# Vibrotactile Pattern Recognition on the Torso with One and Two Dimensional Displays

by

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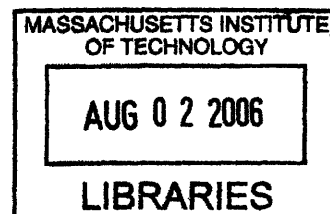
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## ABSTRACT

This research focused on the evaluation of a tactile display that is used for navigation and communication. In the first experiment, a four by four array of vibrating motors (tactors) was mounted on the torso while the subject wore an Interceptor Body Armor (IBA) vest. Subjects were required to identify which of eight patterns was presented. The results indicated that subjects could recognize the patterns presented with perfect accuracy, which indicates that wearing heavy body armor over the display does not affect the ability to perceive tactile inputs. A second set of experiments involved a one-dimension tactile array of eight tactors worn around the waist. The results indicated that the subjects could recognize the six circumferential patterns presented with an accuracy of 98-100% correct. A further experiment confirmed that the linear tactile display could be used to provide cues about the location of an event in the environment. These experiments showed that identification of the vibrotactile patterns was slightly superior on the two-dimension tactile array on the torso as compared to the one-dimension tactile array around the waist. When subjects were required to identify the location of an individual vibrating motor using the one-dimensional array they achieved an accuracy of 94-100% correct. This suggests that a linear tactile array can be used to present navigational cues.

Thesis Supervisor: Lynette A. Jones
Title: Principal Research Scientist

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# Table of Contents

# 1. Introduction

Most communication devices rely on the senses of sight and hearing. As a result, these senses are often overwhelmed with data, making it difficult to transmit signals through these overtaxed channels. Instead of finding ways to transmit additional information through visual and auditory inputs, this research explores the channel of touch. Tactile stimulation of the skin may provide an avenue for communication that is intuitive and attention demanding. The focus of this thesis is on the use of a wearable, wirelessly controlled tactile display to communicate via vibrotactile stimulation of the torso.

The torso provides a relatively large and flat surface area on which vibrotactile stimulation can be applied. Even though the hands and fingers are the most sensitive areas of skin on the body, there are advantages to developing tactile display technology for the torso. The actuators used to stimulate the skin can be spread over a larger surface area to compensate for its decreased sensitivity in comparison to the hand. The torso is also rarely used as a medium for receiving transmitted information, unlike the hands which are used to interact with the environment. When the total area of skin available is considered, the torso is capable of accommodating twice the information of the finger tips (Piateski and Jones, 2005).

# 2. Background

## 2.1. Spatial Acuity of the Torso

A tap on the shoulder is a stimulus that, in the absence of disease or any sensory abnormalities, is processed quickly and its location on the body is identified accurately. The skin contains thousands of mechanoreceptors specialized for the sense of touch, yet there are very few tactile communication devices. The torso, making up approximately half of the total surface area of the body, provides an extensive tactile space for presenting information. It is particularly sensitive to changes in pressure with thresholds averaging 20-40 kPa, which are higher than those on the forearm or face (Saddiki-Traki et al., 1999). The two-point threshold for discriminating vibratory stimuli on the back is 10-11 mm, regardless of whether stimuli are presented simultaneously or successively (Eskildsen et al., 1969). The ability to detect vibrotactile stimuli on the torso varies as a function of frequency, and is optimal between 200-300 Hz. There is no discernable change in vibrotactile thresholds as one moves circumferentially around the torso from the navel to the spine, however (Cholewiak et al., 2004). In the design of a tactile display, these estimates of the spatial and temporal acuity of the skin can be used to optimize the number and spacing of tactors, as well as the vibration frequency and amplitude.

## 2.2. Previous Work

Tactile displays have been designed to provide navigational cues to a human operator, particularly in situations where visual or auditory signals might be difficult to use. These displays have been used to control a vehicle, maintain spatial orientation, alert a human operator, and provide information about key features in an unknown environment (Rupert, 2000; Rochlis and Newman, 2000). They have also been used to

6

provide information about body tilt to individuals with balance disorders (Wall et al., 2001). A common application for tactile orientation systems is representing the location of an object in an environment as a stimulus on the surface of the body, with the user in the center of the field. It has been proposed that military pilots could use this type of display to indicate the direction of an enemy plane. In conjunction with a motion sensor, blind pedestrians could use such a device to aid in navigation.

