and 100% or 0.00cm, see Fig. 1). After that, for each test person a series of consecutive random intensity-values had been generated and wirelessly delivered to the belt – the users estimate for the distance, together with the system-generated distance value, were stored in a database.

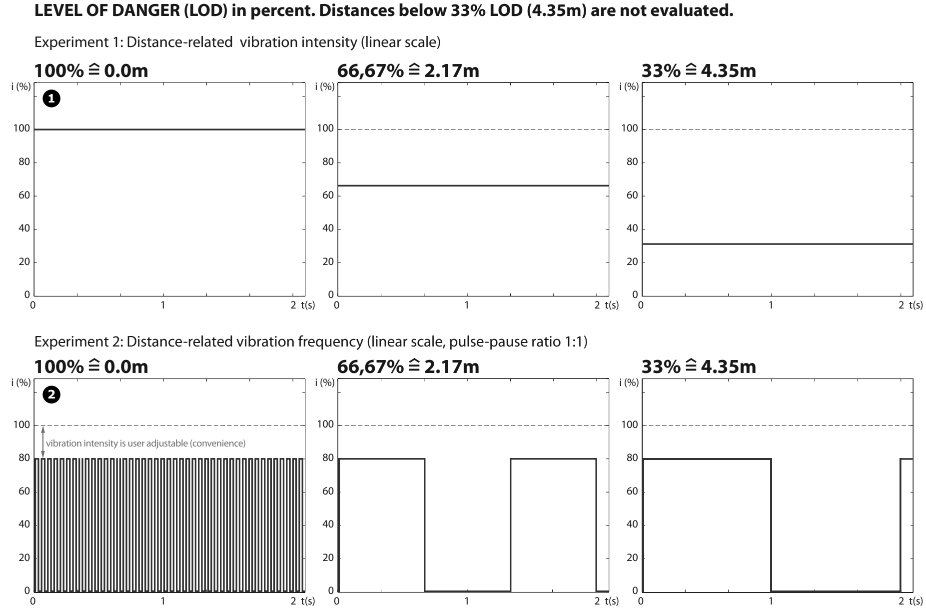

Fig. 3. The two analzyed variants for distance representation

In first user tests with the proposed system we experienced, that low-intensity vibrations (below 33%) were almost indistinguishable. For that reason, the final system configuration had been changed to use only vibration intensities between 33% and 100% (or distance values between person and obstacle of below 4.35m, as depicted in Fig. 3). For comparability issues, this definition has also been applied to the second experiment on variation of vibration frequency.

3.1 Experiment 1: Distance Representation by Variation of Vibration Intensity

In this experiment series, the distance between an obstacle and a test participant was mapped to the vibration intensity of a vibro-tactile actuator. The vibration was initiated on all tactor elements simultanously (this generates a higher perception than activation only a single vibrating element). For the mapping between distance and vibration intensity, a linear correlation function between distance and vibration intensity has been used (inversely proportional). The *level* *of danger* (LOD) for a person, and thus, the vibration intensity, increases with declining distance from the danger object (see top row in Fig. 3).

The entire setting has been installed in a laboratory room, as shown in Fig. 1. Test candidates had been briefed to move forewards and backwards, alongside a floor-mounted ruler, and transmit their opinion for the felt distance of a specific vibration-intensity value verbally. We conducted two different types of runs, the first with no feedback on the real distance values, and another with a direct feedback on estimated values' real counterpart.

3.2 Experiment 2: Distance Representation by Variation of Vibration Frequency

In a second test series we experimented with variation of the interval length for representing changing distances. This approach follows the idea of Park Distance Control (PDC) systems, established in the automotive domain. A PDC is a distance warning system that provides information on the distance to the nearest obstacle. The frequency of the signal increases as the distance to the obstacle decreases, a continuous signal is output in very close proximity to obstacles ($30cm$ or less) [19, p.4].

The vibration strength was adjusted individually for each test person to be of convienent intensity, and was than fixed for the entire experiment. The ratio between pulse- and pause times was set to 1 for the whole experiment. A distance of *zero* between person and object (represented by a minimum value of $0.05m$) was mapped to a (near-continuous) vibration with a frequency of $43.5hz$ (according to the formula below), the maximum distance (according to the first experiment at the LOD-level of 33%, or $4.35m$) between danger object and person was represented by a vibration frequency of $0.5hz$ (this implies a maximum interval length of 2 seconds).

$$\text{pulse time [ms]} = \frac{d\ \text{[distance in } m\text{]} * 2{,}000ms\ \text{[max. interval length]}}{2 * 4.35m\ \text{[max. distance]}}$$

For this experiment, again the two variants (i) without feedback, and (ii) with immediate feedback have been tested. The experiment itself was designed and conducted about 3 month after the first experiment, a subset of the test participants from the first test attended this second experiment series (because of the long time between the two experiments we can almost neglect possible dependencies of the second experiment from the first one).

