Tactor Localization at the Wrist

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Abstract. The present study examined our ability to identify the location of a single vibration delivered to the dorsal and/or volar side of the forearm near the wrist. Three participants took part in three absolute identification experiments. In Exps. I and II, a 3-by-3 tactor array was placed on the dorsal and volar side of the wrist, respectively. In Exp. III, two 3-by-3 tactor arrays were placed on both sides of the wrist. Prior to each experiment, the intensities of the tactors were adjusted to be equally loud. Each participant completed a total of 405, 405 and 810 trials for Exps. I, II and III, respectively. The results indicate that on average, only 2 tactor locations can be correctly identified on either the dorsal or the volar side of the wrist, and 4 locations on both sides. The implications of our results for the design of mobile devices are discussed.

Keywords: tactor localization, mobile device, wrist.

1 Introduction

Haptic interfaces have begun to permeate our everyday life by showing up in pagers, personal digital assistants, cellphones and game consoles. A key desirable feature of vibrotactile feedback on mobile devices is its discreteness. There has been increasing interest in expanding the repertoire of tactile signals for mobile devices while keeping the power consumption down. This requires not only engineering ingenuity but clever exploration of the human tactile perceptual capabilities with the goal to discover intuitive and distinctive tactile patterns for effective communication between the mobile device and its human user.

Earlier attempts at using haptic feedback for mobile applications focused on sensory substitution – the use of haptic stimulation to deliver visual and speech information to individuals with visual or hearing impairments. The most noteworthy systems include the Optacon (Telesensory Corp., Mountain View, CA) [1], the tactile vision substitution system (TVSS) [2][3], and the Tactaid VII (Audiological Engineering Corp., Somerville, MA) [4][5] (see [6] for a review). The Optacon was invented for the blind to read printed texts with their fingertips. The TVSS allowed visually-impaired users to "see" visual scenes on their backs. The Tactaid VII was designed to transmit speech information to

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individuals with severe hearing loss. These devices transform information-rich contents from the visual or auditory modality to touch. They usually require extensive training before a user can interpret the complex tactile stimulation patterns efficiently. In contrast, more recent efforts have focused on delivering simpler messages through a haptic display. For example, many investigators have used tactor arrays to convey directional (e.g., [7][8][9]) and distance information (e.g.,[10][11]). Vibrotactile pattern discrimination and recognition have also been studied extensively (e.g., [12][13]).

The information contents carried by vibrotactile signals designed for, say, mobile phones, are usually much simpler than speech, texts or images, but more complex than, say, directions. In order to design distinctive tactile signals, it is important to explore the attributes that can be used as building blocks. Luk et al. used an array of piezoelectric actuators that provided lateral skin stretches on the thumb, and found that people could perceive direction of motion, waveform (such as triangular waves), amplitude and duration of the stimulation [14]. Other studies have also investigated the design of a “tactile language” such as the “vibratese” [15], “haptic icons” [16], “tactile melodies” [17] and “tactons” [18]. For example, Brown et al. used three tactors equally spaced on the volar forearm with three levels of roughness (through amplitude modulation) and three types of rhythms per tactor [18]. Location on the arm was the best perceived cue and roughness the worst. In a more recent study, Hoggan et al. demonstrated a 100% localization rate for four tactors at the lower thumb, upper thumb, index finger and ring finger [19]. It thus appears that location is an attribute that can be well perceived.

The goal of the present study was to quantify our ability to localize tactile stimulation on the dorsal and volar sides of the forearm near the wrist. The wrist is a good candidate for receiving vibrotactile stimulation from a mobile device since we are already used to wearing watches and jewelries at this location. Oakley et al. mounted a 3-by-3 tactor array on the dorsal side of the wrist [22]. They found that identification accuracy at the nine tactor locations ranged from 22% to 76%. It was also found that the participants were generally better at identifying the tactor location *across* the back of the arm (84% correct along the pinky to thumb direction) than *along* the back of the arm (54% correct along the wrist to elbow direction). The present study extends the work of Oakley et al. in three ways. First, both the volar and dorsal sides of the forearm near the wrist were tested for tactor localization. We reasoned that if a mobile device is to be worn like a watch, then tactors can be placed on both sides of the wrist. Second, the perceived intensities of all the tactors were calibrated to be the same. This ensured that the tactors were localized based on their positions and not on their distinctive loudness levels. Third, an information theoretical analysis was performed to reveal the maximum number of locations that can be identified without error. Percent-correct scores do not provide information on how many locations can be correctly identified, but information transfer estimates can.