Van Erp and Werkhover (1999) tested the ability of subjects to localize stimuli and perceive spatial intervals on the torso. In the experiment, one tactor was activated, then after a delay, another tactor was activated. Subjects were asked to determine whether the second activated tactor was to the left or the right of the first tactor. Results showed that localization was best in the center of the torso and worst on the left side. Also, localization was better on the ventral surface of the torso than on the dorsal surface. Localization ability may be optimal at the body's central axis because when the body is stimulated on both sides, the stimuli are processed in both hemispheres of the brain, resulting in improved localization (Van Erp and Werkhoven, 1999).

Studies of directional cueing have usually wrapped the tactile display around the trunk. Information is transmitted by activating a series of vibrating motors in a pattern corresponding to a command or direction. The subject interprets the pattern or localizes the stimulus to interpret the directional cue. Cholewiak et al. (2004) varied the placement and spacing of tactors in a tactile display worn around the waist and required that subjects indicate the location of stimulation. It was determined that localization accuracy was highest at the spine and navel as these serve as anatomical reference points. It was expected that the left and right sides would also serve as natural reference points because

of their proximity to the arms, however, the experimental results proved otherwise. Spatial localization is relatively poor on the torso. By reducing the number of tactors around a waist belt from twelve to eight, Cholewiak et al. (2004) found that localization accuracy improved from 74% to 92% correct.

## 2.3. Motivation

The goal of this thesis is to evaluate a wirelessly controlled, wearable tactile display for use in navigation. The display presents tactile stimuli to the user as a means of communication and to indicate the direction in which he or she should move in an unfamiliar environment. The experiments described here were designed to determine which vibrotactile patterns are most easily identified. Experiment 1 tested the ability of subjects to identify tactile patterns on the torso while wearing an Interceptor Body Armor (IBA). Experiment 2 evaluated whether a one-dimensional tactile array is as effective as a two-dimensional display in presenting information to the user. The results from these experiments will determine which body site and tactile patterns are likely to be most effective for directional cueing.

The optimal characteristics of a torso-based display in terms of the number of actuators required to present information, their spacing across the skin surface and the desired frequency and amplitude range for stimulating the skin have yet to be established. In addition, it is not clear which patterns of vibrotactile stimulation can readily be perceived on the torso and related to a specific instructional cue (e.g. move to the left) or to the location of an external event in three-dimensional space (e.g. obstacle located at 3 o'clock).

# 3. Experiment 1: Torso-Based Tactile Display

## 3.1. Apparatus

### 3.1.1. Tactor Selection

Tactile displays have been designed to provide navigational cues to human operators. The tactors, mounting, and electronics must be small and lightweight, since the displays are worn by the user. Another requirement is to ensure that the tactors are quiet when activated, since excessive noise could annoy or endanger the user. In addition, the vibration amplitude has to be high enough to surpass the skin's threshold for sensation, but not so high that the user would feel discomfort. Power requirements also have to be considered. The power supply for the tactor array must be portable and last for a reasonably long time (Lockyer, 2004).

Pancake pager motors (Sanko Electric, Model 1E120) were used as tactors for this tactile display. They were an ideal choice because they are small, lightweight, inexpensive and available with varied specifications. These actuators are robust and can be worn safely on the body. The tactors are encased in plastic to make them more robust and to increase the contact area between the skin and tactor. Piateski (2005) tested both pancake and cylindrical motors in her experiments, and found that there was no difference between the two types of motor in terms of human performance.

