Detecting Vibrations Across the Body in Mobile Contexts

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ABSTRACT

In this paper we explore the potential and limitations of vibrotactile displays in practical wearable applications, by comparing users' detection rate and response time to stimuli applied across the body in varied conditions. We examined which body locations are more sensitive to vibrations and more affected by movement; whether visual workload, expectation of location, or gender impact performance; and if users have subjective preferences to any of these conditions. In two experiments we compared these factors using five vibration intensities on up to 13 body locations. Our contributions are comparisons of tactile detection performance under conditions typifying mobile use, an experiment design that supports further investigation in vibrotactile communication, and guidelines for optimal display location given intended use.

Author Keywords

Vibrotactile display, wearable haptics, mobile applications.

ACM Classification Keywords

H.5.2. User Interfaces: Haptic I/O —*Tactile & Haptic UIs, User Interface Design, Handheld Devices and Mobile Computing, Multi-modal Interfaces*

General Terms

Experimentation, Human Factors, Performance.

INTRODUCTION

Graphical and auditory interfaces prevalent today are information-dense, but also lead to problems such as perceptual overload and inefficiency of the visual and auditory channels [9,17], decline in primary task performance from secondary task competition for perceptual resources [18], and situations where vision and/or audition are unavailable or inconvenient [19]. In mobile environments, phones, GPS guidance tools, and music players contribute to sensory resource starvation, where vision is heavily occupied, and auditory channels are compromised by external noise and social concerns.

Tactile display is seen as a promising conduit for mobile communication, lacking the drawbacks of visual or auditory display; but it brings its own challenges. Vibrotactile (VT) displays embedded in a handheld device can notify users, without visual load and in private or noisy situations. However, the device must be held in the hand (a condition incompatible with the secondary or monitoring tasks that typically trigger such alerts) or stowed close to the skin. Tactile sensitivity varies widely by body location [10,11] and with movement [13]; many users have experienced this variance with missed calls and messages. This flaw undermines the whole notion of mobile tactile notification.

One solution is for users to *wear* a tactile display driven through a local body network, which can then be located to optimize tactile communication rather than access to an associated graphical display. With this distributed approach, bodily location of the tactor becomes a design parameter which we do not adequately understand. Local skin sensitivity is critical, but so is context of use, convenience, appearance, and sometimes the tactor technology; some sensitive body regions are impractical for reasons of mobility and wearability. In the absence of a single correct answer, designers need guidelines based on the relative perceivability of body sites under conditions that typify mobile contexts. Of particular interest are bodily movement, for its known impact on sensitivity; and visual workload, for possible mental-resource competition.

The present experiments were constructed to inform such guidelines. While some of the needed data exists, gaps and disparate sources make comparisons difficult. We aimed to systematically address the questions of (a) which body locations are more sensitive to vibrations and (b) which are more affected by movement; whether (c) visual workload, (d) gender, or (e) expectation of location impact performance; and if (f) users subjectively prefer any of these locations. **Our specific contributions are:**

(i) Comprehensive assessment of the effect of *all* of loci, movement, and expectation on detection *probability*;
(ii) An experiment design that can be replicated to answer more questions about vibrotactile communication; and
(iii) Compilation of our results into design guidelines for optimal display location for a given purpose.

Approach

We conducted two experiments. The first, E1, varied factors identified in research questions (a-d) with stimuli

CHI 2011, May 7–12, 2011, Vancouver, BC, Canada.

applied in a random and unanticipated sequence; E2 varied expectation (e). For E1, we chose 13 body sites based on practicality for wearable use; E2 employed the 9 most promising of these. E1 varied body site, movement (sitting or walking on a treadmill), presence or absence of visual workload, and signal intensity (5 levels), counterbalanced by gender. E2 also varied expectation of stimulus site in place of workload. A trial consisted of a single vibration at a single site. We measured subject response time and logged undetected stimuli, and collected subjective preferences. A statistical analysis informed our guidelines.

RELATED WORK

In recent years, tactile displays (individual elements are known as "tactors") have emerged from specialized uses to become accepted consumer gadgetry, with innovation in size, power use, and controllability. VT variants (piezo and oscillating motors are most common) tend to be lowest in cost and power needs and most deployable; designers are already embedding tactors in clothing. A substantial body of pyschophysical and design research exploring tactile sensitivity and wearable potential exists; here we highlight the most relevant works.

Sensitivity to Vibrotactile Stimuli

Spatial Location

Considerable research has examined sensitivity of particular body locations to VT stimuli. One of the most recent and comprehensive is Jones and Sarter's review compilation of the effect of VT stimulus frequency, duration, intensity, and locus on detection [10]. They present sensitivity thresholds of many body locations of interest at different frequencies, and suggest ideal ranges of frequency that are most perceivable by humans. Most commercial VT displays already work within these frequency and intensity ranges.

Lederman and Klatzky provide a research summary on haptic perception. The research cited here is based on two-point and point-localization threshold methods to compare the sensitivity of different body locations [11]. While completely appropriate for the design of closely-spaced tactor arrays, these methods are mismatched to a large class of mobile contexts. For single-tactor displays (e.g. held or worn cellphone), users do not identify exact vibratory location or spatial pattern; relevant metrics are likelihood and speed of detection and response. Furthermore, consumer-grade VT display diameters exceed the body's largest point-localization threshold (e.g. back).

Hoggan et al. used consumer-grade VT displays in a handheld device and compared location recognition of vibration on fingers under different stationary conditions [9], with promise for loci and rhythm for encoding information.

However, two factors that remain unexamined in a practical context are (a) movement and its interference with other factors and (b) expectations about stimulus locus.