2 General Methods

2.1 Participants

Three individuals (P1, P2, P3; 2 males and 1 female, age range 22-25 years old) participated in each of the three experiments. Participant P2 designed the experiments and was therefore more experienced with the setup. Participants P1 and P3 had never taken part in any haptic experiment prior to the present study. Of the three participants, P1 is left-handed, and P2 and P3 are right-handed. All participants were tested with their left forearms.

2.2 Apparatus

Tactors with a diameter of 8.5 mm and a resonant frequency around 150 Hz were used in all experiments (LVM8, Matsushita Electric Industrial Co., Japan). The tactors were arranged in a 3-by-3 array (Figure 1) on stretchy Velcro substrates. The spacing of tactors was 25mm as suggested in [20]. To ensure proper contact with the skin, a sports wristband was worn on top of the Velcro band as shown in Figure 2. Custom-designed tactor driver control boxes developed at the Haptics Interface Research Lab at Purdue [8] were used to set the vibration frequency and control the onset/offset of each tactor.

2.3 Procedures

The experiments utilized a 1-interval forced-choice absolute identification procedure with trial-by-trial correct-answer feedback. There were 9 tactor-location alternatives in Exps. I and II, respectively. The participants were asked to rest their arms on a table with either the dorsal side (Exp. I) or the volar side (Exp. II) facing up. The layout of the response codes in Exps. I and II was chosen such that it was identical to the configuration of the numeric keys 1-9 on a standard computer keyboard when the dorsal side (Exp. I) or the volar side (Exp. II) of the forearm was visible to the participant (see Figure 3). There were 18 tactor-location alternatives in Exp. III where 9 tactors were placed on the dorsal wrist

Fig. 1. The 3x3 tactor array with an inter-element spacing of 25mm

Fig. 2. The wristband for ensuring contact between the tactors and skin

and another 9 on the volar wrist. The participants held the forearm horizontally with the dorsal side facing up while avoiding touching the table with their forearm. The numbering scheme for the dorsal side was the same as that used in Exp. I (Figure 3(a)). The numbering of the volar-side tactors was the mirror image of that on the dorsal side (e.g., the tactor on the volar side underneath tactor #7 on the dorsal side was numbered 77). The double digits were used as responses to volar-side tactors while the single digit to dorsal-side tactors.

Intensity calibration was conducted each time a participant attached the tactor array to the wrist. For Exps. I and II, the intensity of the center tactor (#5) was adjusted to be comfortably loud. The participant then felt two 500-ms vibrations, one from one of the 8 remaining tactors and one from tactor #5, separated by a 250-ms pause. The participant adjusted the intensity of the non-centered tactor until it felt equally loud as tactor #5. This continued until all 8 peripheral tactors were calibrated against the center tactor #5. For Exp. III, the calibration was performed on the dorsal-side tactors first. The participant then adjusted the intensity of the volar-side center tactor #55 so that it felt equally strong as the dorsal-side center tactor #5. The remaining 8 surrounding tactors on the volar wrist were then calibrated against the volar-side tactor #55.

Training was provided following the calibration. The participants learned to associate response labels with the locations of the tactors. Each participant spent about 10 min on training. During the main experiment, the participant felt a 500-ms vibration on a randomly-selected tactor and was asked to indicate its location by entering the response code on the numeric keypad. A randomization without replacement method was used to ensure that the *a priori* probability of each stimulus remained the same throughout the experiment. As a consequence, the total number of times each stimulus was presented was different. Correct-answer feedback was provided after each trial.

Each participant completed a total of 405, 405 and 810 trials in Exps. I, II and III, respectively. The total number of trials were divided into 45-trial runs. All participants completed Exps. I and II first (with mixed runs from the two experiments so as to minimize training effect) before proceeding to Exp. III. A 3 min break was enforced between runs to minimize fatigue. All three experiments were completed over a course of two to three days.