### 3.1.2. Torso-Based Tactile Display

The torso-based display comprises an array of electromechanical vibrators that is positioned across the lower back. The temporal and spatial sequence of activation of the motors is used to communicate with the wearer. Due to the indentation at the spine, a

four-by-four array of tactors was used so that it was symmetrically placed across the
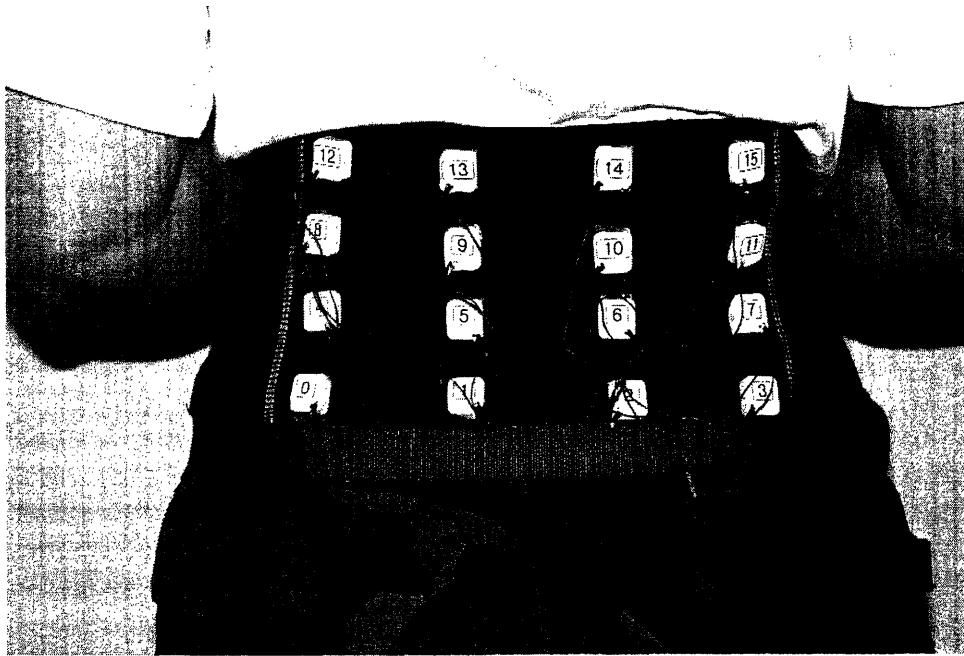
back.



**Figure 1.** Back view of Torso Display

The tactors were glued on a spandex waist band (See Figure 1) with an inter-tactor

vertical spacing of 40 mm and a horizontal spacing of 60 mm. These values were greater

than the 11 mm threshold for localizing vibrotactile stimuli on the back (Eskildsen et al.,

1969). Velcro straps were used to secure the band around the torso of the subject. The

wiring, WTCU box, and battery were all stored in a small pouch that also fastened around

the waist (below the tactile vest).

### 3.1.3. Wireless Tactile Control Unit

Tactile displays were connected to the Wireless Tactile Control Unit (WTCU)

(See Figure 2), a custom-designed circuit board that communicates wirelessly with a

computer using a 2.4 GHz Bluetooth Class 1 Device (Lockyer, 2004). The WTCU has an

AT90LS8535 microcontroller, from the Atmel AVR family. The board was programmed

with the patterns of tactor activation. A Visual Basic interface was used to send signals wirelessly to the control board, activating the desired patterns. The WTCU was designed to apply 3.3 V to each activated tactor. The input voltage produced a vibration frequency of approximately 115 Hz; this value varies by about ±5 Hz, depending on the motor (Piateski and Jones, 2005). This vibration frequency lies within the range of 100-500 Hz, for which hairy skin has high sensitivity (Bolanowski et al., 1994). Distinctive patterns were used in both of these experiments. Each pulse activation of the tactors lasted approximately 0.5 s, followed by a delay of 0.5 s. The time required to display each pattern was equalized.



**Figure 2.** Wireless Tactile Control Unit

### 3.1.4. Interceptor Body Armor

In the first experiment, the Interceptor Body Armor (IBA) was worn over the subject's shirt (See Figure 3). The large sized IBA weighed 7.794 kg, and the medium

11

sized IBA weighed 6.850 kg. This body armor was on loan from the Army, so that it could be determined if wearing the body armor affected the ability to perceive the tactile cues. In many occupations in which it is envisaged that tactile displays will be used, such as fire fighting, it is anticipated that there will be considerable mass on the torso over the display.