4 Evaluation

Experiment 1: Variation of vibration intensity: The mean value of estimation errors is $0.438m$ for the experiment without feedback, and $0.299m$ for the second case with immediate feedback (see Table 1, and charts (1) and (3) in Fig. 4). This is a qualitative improvement of the second setting of 46.49% and confirms the assumption that *training* or *learning* is essential for a reliable

Table 1. Distance representation by variation of vibration intensity: No feedback (left), immediate feedback (right). Data represents the deviations from the real distance in meters.

Test Person	Min x_{min}	Max x_{max}	Mean $\overline{x}$	Median $\widetilde{x}$	Std.Dev. σ	Min x_{min}	Max x_{max}	Mean $\overline{x}$	Median $\widetilde{x}$	Std.Dev. σ
	Series without feedback					Series with immediate feedback				
1	0.005	1.070	0.346	0.315	0.267	0.030	0.710	0.313	0.315	0.193
2	0.040	0.960	0.390	0.270	0.290	0.005	1.130	0.357	0.255	0.296
3	0.055	1.470	0.563	0.370	0.412	0.015	0.735	0.250	0.255	0.207
4	0.010	1.295	0.470	0.455	0.358	0.000	0.830	0.307	0.220	0.258
5	0.030	1.610	0.734	0.660	0.470	0.030	0.950	0.317	0.255	0.219
6	0.010	0.805	0.261	0.195	0.214	0.035	0.665	0.295	0.270	0.191
7	0.015	0.990	0.487	0.440	0.267	0.010	0.805	0.301	0.250	0.253
8	0.005	1.240	0.455	0.355	0.368	0.045	0.435	0.247	0.260	0.137
9	0.000	0.835	0.351	0.255	0.282	0.025	0.755	0.334	0.255	0.217
10	0.000	0.985	0.382	0.350	0.272	0.025	0.820	0.326	0.290	0.206
All	**0.000**	**1.610**	**0.438**	**0.363**	**0.350**	**0.000**	**1.130**	**0.299**	**0.255**	**0.223**

user interface. This tendency is valid for all test candidates, except participant number 6 – here the statistical results are better for the feedback-free first experiment, although the maximum deviation error ($0.805m$) is somewhat higher in the first experiment ($0.665m$). This could be interpreted either as higher tactile sensibility of the person or simply as statistical outlier.

The left column in Fig. 4 shows the corresponding deviation errors in meters for both experiment variants. Dotted and dashed lines indicates the linear tendencies for the deviation error. They suggest the assumption that the error increases with number of experiments in the first case (without feedback), and decreases for the second case with permanent feedback (the slope of the trend lines is more pronounced when viewing the charts for individual test attendees). To find the upper and lower convergence boundaries for the error values, larger test series with 100+ readings for both experiments would have to be accomplished.

During experimentation we perceived several qualitative remarks from the test candidates:

(i) Not only the felt vibration, but also the "noise" caused by this vibration, has been used as information channel for distance-perception.
(ii) The self-assurance with estimating distances increased with increasing duration of the experiment.
(iii) The first series of experiments (without any feedback) provoked less cognitive load.
(iv) A major variation in vibration intensity, e.g. a high vibration value followed by a low one and vice versa, makes it harder to estimate the corresponding distance (consequently, such variations results in higher estimation errors).

Experiment 2: Variation of vibration frequency: The results of this exeriment contrast the ones from the first experiment.

Table 2. Distance representation by variation of vibration frequency: No feedback (left), direct feedback (right). Data represents the deviations from the real distance in meters.