2.4 Data Analysis

A 9-by-9 (Exps. I or II) or 18-by-18 (Exp. III) stimulus-response confusion matrix was formed to summarize the results. The rows of the matrix corresponded to the vibrating tactor and the columns the response. Each cell contained the number of times a particular tactor was identified as being at a specific location. The dependent variable, information transfer (IT_{est}), was calculated as

$$IT_{est} = \sum_{j=1}^{k} \sum_{i=1}^{k} (\frac{n_{ij}}{n}) \log_2 (\frac{n_{ij} \cdot n}{n_i \cdot n_j}) \tag{1}$$

where i and j were the indices for stimuli and responses, respectively, n_{ij} was the number of times stimulus i was called response j, n_i the sum of n_{ij} over all j values (i.e., the total number of times stimulus i was presented), n_j the sum of n_{ij} over all i values (i.e., the total number of times response j was called), n the total number of trials, and k the number of stimulus alternatives. The quantity IT_{est} measures the amount of information transmitted from the stimuli to the responses. The integer part of $2^{IT_{est}}$ is interpreted as the maximum number of tactor locations that can be correctly identified.

3 Results

3.1 Exp. 1: Tactor Localization on the Dorsal Wrist

Table 1 lists data pooled from all three participants. Localization accuracy ranged from 25% (tactor #9) to 72% (tactor #4). A visual inspection reveals that most trials fall on the main diagonal cells corresponding to correct responses. In addition, a substantial number of trials fall on two secondary diagonals corresponding to stimulus-response pairs that are in the same column but different rows. This indicates a tendency to mislocalize tactors in the same column with respect to their row positions. Information transfer for localization was estimated at 1.00 bits (2.0 locations). Essentially, the participants could only correctly identify 2 tactor locations on the dorsal wrist.

The matrix shown in Table 1 was collapsed into two 3-by-3 matrices to investigate the participant's ability to identify a tactor's column and row positions. For example, data from tactors in the same column (e.g., tactors 1, 4 and 7 in Figure 3(a)) were combined, so that confusions across the columns can be examined. To examine confusions across rows, data from tactors 1, 2 and 3 in Figure 3(a) were combined, so were data from tactors 4, 5 and 6, etc. The IT_{est} for column identification was 0.53 bits (1.4 locations). The IT_{est} for row identification was 0.30 bits (1.2 locations).

Table 1. Stimulus (T1-T9) and response (R1-R9) confusion matrix for tactor localization on the dorsal wrist with data pooled from all participants

	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	sum
T1	44	13	3	34	1	5	2	12	2	116
T2	11	67	7	8	20	8	2	3	3	129
T3	2	15	54	1	5	21	2	6	1	107
T4	25	4	0	116	2	0	12	2	0	161
T5	2	10	2	18	90	6	5	6	2	141
T6	4	10	32	8	12	79	2	14	13	174
T7	5	6	1	17	5	2	94	7	4	141
T8	3	3	3	10	30	8	15	50	4	126
T9	0	13	6	3	15	22	4	26	31	120
sum	96	141	108	215	180	151	138	126	60	1215

Table 2. Stimulus (T1-T9) and response (R1-R9) confusion matrix for tactor localization on the volar wrist with data pooled from all participants

	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	sum
T1	49	4	0	49	9	3	2	0	1	117
T2	5	81	11	8	21	2	0	5	1	134
T3	2	13	82	0	1	18	0	3	2	121
T4	18	2	0	106	5	0	19	1	0	151
T5	0	19	6	9	86	5	1	8	2	136
T6	2	17	41	1	2	76	0	9	7	155
T7	2	0	2	37	3	1	83	15	1	144
T8	2	5	0	5	26	14	4	67	12	135
T9	0	3	7	3	18	31	1	17	42	122
sum	80	144	149	218	171	150	110	125	68	1215

3.2 Exp. II: Tactor Localization on the Volar Wrist

Table 2 shows the confusion matrix for data pooled from all three participants. Percent correct scores ranged from 34% (tactor #9) to 70% (tactor #4). A large number of trials fall on the two secondary diagonals, indicating confusions of tactors in the same column with respect to their row positions. There were additional errors associated with adjacent tactors in the same row or column (e.g., see cells T2-R3, T3-R2, T9-R8 and T8-R9). Information transfer was estimated to be 1.24 bits (2.4 locations). The results from the volar wrist appeared to be slightly better than those obtained from the dorsal wrist. However, 2.4 tactor locations on the volar wrist (Exp. II) and 2.0 on the dorsal wrist (Exp. I) were essentially the same; the participants could only correctly identify a maximum of 2 tactors on either side of the wrist.