**Figure 3.** Back and side view of Interceptor Body Armor

## 3.2. Method

The goal of the experiment was to measure the accuracy of vibrotactile pattern identification while wearing an IBA vest.

### 3.2.1. Subjects

Experiment 1 was performed on a group of eight subjects, who were all MIT students. All subjects were between the ages of 19 and 22. Experiment 1 was conducted on four men and four women. None of the subjects reported any sensory difficulties. The experiments were approved by the local ethics committee, and all subjects signed

informed consent forms. The dimensions of the subject's torso were measured. The self-reported height and weight of the subject were also recorded.

### 3.2.2. Stimuli

Most of the patterns used in Experiment 1 were chosen to represent possible navigational commands that had intuitive meaning (See Figure 4). Patterns A, B, C, and D represent navigational cues for directions of motion, such as move forward. Patterns G and H represent possible instructional signals, such as warning or stop. Patterns E and F could represent additional navigational cues, or could prompt the user to perform an action unrelated to navigation, such as raising an arm.
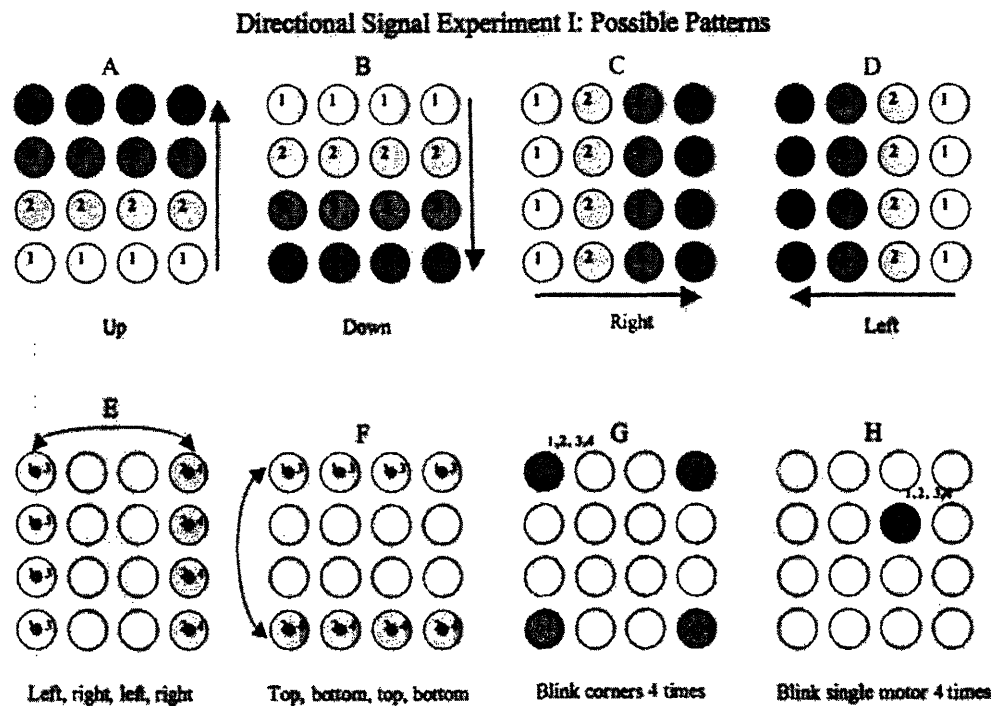


**Figure 4.** Visual representation of patterns used in Experiment 1

### 3.2.3. Procedure

The experimental procedure was explained to the subjects. They were told that the experiment would test their ability to identify various vibrotactile patterns. They were

shown a diagram of the possible patterns (See Figure 4). The arrows, numbers, and colors provide three different ways of showing the pattern of activation. The numbers indicate the order of activation. Tactors with the same number are activated at the same time. The colors reinforce this information, while the arrows indicate the direction of the wave of activations. After the notation of the diagram was explained to the subjects, the torso display was put on underneath the clothing, so that the tactor array was centered on the lower back. Every tactor made firm contact with the body as the waist band was a stretch fabric. The band was tightened with the Velcro straps until it was firmly attached. The IBA vest of best fit (medium or large) was put on the subject over the clothing. The IBA vest was tightened until it was appropriately placed. The subjects were asked to stand for the duration of the experiment.