Movement

Studies connecting movement to tactile sensitivity have involved animal and human models, and vibro- and electrotactile stimulation. For example, Chapin and Woodward found suppression in movement conditions in SI cortical response of rats to electrical stimulation through electrodes implanted in the forepaw, when comparing treadmill locomotion, spontaneous grooming, quiet resting and "tensed-up" mobility [5].

Using electrotactile stimulation on the forefingers of human subjects, Angel and Malenka [1] found correlations between sensory suppression and movement speed in detection rates. In a similar experiment, Chapman et al. found that both active and passive movement of the ipsilateral arm increased the detection threshold by 50% on the mid-ventral aspect of the right forearm [6].

Post et al. studied the same effect but with VT stimulation [13] on the operant arm (forearm, thenar eminence and distal digit) under different motor activity levels. Voluntary motor activity increased the VT detection threshold.

The above papers consistently indicate that body motion directly affects the detection of vibro- or electrotactile stimuli. However, none compare relative VT sensitivity by site, for activities of interest here such as natural walking.

Wearable Haptic Systems

Bosman et al. developed a dual-wrist system to guide a pedestrian inside an unknown building; vibrations indicated directions and stops [3]. Although their design could help blind or visually impaired users, it was intended to augment unimpaired space perception, and improved performance. In a different strategy, Rukzio et al. developed a guidance system based on the single palmar VT phone display and a public display with 8 lights [14]. The lights toggled in a rotation, while the phone vibrateed when the public display direction matched the user's route direction. Tsukada and Yasumura developed a belt with eight VT displays distributed evenly around the waist to guide a pedestrian towards destinations, given realtime user location and user orientation [18]. Subjects felt vibrations when stopped; but when walking, often failed to recognize vibrations with intervals less than 500ms, and stopped to assess it.

Driving support systems are natural targets for body-situated guidance and alerts. Ho et al. examined spatially informative VT signals in a driving simulation where front vs back stimuli might indicate direction of an oncoming car [8], and found promise for encoding directional information to locus of stimuli. Meanwhile, Straughn et al. compared auditory and tactile pedestrian warning systems for drivers, finding two VT displays on the driver's biceps more effective than auditory signals [16]. For short time to collision (TTC), the warning signal was best utilized to generate a reactive motor response (warning direction = safe direction), whereas for long TTC, attention is best served with warning = hazard direction.

In summary, numerous tactile display setups have been prototyped; these, and others featuring back and arm. Their use confirms reduced performance during movement, which might however be confounded with workload. To our knowledge, relative site sensitivity has not been systematically explored in mobile contexts.

APPARATUS AND SETUP

Our setup consisted of a tactor array, a treadmill or tall chair, and a large-screen display, which were deployed to create the conditions described below (Figure 1).

Vibrotactile Array and Calibration

We built an array of tactors of which different subsets could be activated (Figure 2), with inexpensive VPM2 eccentric-mass tactors from Solarbotics Ltd. [15], 12mm in diameter and 3.4mm thick. A Duemilanove Arduino processor [2] drove a tactor drive circuit with quick release connectors. Resister networks and Darlington arrays provided 80mA at 3V to each motor (Figure 2).

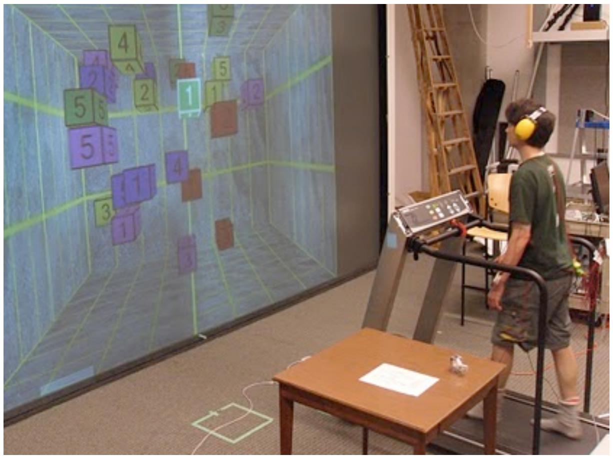


Figure 1. Setup of experiment 1. Tall chair is not shown.

The tactors were energized with pulsewidth (PW) modulated signals. To maintain resolution despite variable site sensitivity but without concern for discriminability, we specified five excitation levels spanning all site detection thresholds. We performed an iterative perceptual calibration in which we recorded pilot-subject detection rate, beginning with a logarithmic PW distribution and adjusting it to achieve satisfactory perceptual separation.

To check for inter-unit variability, we measured the output of all the tactors used with a piezo-electric accelerometer (PCB Inc) aligned normal to the eccentric mass rotation plane and sampled at 5kHz, with the tactor restrained by a magnetic mount screwed onto the clamped accelerometer. A Welch power spectrum analysis on 20s samples indicated frequency varied by 16% (mean 190Hz, SD 30), and power by 5% (59.0 dB/Hz, SD 2.87). We addressed this variance by placing tactors on body sites with a different random layout for each participant.

Movement Setup and Task

The sitting and walking conditions were chosen as typical and distinctive movement states in wearable contexts. For the former, particpants sat in a tall chair for a consistent screen view. When walking, participants chose a comfortable treadmill pace that they could maintain for twenty minutes. The mean speed chosen was 2.4 kilometers/hour (SD 0.5).

Figure 2. VPM2 eccentric-mass tactor

Visual Workload Setup and Task

During trials with visual workload, participants sat and walked approximately two meters from a simple geometric scene on a 4(H) x 3(W) meter display (Figure 1). The scene showed twenty-five red, green, blue, yellow, and pink blocks in equal quantities, each numbered between 1-5, bouncing slowly around a three-dimensional room. Participants were asked to count the times a single highlighted block hit any walls in the room, including the invisible wall represented by the screen. This task was chosen as controllable continuous visual workload characteristic of a pedestrian's everyday attention and memory tasks, but not so distracting that participants were liable to stumble. The collision count was meant to reproduce the mental activity of a pedestrian keeping track of nearby cars and pedestrians. The other blocks simulated local objects that are distracting but need not be tracked.