The matrix shown in Table 2 was collapsed to investigate the participants' ability to identify a tactor's column and row positions. The IT_{est} for column identification was 0.77 bits (1.7 locations). The IT_{est} for row identification was 0.37 bits (1.3 locations). These results were essentially the same as those obtained from the dorsal forearm.

3.3 Exp. III: Tactor Localization on the Dorsal and Volar Wrists

The data pooled from all three participants are shown in Table 3. The percent-correct scores for tactor localization varied from 30% (dorsal tactor #9) to 73% (dorsal tactor #5). Information transfer was estimated to be 1.99 bits (4.0 locations). Compared to the results from Exps. I and II, it appears that the total number of correctly-identifiable tactor locations were the sum of those on each side of the wrist. There was therefore little interference in tactor localization on the dorsal and volar sides of the wrist.

The matrix shown in Table 3 was collapsed in several ways to investigate the participants' ability to identify a tactor's column and row positions on the

Table 3. Stimulus-response confusion matrix for tactor localization on both the dorsal and volar wrists

		Dorsal									**Volar**									
		R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	sum
Dorsal	**T1**	60	3	0	47	1	1	7	3	0	7	2	0	9	0	0	4	0	0	144
	T2	20	36	1	17	13	1	3	5	0	0	0	0	0	0	0	0	1	0	97
	T3	1	28	38	5	6	11	3	4	1	0	2	0	1	0	1	0	0	0	101
	T4	14	0	0	100	1	6	24	4	0	1	0	0	5	0	0	6	0	0	161
	T5	7	11	0	10	81	0	0	2	0	0	0	0	0	0	0	0	0	0	111
	T6	2	15	13	21	20	57	3	8	2	1	1	1	1	0	1	1	0	0	147
	T7	1	2	0	12	1	1	80	5	0	0	0	0	4	0	0	4	0	0	110
	T8	0	1	0	28	27	2	20	54	4	1	0	0	0	0	0	1	3	0	141
	T9	1	4	3	5	21	20	9	65	56	0	0	0	0	0	0	1	1	0	186
Volar	**T1**	0	1	0	1	0	2	0	2	0	84	8	0	16	1	0	3	1	0	119
	T2	0	3	0	1	0	0	2	1	0	7	116	16	1	23	5	0	1	0	176
	T3	0	4	12	3	0	9	1	0	3	0	7	80	1	1	36	1	0	3	161
	T4	4	0	0	9	0	0	0	0	0	27	20	0	66	11	1	9	4	0	151
	T5	0	1	0	0	1	0	0	1	0	0	18	11	0	59	6	0	1	1	99
	T6	1	2	10	0	0	9	0	0	0	0	2	67	0	2	46	0	2	8	149
	T7	1	0	0	1	0	0	0	3	0	3	0	0	21	3	1	72	28	4	137
	T8	0	0	0	0	1	1	0	1	0	1	3	0	2	4	13	3	71	14	114
	T9	0	0	0	0	1	9	0	1	11	0	0	6	2	1	19	0	3	69	122
	sum	112	111	77	260	174	129	152	159	77	132	179	181	129	105	129	105	116	99	2426

dorsal forearm and on the volar forearm, as well as the confusion pattern between the tactors on the dorsal and volar sides. By collapsing cells in the upper-left quadrant of Table 3 along the column or row tactors, we found the IT_{est} for column identification on the dorsal wrist alone to be 0.53 bits (1.4 locations). The IT_{est} for row identification on the dorsal wrist was 0.42 bits (1.3 locations). Both results were essentially the same as those obtained in Exp. I when the tactors were applied to the dorsal wrist only. By collapsing cells in the lower-right quadrant of Table 3 along the column or row tactors, we found the IT_{est} for column identification on the volar wrist to be 0.53 bits (1.4 locations). The IT_{est} for row identification on the volar wrist was 0.87 bits (1.8 locations). Again, the results were similar to those obtained in Exp. II when the tactors were applied to the volar wrist only.