Subjects were familiarized with the eight tactile patterns, which were each presented three times during a training period. During training, the experimenter identified the patterns by letter. After the third presentation of the set of eight patterns, the subject was permitted to ask that any pattern be repeated. Subjects were allowed to look at the visual representation of the patterns at all times.

After the training, forty stimuli were presented. Each of the eight patterns was repeated five times in a random order. After each stimulus, the subject told the investigator which pattern had been detected, and the investigator recorded the response. Subjects were given an unlimited time to respond to each stimulus.

### 3.2.4. Results

Table 1 shows the percentage of correct responses for each vibrotactile pattern. The data are averaged over all subjects. All eight subjects identified each pattern

presented with 100% accuracy. In this experiment, there was no effect of sex or torso

dimensions. Clearly, a ceiling effect was evident in the data. There was no difference

between the identification rates of the various tactile patterns presented on the torso. All

of the patterns were easily identified.

| Actual Pattern | Subject Response | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H |
| A | 100% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| B | 0% | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| C | 0% | 0% | 100% | 0% | 0% | 0% | 0% | 0% |
| D | 0% | 0% | 0% | 100% | 0% | 0% | 0% | 0% |
| E | 0% | 0% | 0% | 0% | 100% | 0% | 0% | 0% |
| F | 0% | 0% | 0% | 0% | 0% | 100% | 0% | 0% |
| G | 0% | 0% | 0% | 0% | 0% | 0% | 100% | 0% |
| H | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 100% |

**Table 1.** Experiment 1: Group Mean Responses

The ability to identify these vibrotactile patterns was also tested by Piateski

(2005) with subjects who did not wear the IBA vest. Her subjects sat down on a stool

instead of standing up. In her experiment, B and G were identified correctly 99% of the

time, and pattern A was identified correctly 97% of the time. The results from the present

experiment indicate that wearing an IBA vest does not interfere with identifying tactile

patterns presented to the torso.

# 4. Experiment 2: Waist Belt Tactile Display

## 4.1. Apparatus

### 4.1.1. Tactor Selection

The same pancake pager motors were used as tactors for this second experiment. Again, they were an ideal choice because they are small, lightweight, and inexpensive.

### 4.1.2. Waist Belt Tactile Display

The waist belt display comprises a one-dimensional array of electromechanical vibrators that are positioned around the waist. The temporal and spatial sequence of activation of the motors is used to communicate with the wearer. Tactors were placed on the subject's navel, spine, right side, and left side above the hip, and at the mid-point location between these set points (See Figure 5). Unlike the first experiment, one of the tactors was placed directly over the spine. Despite the indentation there, Cholewiak et al. (2004) found that the spine serves as a natural marker when dealing with circumferential tactile displays.