Metrics and Analysis Technique

Our primary metric to assess site sensitivity as a function of condition was number of detected vs. missed vibrations (detection rate or DR); we also used response time (RT) as a secondary indicator. Because detection data is distributed binomially, we statistically analyzed Detctions with a generalized linear mixed model (GLMM) using "R" and the glmmML package [4]. We refined the model with backwards selection, beginning with many terms then iteratively removing those with the largest p-value until all the terms had significant p-values ($p<0.005$). Only main effects and significant interactions are reported.

The presence of missed-stimuli trials prevented a normal RT distribution and use of ANOVA. We replaced the censored data points (missed trials) of RT with a "sufficiently" large value and used a Kruskal-Wallis analysis, which uses metric rank rather than value to compute a test statistic. The value chosen for censored data points then needs only be larger than the maximum; we set RT_m=3500 ms for "miss" trials. RT_m renders RT means meaningless for conditions with many Miss trials, which are common at low amplitudes for some body sites.

Therefore in graphical comparisions of RT (but not DR) between conditions, we focus on high intensity stimuli with their higher detection rates. We also ran the Kruskal-Wallis test on the high-intensity subset, which were detected at >=98% for all factors except intensity; and on the "all detected" subset for intensity, to confirm that the results are not simply due to the missed data points.

EXPERIMENT 1: RANDOM SITE WITH VISUAL LOAD

In our first pass (E1), we tested potentially relevant body sites at five amplitudes while addressing initial experimental factors of visual load and movement. We balanced gender to allow the consideration of its impact, which could arise through, for example, gender-linked differences in body fat composition. Specifically, we examined the following hypotheses:

H1: Intensity increases DR and decreases RT.

H2: Body sites will differ in terms of DR and RT.

H3: Movement decreases DR and increases RT; and it affects different body sites to different degrees.

H4: Visual workload decreases DR and increases RT.

H5: Gender differences in DR and RT exist.

Design

Experiment size imposed a limit of 15 tactor sites. We chose seven sites corresponding to common or potential wearable locations, and mirrored these to address possible response assymmetry (Figure 3 and Table 1). 500ms vibrations were presented in randomized order across the body sites. Per condition, each intensity was displayed twice at each right and left site, or four times at the spine.

Half the male and half the female participants first sat in a chair and subsequently walked on a treadmill, while the other half walked first then sat in a chair. During half of the walking and half of the sitting trials, we asked participants to direct their attention to the visual scene, which was turned off during the other trials.

Using a full-factorial design, we ran 5x4x7x2x2 (intensity x repetitions x site x movement x visual workload) trials, for a total of 560 trials per participant.

Procedure

Participants changed into sports clothing. We attached tactors (which vibrated normal to skin without slip or shear) directly to the skin at defined locations with Lightplast Pro sports tape. Except for the feet (tactors covered with socks but no shoes), no clothing covered the tactors.

The interval between tactor vibrations was randomized to between four and six seconds, with interval length doubled on random trials (odds of 1 to 7) for a more arrhythmic pattern. We asked participants to press the right button on a modified computer mouse when they detected a vibration. We recorded RT up to a cutoff of 3500ms, noting missed responses. No feedback was given to responses.

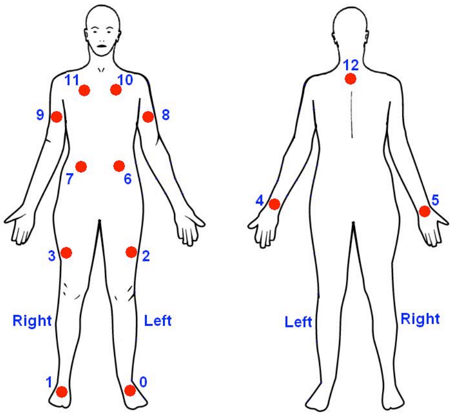


Figure 3. Body sites used in E1; and E2 omitting 6, 7, 10, 11.

a) **Foot:** 0/1, top surface of the foot, e.g. tongue of a shoe*
b) **Thigh:** 2/3, outer thigh, halfway between knee and hip joint, e.g. hem of shorts on the sides*
c) **Wrist:** 4/5, posterior between small bones, e.g. watch face*
d) **Stomach:** 6/7, halfway between navel and hip bone, e.g. belt or waist band
e) **Upper arm:** 8/9, halfway between shoulder and elbow on the sides, e.g. arm band*
f) **Chest**: 10/11, below collar bone, e.g. necklace or shirt collar
g) **Spine**: 12, four centimeters below C7 vertebrae*

Table 1. Body sites used in E1. '*' indicates sites used in E2.

Training conducted before experiment trials:

1. Experience maximal vibrations on each site.
2. Experience each of the five intensities on the wrist.
3. Respond to ten maximal vibrations at random sites.
4. Count ten wall collisions in the visual task.
5. Respond to ten maximal vibrations in four conditions: Sit+No Workload, Sit+W, Walk+No W, Walk+W.

Experiment: Respond to 140 vibrations (location x intensity x reps) in four conditions, order counterbalanced by participant.

Participants took a short break after each condition and a longer break before switching movement state. After training, between conditions, and at experiment end, tactor function was verified. Participants answered online survey questions between sitting and walking conditions and at experiment end. During trials, participants wore noise canceling headphones. Sessions lasted 90-110 minutes.