Further more, the column and row data from both the dorsal and volar wrists were combined. For example, all trials involving tactors 1, 11, 4, 44, 7 and 77 were added to form one entry in a 3-by-3 matrix examining confusions across the columns regardless of the side of the wrist. The IT_{est} for column identification on both sides of the wrist was 0.61 bits (1.5 locations). The IT_{est} for row identification on both sides of the wrist was 0.44 bits (1.4 locations). These results were again similar to those obtained in Exps. I and II.

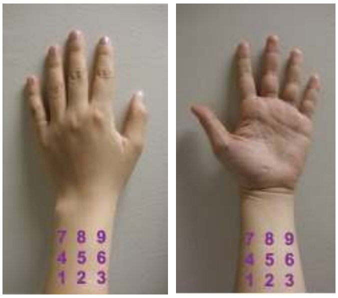
Finally, to examine the dorsal/volar reversal effect, Table 3 was collapsed by its quadrants (i.e., all cells in the same quadrant were added). The participants identified the tactors to be on the wrong side of the wrist for only 7% of all the trials. This indicates little confusion on the side of the wrist where the vibrating tactors were located.

4 Concluding Remarks

The present study investigated our ability to localize vibrotactile stimulation on the forearm near the wrist. Three experiments were conducted on the dorsal wrist, the volar wrist, and both sides of the wrist, respectively. On average, the participants could only localize 2 tactors on the dorsal wrist and 2 tactors on the volar wrist. A total of 4 tactors could be correctly localized on both sides of the wrist. Tactile localization has been studied on many body sites including the arm and the abdomen [20][21]. An important finding is that performance is enhanced at natural anatomical anchor points such as the wrist, elbow and shoulder [20]. In the present study, localization performance was slightly better at tactors located near the wrist (an anatomical landmark) than those more proximal to the elbow. Another finding of our study was that tactor localization was slightly better with regard to columns than rows on the forearm. This is consistent with the findings by Oakley et al. (2006) [22]. It was also found that most dorsal/volar reversal occurred along the lateral (pinky side) and medial (thumb side) columns of the forearm as opposed to the central column.

Of the three participants tested in the present study, one participant (P2) performed twice as well as the group average: she was able to localize 4 tactors on either the dorsal or the volar wrist and 8 tactors on both sides. As the experimenter, P2 was more familiar with the experimental setup and had a lot more training with the identification task while debugging the experiment. We therefore attribute P2's superior performance to possible training effects.

Our results have implications for the design of multi-tactor mobile displays. Several previous studies have identified tactor location as a salient cue for vibrotactile stimulation [18][19][22]. The present study provides quantitative results on the maximum number of tactors that can be reliably identified based on the location only. One possible tactor configuration recommended for mobile devices worn on the wrist is shown in Figure 4. In this configuration, 3 tactors are placed on each side of the wrist. Even though the total number of tactors exceeds the average results obtained in the present study, we believe that error-free tactor localization may be achievable due to the redundant coding of column-row positions (i.e., the single-row tactor is in the middle column and the row containing two tactors occupies the lateral and medial columns). Dorsal/volar reversal is minimized by avoiding mirror-image tactor locations on the wrist (i.e., one tactor near the wrist on the dorsal side and two tactors near the wrist on the volar side). It is quite possible that through additional redundant coding, such as associating different rhythms with different locations, more tactors can be localized near the wrist. Future experiments will continue to explore our ability to identify the attributes of vibrotactile signals in multi-tactor mobile devices using the methodology outlined in the present study.



(a) (b)

Fig. 3. Illustration of response labels for the 3-by-3 tactor array on the (a) dorsal and (b) volar sides of the forearm

(a) (b)

Fig. 4. Recommended tactor configuration for mobile devices worn on the (a) dorsal and (b) volar wrist

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