The tactors were attached to the waist band with Velcro, so that their position could be adjusted based on the subject's waist size. The inter-tactor horizontal spacing ranged from 80-100 mm. Velcro straps were used to secure the band around the torso of the subject. The wiring, WTCU box, and battery were all stored in a small pouch that also fastened around the waist (below the tactile belt).
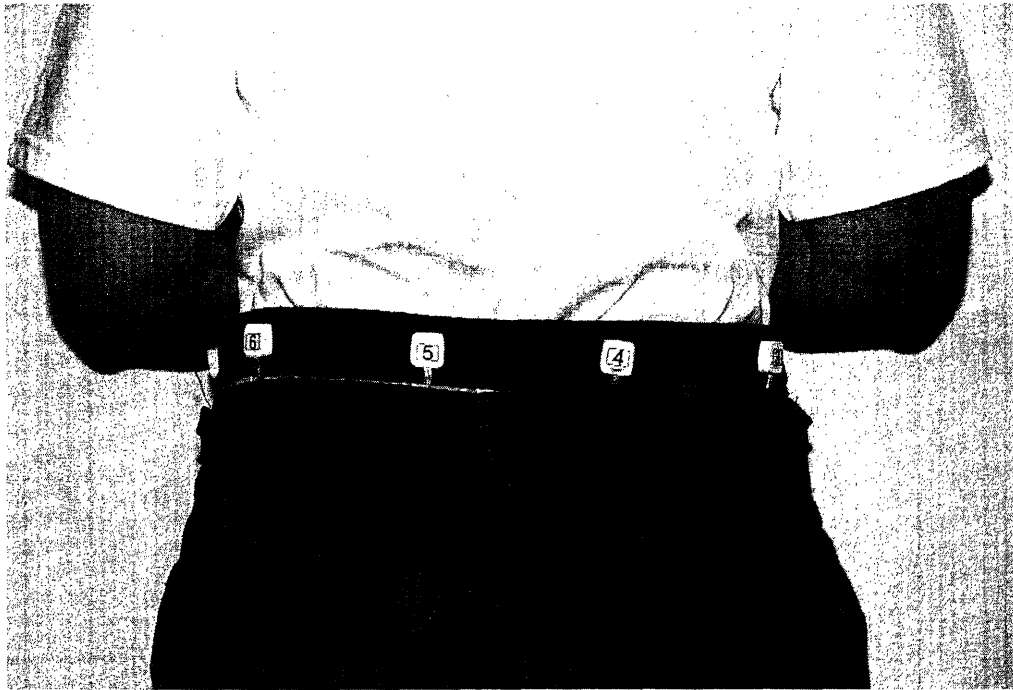
**Figure 5.** Back view of Waist Belt Display

### 4.1.3. Wireless Control Tactile Unit

The waist belt display was connected to the same WTCU that was used in the first

experiment. The board was programmed with the different set of patterns of tactor

activation. A Visual Basic interface was used to send signals wireless to the control

board, activating the desired patterns. The time required to display each pattern in

Experiment 2a was equalized. The time required to display each individual motor in

Experiment 2b was equalized.

## 4.2. Method

The goal of the waist belt experiment was to measure the accuracy of vibrotactile

pattern identification around the waist. The subjects did not wear the IBA vest. A second

experiment was conducted to measure the accuracy of identifying the location of

vibrotactile stimulation.

### 4.2.1. Subjects

Experiment 2 was performed on a group of ten subjects, who were all MIT students. All subjects were between the ages of 19 and 22 and none of these subjects participated in Experiment 1. Experiment 2 was conducted on five men and five women. None of the subjects reported any sensory difficulties. The experiments were approved by the local ethics committee, and all subjects signed informed consent forms. The dimensions of the subject's torso were measured and the self-reported height and weight of each subject were also recorded.

### 4.2.2. Stimuli: Experiment 2a

Most of the patterns used in Experiment 2a were chosen to represent possible navigational commands that had intuitive meaning (See Figure 6). Patterns A, B, D, and E represent navigational cues for directions of motion, such as more forward. Pattern C represents a possible instructional signal, such as a warning or stop. Pattern F could represent an additional navigational cue, or could prompt the user to perform an action unrelated to navigation, such as raising an arm.
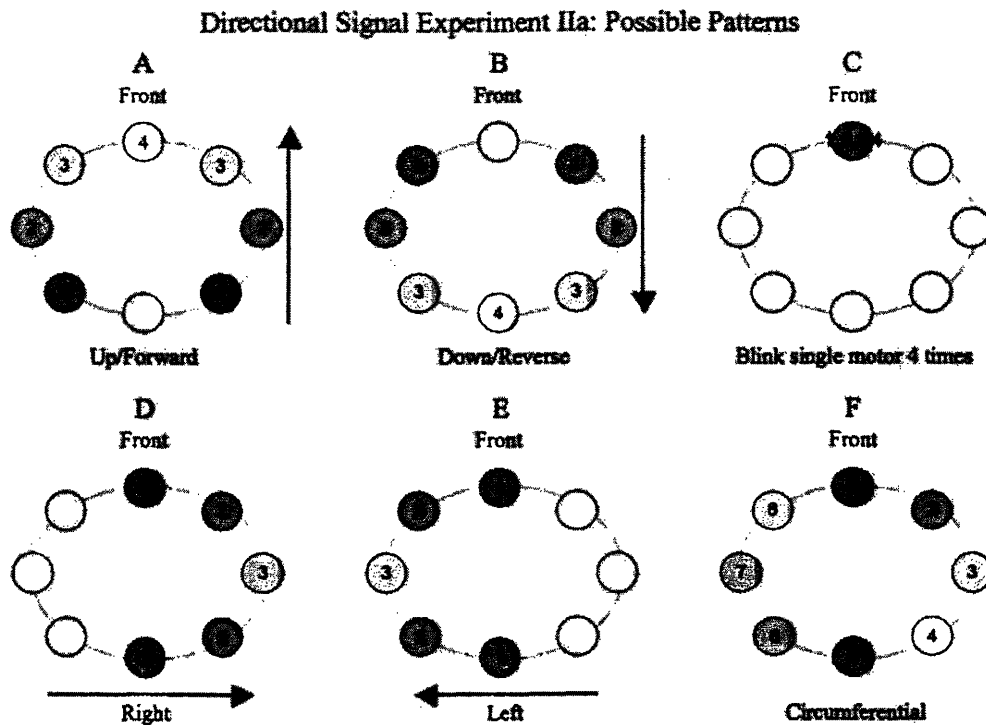
**Directional Signal Experiment IIa: Possible Patterns**