Results

16 participants (8 male) volunteered. These were distributed in *age* as 18-25 (12), 31-40 (2) and 40-60 (2); in *height* as tall (8), average (3) and short (5); and *body type* as ecto (6), meso (7) and endomorph (3). In the prior year, *participant use of portable devices with tactile feedback* was distributed as daily (10), 2-3 times/week (4), and <1 time/week (2).

Participants *used a treadmill* <=1 time/month (14) and 1 time/week (2). All reported themselves righthanded.

Detected/Missed Stimuli (DR)

Intensity initially had a nearly linear effect on the estimated odds ratio of DR in our GLMM model. Therefore, we considered it as a continuous variable to increase model readability, causing only slight differences in estimates and corresponding p-values for other covariates. Finding no differences between sides, we merged left and right body sites except for spine. Feet are the baseline for sites, male for gender, sitting for movement, no workload for workload, and first trial for trial number.

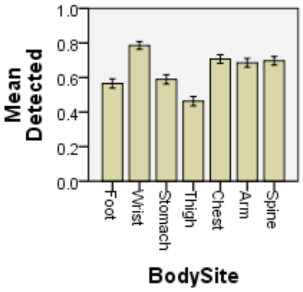


Figure 4. Mean detected vibrations per body site in E1.

In the GLMM results (Table 2), p-value indicates effect significance (p<0.05). For a significant *p*, a negative *coef* decreases and a positive *coef* increases *odds of detection*, i.e. the quotient of the probability of detecting (*p*) and missing (*1-p*) a signal, i.e. *p/(1-p)*. The odds *ratio* of a particular factor (e.g. wrist in Table 2) is the ratio of the odds of detection under that condition (e.g. wrist) to the odds of detection under the reference condition (e.g. foot). There were very few false positives (1.2%), therefore we neglected their effect in the analysis.

Main effects: As we can see in Table 2 and Figure 4, all body sites except thighs are significantly different from feet. In terms of detecting VT signals, thighs are as bad as feet; stomach, chest, and arms are slightly better; wrists and spine are best. Walking greatly decreases odds of detection. Intensity has a significant effect (Figure 5), as is expected. Gender and the presence of the visual task do not have a significant effect on detection of vibrations.

Trial number, which accounts for the opposing differences caused by learning and fatigue, is marginally significant (p=0.048). Since its coefficient is very small (-5.7E-4), we computed the odds ratio of detecting a vibration after 100 trials as (*exp(coef × 100)=0.94*); i.e., the odds of detecting a vibration decreases by 6% after 100 trials, suggesting minimal practical impact.

Interactions: Several factors interact with body sites. By Gender: females detect significantly more vibrations on their thighs. By Intensity: higher intensity increases detection on spine, arms, wrists, and stomach *less* than other sites, with spine the least sensitive.

For all sites except spine and stomach (e.g. Wrists:Walking), Movement decreases DR but it affects chest, arms and wrists least (Figure 6). The positive coefficients for interactions between Movement and these body sites do not compensate for the negative main-effect of movement coefficient.

	coef	se(coef)	z	Pr(>|z|)	O.R.
(Intercept)*	-4.02	0.31	-12.81	<0.001	0.02
Female	-0.40	0.25	-1.60	0.11	0.67
Wrists*	2.57	0.36	7.07	<0.001	13.11
Stomach*	1.28	0.36	3.54	<0.001	3.60
Thighs	-0.36	0.41	-0.89	0.37	0.69
Chest*	1.07	0.38	2.82	<0.001	2.90
Arms*	1.62	0.36	4.49	<0.001	5.06
Spine*	2.28	0.35	6.43	<0.001	9.73
Intensity*	2.02	0.11	18.73	<0.001	7.55
Walking*	-1.95	0.20	-9.56	<0.001	0.14
Workload	-0.06	0.07	-0.85	0.40	0.95
TrialID*	0.00	0.00	-2.82	<0.001	1.00
Female:Wrists	0.23	0.25	0.91	0.36	1.26
Female:Stomach	0.18	0.25	0.75	0.46	1.20
Female:Thighs*	0.62	0.25	2.47	0.01	1.87
Female:Chest	0.37	0.25	1.47	0.14	1.45
Female:Arms	0.11	0.25	0.43	0.67	1.11
Female:Spine	-0.21	0.25	-0.82	0.41	0.81
Wrists:Walking*	0.58	0.28	2.07	0.04	1.78
Stomach:Walking	-0.26	0.28	-0.93	0.35	0.77
Thighs:Walking*	-1.33	0.31	-4.25	<0.001	0.26
Chest:Walking*	0.86	0.28	3.14	<0.001	2.37
Arms:Walking*	0.66	0.27	2.42	0.02	1.93
Spine:Walking	0.16	0.28	0.59	0.56	1.18
Wrists:Intensity*	-0.35	0.15	-2.30	0.02	0.70
Stomach:Intensity*	-0.38	0.14	-2.72	0.01	0.69
Thighs:Intensity	-0.11	0.15	-0.72	0.47	0.90
Chest:Intensity	-0.10	0.15	-0.68	0.50	0.90
Arms:Intensity*	-0.35	0.14	-2.42	0.02	0.71
Spine:Intensity*	-0.41	0.14	-2.86	<0.001	0.67

Table 2. Generalized Linear Mixed Model (GLMM) of DR in E1. Pr indicates that DR is significantly different from the reference for that factor (e.g. from feet, for body sites). '*' indicates statistical significance.

Reaction Time (RT)

We ran two sets of Kruskal-Wallis tests for RT: on the entire dataset, using 3500ms for missed vibrations, and on a data subset containing only high-intensity trials where most of the vibrations (99.2%) were detected. Both sets show that Intensity, Site, Movement and Task have a significant effect on RT, but gender and trial ID do not (Table 3). Intense vibrations are detected faster (Figure 5), and movement and visual workload increase RT (Figure 7).