Test Person	Min x_{min}	Max x_{max}	Mean $\overline{x}$	Median $\widetilde{x}$	Std.Dev. σ	Min x_{min}	Max x_{max}	Mean $\overline{x}$	Median $\widetilde{x}$	Std.Dev. σ
	Series without feedback					Series with immediate feedback				
1	0.000	1.670	0.529	0.385	0.491	0.010	1.040	0.401	0.380	0.264
2	0.040	1.220	0.428	0.295	0.314	0.010	1.650	0.489	0.375	0.425
3	0.050	1.860	0.588	0.480	0.458	0.010	1.030	0.355	0.330	0.277
4	0.010	1.130	0.391	0.245	0.329	0.000	1.230	0.325	0.225	0.292
5	0.030	2.600	0.528	0.445	0.518	0.010	1.140	0.433	0.395	0.317
All	**0.000**	**2.600**	**0.492**	**0.380**	**0.430**	**0.000**	**1.650**	**0.401**	**0.370**	**0.321**

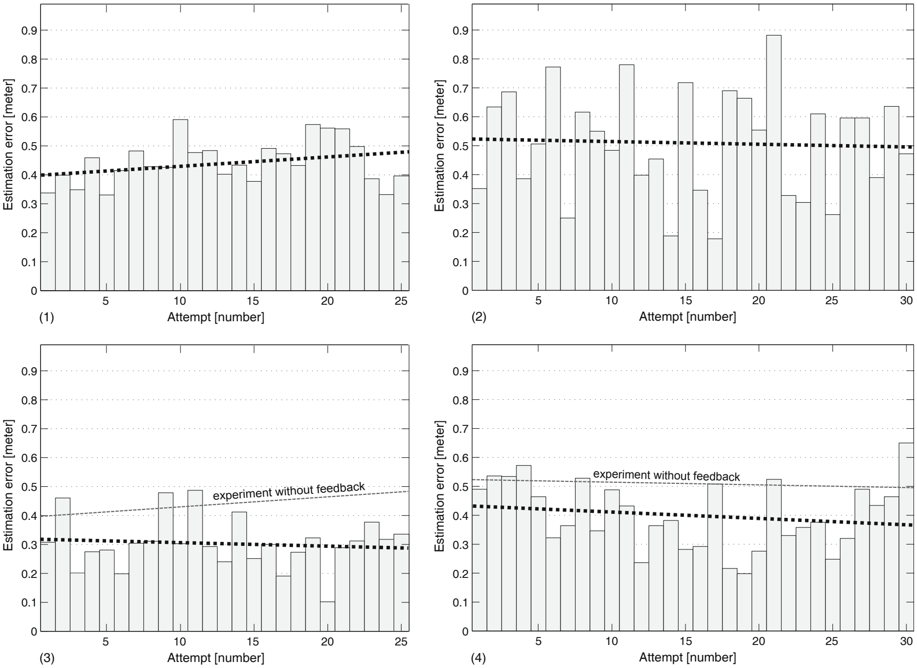

Fig. 4. Plot of averaged estimated values and their corresponding errors for both styles of the conducted experiments, ”level of danger according to vibration intensity” (left column) respectively ”vibration frequency” (right colum). The top row represents the test series with no feedback, the bottom row depicts the test series with immediate feedback. Dotted and dashed lines shows the deviation-tendency (linear trend lines).

Mean estimation errors are $0.492m$ (no feedback), respectively $0.401m$ (immediate feedback), see Table 2. The improvement is with 22.69% below the half of the improvement of experiment one (which was 46.49%). Comparing the absolute estimation errors we can clearly see that the second experiment performs worse compared to the first: A mean estimation error of $0.492m$ compared to

$0.438m$ stands for a degradation of 12.3% for the feedback-free case, $0.401m$ compared to $0.299m$ means a degradation of 34.11% for the second case with direct feedback.

Furthermore, the chart of estimations with associated errors (right column in Fig. 4) shows, that the trendlines are nearly flat (gently sloping). This encourages the assumption that a decrease in estimation error is hardly possible by training for this kind of stimulation.

Most of the experiment attendees (which were the same as in the first experiment) reported, that distance estimation from the experimental system with varying the vibration intensity was more intuitive than the second setting with varying the vibration frequency. Evaluation results confirmed these statements (see Table 2, and charts (2) and (4) in Fig. 4).

5 Conclusions

Motivated by the aim for raising human attention, or subtly delivering information about a users environment aside the vision and hearing channel of perception, we have developed a vibro-tactile distance awareness system, implemented as a waist belt. User studies confirmed our hypothesis, that physical distance, to walls, furniture or obstacles in general, can be ”felt” by considerate variations of the vibration intensity or frequency.

A further finding of the experiments is, that direct feedback improves on the estimation precision.

The results encourage for a whole new class of pervasive and ubiquitous computing applications and user interface designs, that lets users ”feel” the environment they are in.

Above these results, we expect further improvements on haptic distance awareness by (*i*) integrating notions of orientation and direction, (*ii*) further experiments with different models of distance and vibration-intensity mapping, e.g. non-linear variations of intensity and frequency, and (*iii*) additional experiments based on high-quality vibro-tactile elements to avoid faults and signal noise.

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