**Figure 6.** Visual representation of patterns used in Experiment 2a

### 4.2.3. Stimuli: Experiment 2b

In Experiment 2b, the stimuli presented activated an individual motor (See Figure 7). A common application for tactile orientation systems is representing the location of an object in an environment as a stimulus on the surface of the body, with the user in the center of the field. It would be intuitive to have the tactors represent the hands of the clock. However, previous work (Cholewiak et al., 2004) has shown that optimal performance is achieved with eight or fewer tactors mounted around the waist.

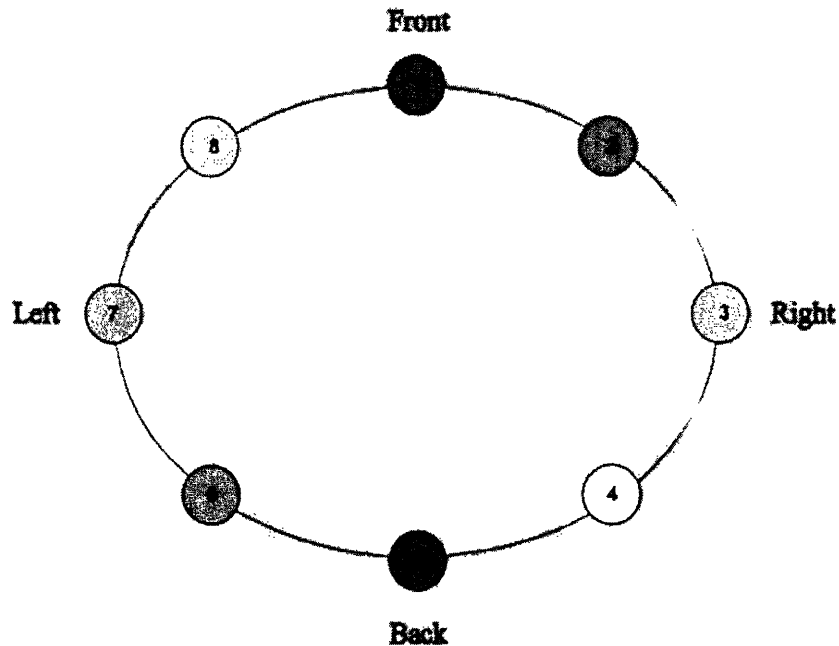**Directional Signal Experiment IIb: Identifying Motors**



**Figure 7.** Motor location diagram for Experiment 2b

## 4.2.4. Procedure

Five subjects (three male, two female) completed Experiment 2a first and then 2b. The other five subjects (two male, three female) completed Experiment 2b first and then 2a. There was a five minute break between the two experiments.