We also ran the Kruskal-Wallis test on Intensity for only the trials that were detected (excluding Misses), finding a significant effect of Intensity on RT (p<0.005).

Subjective Results

Users preferred wrists and arms the most, feet and thighs the least. When we asked which site they would choose for notifications, directional guidance, and for cues during exercise, they chose wrists, arms, and spine.

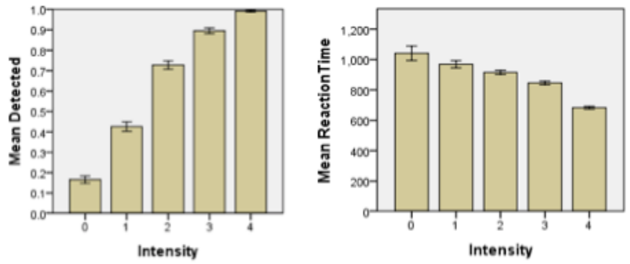


Figure 5. Mean detected vibrations (Left) and Mean reaction time (Right) for different intensities in E1.

	chi-square	df	p-value
Full Set			
BodySite*	434.3	12	<0.001
Task*	24.1	1	<0.001
Movement*	422.7	1	<0.001
Gender	11.3	1	0.596
Intensity*	4517.2	4	<0.001
TrialID	509.4	559	0.162
Subset: High Intensity			
BodySite*	130.9	12	<0.001
Task*	48.4	1	<0.001
Movement*	62.6	1	<0.001
Gender	1.3	1	0.249
TrialID	487	528	0.899
Subset: All Detected			
Intensity*	4517	4	<0.001

Table 3. Results of Kruskal-Wallis tests on reaction time, E1. '*' indicates statistical significance.

EXPERIMENT 2: RANDOM VS. EXPECTED SITE

In E1, participants did not know which of 15 sites would receive the next vibration, whereas in actual wearable use, usually only one site would be used. We theorized that there could be a performance cost associated with scanning multiple body sites, and therefore performed a second experiment (E2) where site *expectation mode* is controlled. To maintain experiment size, we also removed the two least-likely body sites pairs (stomach and chest), and the visual task condition because it did not have a significant effect on DR, our primary metric. All other aspects were identical to E1. In addition to verifying H1-H3 and H5 from E1, we examined the following E2 hypotheses:

H6: Expectation of site increases DR and decreases RT.

H7: Expectation reduces the effect of movement.

H8: Expectation impacts different genders differently.

Design

In E2, we used five paired body sites (Table 1). Half the male and half the female participants first sat in a chair and subsequently walked on a treadmill, while the other half walked on a treadmill first then sat in a chair. During half of the walking and half of the sitting trials, the vibrations were displayed in 10-trial clusters (5 intensities x 2 repetitions) at each body site and participants were informed of the site (Expectation condition). During the other half, the vibrations were randomly displayed on any site and participants were not informed of location.

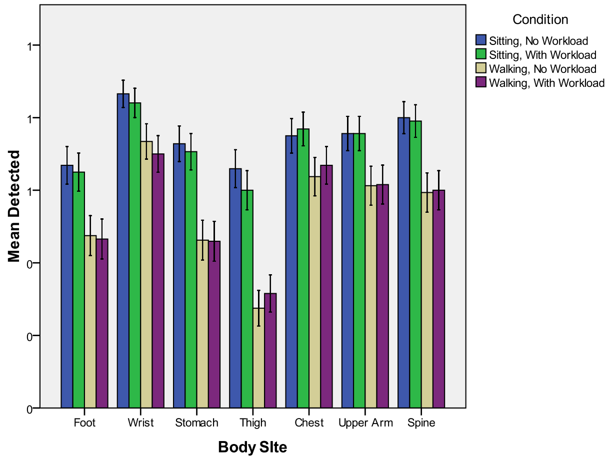


Figure 6. Mean detected vibrations per body site and condition, E1. Error bars show the 95% confidence interval.

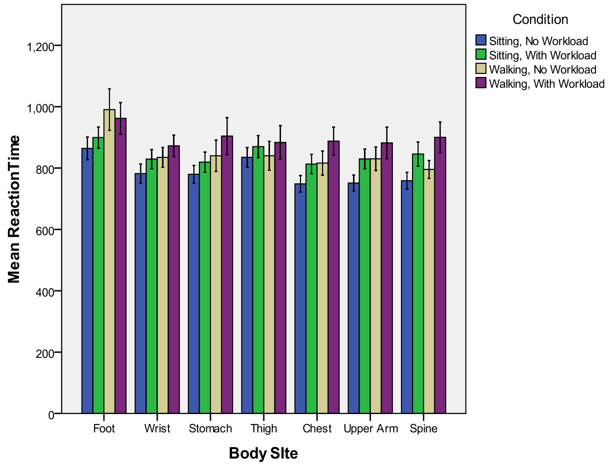


Figure 7. Mean reaction time by site and condition, E1.

Before experiment trials, participants completed the following training steps (1-3 are the same in E1):

Training 1:

1. Experience maximal vibration on each site.
2. Experience each of the five intensities on the wrist.
3. Respond to ten maximal vibrations at random sites.

Training 2: respond to 4 counterbalanced conditions of:

4. Sitting+Expectation: sets of four vibrations, random intensity on three randomly selected sites, sitting.
5. Sitting+No Expectation: twelve vibrations of random intensity on randomly selected sites, sitting.
6. Walking+Expectation: sets of four vibrations, random intensity, on three randomly selected sites, walking..
7. Walking+No Expectation: twelve vibrations of random intensity on randomly selected sites, walking.

Experiment: Respond to 100 vibrations (location x intensity x reps) in four conditions, order counterbalanced by participant.

Participants took a short break after training and between the second and third conditions, and filled questionnaires at the beginning (profile) and end (preferences) of the experiment. Each person was compensated $15 for participation. Total experiment time was 90 minutes.

Results

16 participants (8 male) volunteered, none from E1. These were distributed in age as 22-24 (4), 25-27 (6), 28-30 (6); in *height* as tall (4), average (10), short (2); and *body type* as ecto (5), meso (9), endomorph (2). In prior year, *participant use of portable devices with tactile feedback* was distributed as daily (9), 2-3 times/week (2), 1 times/week (1), <1 time/month (4); and participants *used a treadmill <1 time/year (3), <=1 times/month (9), 2-3 times/month (1), 1 time/week (3).* 4/16 reported themselves lefthanded*.* As in E1, false positive effect was negligible (0.8%).

Detected/Missed Stimuli (DR)

Our GLM analysis was conducted as for E1. *With expectation* is the reference for the new expectation factor.

Main effects: All body sites are significantly different from feet (Table 4, Figure 8), with wrists and spine best and feet worst at detecting vibrations. Walking greatly decreases detection odds. As expected, intensity is significant.

Gender has a significant effect on the odds of detecting a vibration (females seem to have higher DR) but it is cancelled out with the interaction effects (see below).

TrialID (time into the experiment) and Expectation have no significant effect on the odds of detecting a vibration.

An interaction between Intensity and spine reduces the main effect of Intensity, suggesting Intensity plays a less important role for spine than for other body sites.

Movement decreases detection odds at all sites (Figure 8); wrists and spine least, thighs and feet most. Again, positive interaction coefficients for Movement and sites do not compensate for the negative main Movement coefficient. Movement:Intensity reduces the main effect for Movement.

The interaction effect between Gender and body sites indicates that females have higher odds of detection only on their feet.

Reaction Time (RT)

As with E1, we ran two sets of Kruskal-Wallis tests: one on the entire data set, using 3500ms for missed vibrations, and another on the subset of high-intensity trials where most of the vibrations (98.4%) were detected (Table 5).

Both tests show that Intensity, Movement, Expectation, and Gender have a significant effect on RT but Trial ID does not (Figure 9). More intense vibrations are detected faster, movement and lack of expectation increase RT, and males are slightly faster to respond than females.

A Kruskal-Wallis test on Intensity for the trials where vibrations were detected showed a significant effect of Intensity on RT (Table 5, Subset=All detected).

	coef	se(coef)	z	Pr(>|z|)	O.R.
(Intercept)*	-1.36	0.35	-3.85	<0.001	0.26
Female*	0.89	0.34	2.63	0.009	2.42
Thigh*	0.65	0.28	2.32	0.021	1.92
Wrist*	1.84	0.29	6.29	<0.001	5.32
Arm*	0.76	0.29	2.61	0.009	2.14
Spine*	1.84	0.28	6.66	<0.001	6.28
Intensity*	1.70	0.11	15.72	<0.001	5.50
Walking*	-2.91	0.25	-11.48	<0.001	0.05
Randomized	-0.01	0.19	-0.05	0.960	0.99
TrialID	0.00	0.00	-1.78	0.075	1.00
Female:Thigh*	-1.02	0.25	-4.14	<0.001	0.36
Female:Wrist*	-1.39	0.26	-5.26	<0.001	0.25
Female:Arm*	-0.62	0.26	-2.40	0.016	0.54
Female:Spine*	-1.45	0.25	-5.91	<0.001	0.23
Female:Randomized*	-0.42	0.16	-2.63	0.009	0.65
Thigh:Intensity	-0.17	0.14	-1.27	0.204	0.84
Wrist:Intensity	-0.08	0.16	-0.47	0.638	0.93
Arm:Intensity	0.24	0.16	1.51	0.132	1.27
Spine:Intensity*	-0.39	0.13	-3.00	0.003	0.68
Thigh:Walking*	-1.26	0.32	-3.99	<0.001	0.28
Wrist:Walking*	1.84	0.30	6.20	<0.001	6.30
Arm:Walking*	1.16	0.29	3.96	<0.001	3.18
Spine:Walking*	1.54	0.27	5.70	<0.001	4.68
Thigh:Randomized*	-0.09	0.24	-0.38	<0.001	0.91
Wrist:Randomized*	0.87	0.26	3.31	0.001	2.38
Arm:Randomized	0.16	0.26	0.63	0.531	1.17
Spine:Randomized	-0.31	0.24	-1.27	0.204	0.73
Intensity:Walking*	0.28	0.09	3.17	0.002	1.33

Table 4. GLMM of DR in E2. Pr indicates that DR is significantly different from the reference for that factor. Coef>0 indicates increased odds of detecting a vibration. '*' indicates statistical significance.

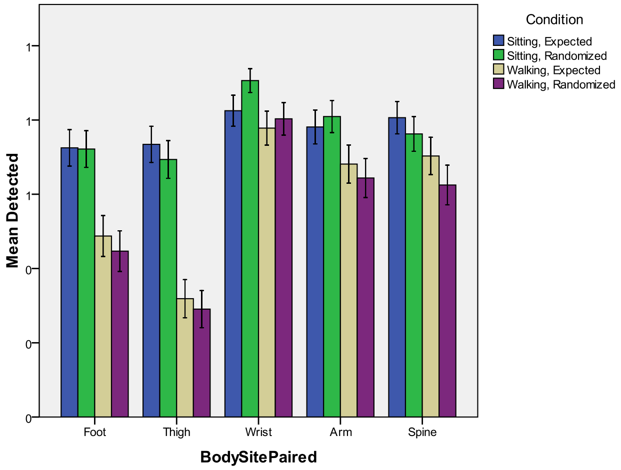


Figure 8. Mean detection rate by body site and condition, E2.

Subjective Results

E2 participants preferred spine and wrists the most, feet and thighs the least (relative to E1, spine replaced arms as a preferred site). For notifications and directional guidance they chose wrists and for exercise cues they chose spine.

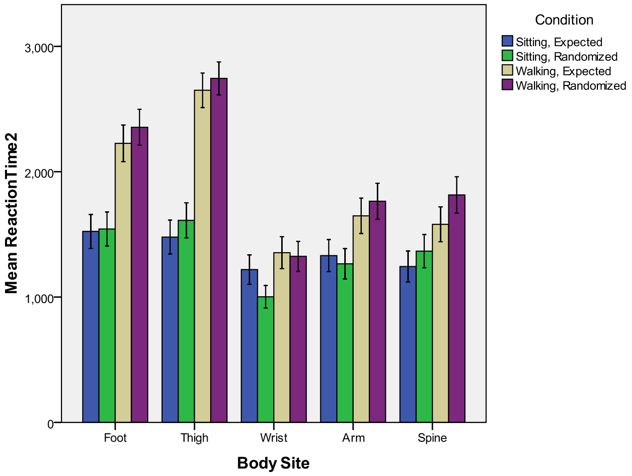
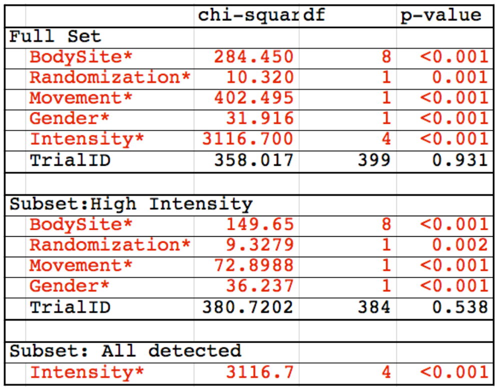


Figure 9. Mean reaction time by site and condition, E2.



	chi-squar	df	p-value
Full Set			
BodySite*	284.450	8	<0.001
Randomization*	10.320	1	0.001
Movement*	402.495	1	<0.001
Gender*	31.916	1	<0.001
Intensity*	3116.700	4	<0.001
TrialID	358.017	399	0.931
Subset:High Intensity			
BodySite*	149.65	8	<0.001
Randomization*	9.3279	1	0.002
Movement*	72.8988	1	<0.001
Gender*	36.237	1	<0.001
TrialID	380.7202	384	0.538
Subset: All detected			
Intensity*	3116.7	4	<0.001

Table 5. Results of Kruskal-Wallis tests on reaction time, E2. '*' indicates statistical significance.

SUMMARY AND DISCUSSION

We begin our discussion with an examination of our hypotheses, then further reflect on their implications.

H1 - Vibration Intensity: Both E1 and E2 showed that increasing vibration intensity strongly increases detection odds and reduces reaction time, supporting H1. However, impact of DR varies across the body. In E1, DR increases with intensity for all body sites but less so for spine, wrists, arms and stomach; in E2, less so for the spine.

H2 - Body Sites: E1 and E2 consistently show that wrists and spine are most sensitive in detecting VT signals, whereas feet and thighs are least sensitive. As described for H1, body sites are differentially sensitive to intensity in terms of absolute detection. However, E1 and E2 also demonstrate that response time for high intensity signals (>= 98% detection) is similar across the body. Thus, H2 is confirmed for detection rate, but not for response time.

H3 - Movement: Walking significantly reduces odds of detecting a vibration, and increases reaction time even to high intensity vibrations. Both experiments further confirmed that the detection rate of thighs and feet are most affected by walking. H3 is thus confirmed.

We note that while thighs and feet moved the most during walking in this experiment, participants also swung their arms. Walking was chosen as a representative movement in mobile contexts. Further work is required to establish more generalizable patterns of body sensitivity to different types of movement; but the present result is highly relevant to designing for mobile uses.

H4 - Visual Workload: Our visual workload task did not have any apparent effect on vibration detection. It did significantly impair reaction time, increasing even for the most intense vibrations. H4 is thus partially rejected and partially confirmed. There is no evidence in our results of body site specificity in impact of the workload task.

Wickens proposes four qualities to describe workload: mental stage, modality, channel and processing code [20]. *Stage* can be perceptual or responsive. *Modality* is typically visual or auditory, and it is better to spread work across modalities rather than on time-sharing a single modality. Visual workload can be focal or ambient without competition. *Codes* are analogue/spatial or categorical/symbolic. Typically, people perform simultaneous manual and focal tasks well. Thus, our visual task (focal) and vibration response modality (manual) do not compete heavily for the same resources.

Ferris et al. presented vibration patterns from back-mounted tactors to participants in a driving simulation, with categorical (TC) or spatial (TS) visual tasks [7]. Their visual task had a significant effect on RT but similarly to our results, the overall effect of task on accuracy (detection of the type of visual stimuli) did not reach significance; in particular, while their TC task impacted accuracy, their TS task (which seems more similar to our visual task) did not.

We did not choose a harder visual task or one which more specifically interfered with detecting and responding to signals because we aimed to simulate a typical mobile context, i.e. watching for other pedestrians and cars over a wide field of view. However, there will be situations when more severe competition does occur, even if not endemic.

H6 and H7: Expectation

Expectation had a significant effect on detection only at the wrists where surprisingly, it reduced detection odds. One possible explanation is that in the no-expectation mode where in recent trials a perceptually weaker stimulus had been felt elsewhere, the wrist percept was relatively more salient. Another possibility is that sensory adaptation acted as a side effect of sending a number of signals to the wrists. Because wrists detect more vibrations than other sites, the adaptation effect on wrists should be larger than elsewhere. However, the positive effect of expectation (which cancels adaptation on other body sites) is not large enough for wrists to compensate for adaptation. Finally, there is a one in 20 chance that this result is simply due to chance; our analysis employed a 95% confidence level.

Expectation significantly reduced response time: scanning the whole body when the stimulus site is unknown slows the process of vibration detection and response. Thus, H6 is confirmed with respect to reaction time.

Expectation did not have a significant effect on detection rate and (compared to movement) it had a very small effect on reaction time. Therefore, expectation alone cannot cancel the effect of movement, and H7 was not confirmed.

H5: Gender

In E1, males were better than females at detecting vibrations on the chest and stomach, the sites omitted from E2. For the remaining sites, males always detected vibrations on wrists and spine better than females. However, E1 and E2 disagree as to the body sites where females were best – thighs in E1, arms and feet in E2.

In general, females' reaction times were slightly longer than males, with the exception of the feet where females were faster. Thus overall, while H5 is confirmed (gender does have some impact) the difference is not consistent or large.

Subjective Results

On average, E1 participants preferred vibrations on their wrists most, arms the second; E2 participants preferred spine, then wrist. Grouping the 32 participants of both experiments, there is a tie for highest preference between spine and wrists. Both groups disliked vibrations on their feet by far the most; thigh is second least preferred.

Both groups chose wrists for notification applications, arms and wrists for directional guidance, and spine as the most appropriate spot for vibrotactile signals during exercise.

CONCLUSION AND FUTURE WORK

We ran two experiments to study the differences between sensitivity of several body sites to vibrotactile signals. We narrowed down the number of body sites to those most practicable for wearable haptics and mobile applications: wrists, upper arms, outer thighs, feet, chest, stomach, and spine. Most of these locations have been suggested or used in past wearable tactile systems such as belts, back arrays, wrist and arm bands, tactile shoes, and most commonly, cellphones in pockets (on the thighs).

We compared these body sites under conditions of presence or absence of a visual workload, sitting in a chair or walking on a treadmill, and with or without knowledge of location of the next stimuli. We also looked at gender differences, and considered five vibration intensities.

One of our most important and perhaps surprising results is that expectation of stimulus location does not improve detection rate, under the conditions of E2; but it does decrease reaction time. We did not include a visual workload condition in E2 because of its limited impact in E1; however, it will be of interest to see if expectation can counteract negative effects of workload tasks which cause more interference.

The fact that our workload task did not interfere with vibration detection in E1, i.e. even when the next vibration location was unknown and participants had to scan their body to detect it, is an encouraging result. To the extent that this kind of workload is realistic, vibrotactile signals can still "get through" anywhere on the body even under load conditions, albeit more slowly when the user is under mental effort. The implication is that the detection and some kinds of workload typical of mobile contexts do not directly compete for mental resources.

In another notable result, thigh was among the least effective and least preferred stimulus site we tested; and yet, front pocket is a common location to stow a mobile device, particularly for men.

Although H1-H5 seem to be predictable from past work **none** of our hypotheses have ever been confirmed in a controlled comparison with realistic display technology and is very necessary from a design perpective. For example, H1 confirmation informed/justified our choice of intensity levels and assumptions on its linearity (which were used later in the GLMM). Furthermore, the secondary results of H2-H5 (e.g. interaction effects, change in the ordering pattern) were not predictable from published data.

Design Guidelines

From our results, we propose the following guidelines. We note that these heuristics have particular relevance for applications which have either of two attributes: intolerance to missed signals, and/or a requirement for fast responses. The first is typified by tasks which rely on background processes, such as notification, or those where signals carry notable content, e.g. haptic icons [12] where inattention could distort the signal's meaning. The second includes gaming and time-and-safety-critical guidance systems. Others have need of both, e.g. driving systems which use both guidance and notifications.

Location, Location, Location

Wrists and spine are generally best for detecting vibrations, and are also the most preferred, with arms next in line. Feet and thighs are poor candidates for vibrotactile displays, exhibiting the worst detection performance of those we tested and ranking lowest in user esteem. However, for reaction time, location does not matter.

Stronger Vibes Are Felt Faster

Unsurprisingly, increasing intensity increases detection rate and reduces reaction time, particularly on the lower-body sites tested here. This result does not imply that strong vibrations will always be preferred or appropriate; but when a notification must get through, intensity increases salience.

Don't Take Movement For Granted

Movement can decrease detection rate and increases response time. Walking (the movement we tested) affects lower body sites the most. For applications that involve a considerable movement, other factors such as intensity and body location need to be adjusted to compensate for this.

Visual Workload Slows Users Down

Although workload of the type we employed (visual search) does not apparently impact vibration detection rate, it does increase response time. Therefore, expect some lags and irregularities in user response to vibrotactile displays in visually demanding situations.

Users React Slower to Unexpected Vibrations

Multiple site tactile interfaces mean surprises for the user; single site interfaces mean the user always knows where to "watch". If reaction time is critical, designers should be cautious in proliferating display sites across the body. If only detection matters and time is not critical, the number of sites does not matter, and the redundancy may in fact prove more robust to local interference.

Gender Differences do not Change Our Suggestions

Men detect vibrations on their wrists and spine a little better than women. Women detect vibrations somewhat better on thighs and arms. However, wrists and spine are still the best choices for both genders, and differences are not large.

Future Work

We embarked on this study because we required guidelines of this sort to reduce design errors and shorten the iterative design process for our wearable haptic systems. These results solve our immediate needs, and the body sites investigated are a good sample of those that might ever be successfully used in wearable contexts.

However, other factors deserve broader investigation. Of greatest importance will be to encompass a broader set of workload tasks and movement types and to incorporate typical auditory and vibrotactile noise of moving vehicles.

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