The experimental procedure was explained to the subjects. They were told that the experiment would test their ability to identify various vibrotactile patterns. They were shown a diagram of the possible patterns used in the experiment. After the notation of the diagram was explained to the subjects, the waist belt display was put on over light clothing. The tactors were evenly placed around the waist 80-100 mm apart following the pattern shown in Figure 7. Every tactor was firmly connected to the belt with Velcro. The belt was tightened until it was firmly on. The subjects were asked to stand for the duration of the experiment.

### 4.2.4.1. Experiment 2a: Identifying Patterns

Subjects were familiarized with the six tactile patterns (See Figure 6), which were each presented three times during a training period. The arrows, numbers, and colors in Figure 6 provide three different ways of showing the pattern of activation. Tactors with the same number are activated at the same time. The colors reinforce this information, while the arrows indicate the direction of the wave of activations. During the training period, the experimenter identified the patterns by letter. After the third presentation of the set of six patterns, the subject was permitted to ask that any pattern be repeated. Subjects were allowed to look at the visual representation of the patterns at all times.

After the training, thirty stimuli were presented. Each of the six patterns was repeated five times in a random order. After each stimulus, the subject told the investigator which pattern had been detected, and the investigator recorded the response. Subjects were given an unlimited time to respond after each stimulus.

### 4.2.4.2. Experiment 2b: Identifying Motors

Subjects were familiarized with the eight motor cues (See Figure 7), which were each presented three times during a training period. The number and colors in Figure 7 indicate the separate tactors. During the training period, the experimenter identified the motors by number. After the third presentation of stimuli, the subject was permitted to ask that any number be repeated. Subjects were allowed to look at the visual representation of the belt at all times.

After the training, forty stimuli were presented. Each of the eight motors was activated five times in a random order. After each stimulus, the subject told the

investigator which number had been detected, and the investigator recorded the response. Subjects were given an unlimited time to respond after each stimulus.

### 4.2.5. Results

| Actual Pattern | Subject Response | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| A | 98% | 2% | 0% | 0% | 0% | 0% |
| B | 0% | 100% | 0% | 0% | 0% | 0% |
| C | 0% | 0% | 100% | 0% | 0% | 0% |
| D | 0% | 0% | 0% | 100% | 0% | 0% |
| E | 0% | 0% | 0% | 2% | 98% | 0% |
| F | 0% | 0% | 0% | 0% | 0% | 100% |

**Table 2:** Experiment 2a: Group Mean Responses

Table 2 and 3 shows a summary of the results from this experiment. The data are averaged over all subjects. For the pattern experiment (Experiment 2a), eight of the ten subjects had 100% identification accuracy. Two subjects had one incorrect response each. The first gave the "B" or Down response instead of "A" or Up. The second gave the "D" or Right response instead of "E" or Left. In both errors, the subject gave the opposite direction. Subjects commented that Pattern C (a single tactor blinking) and Pattern F (circumferential) were highly distinctive.

For the motor identification experiment (Experiment 2b), there was more variability in the subjects' responses. As can be seen in Table 3, subjects mislocalized the point of stimulation by naming a tactor adjacent to the site of stimulation. It was thought that the navel (tactor 1) and the spine (tactor 5) would serve as natural markers (Cholewiak et al., 2004), but there was one error at the navel in this experiment. When vibrotactile stimulation was presented on the left side (tactors 6-8) there were two errors of localization and when presented to the right side (tactors 2-4) there were five errors.

|  | Subject Response | | | | | | | |
| Actual Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| 1 | 98% | 2% | 0% | 0% | 0% | 0% | 0% | 0% |
| 2 | 0% | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| 3 | 0% | 0% | 94% | 6% | 0% | 0% | 0% | 0% |
| 4 | 0% | 0% | 4% | 96% | 0% | 0% | 0% | 0% |
| 5 | 0% | 0% | 0% | 0% | 100% | 0% | 0% | 0% |
| 6 | 0% | 0% | 0% | 0% | 0% | 98% | 2% | 0% |
| 7 | 0% | 0% | 0% | 0% | 0% | 0% | 100% | 0% |
| 8 | 0% | 0% | 0% | 0% | 0% | 0% | 2% | 98% |

**Table 3:** Experiment 2b: Group Mean Responses

The results from this experiment show that identifying the location of stimulation is more difficult than identifying a pattern. In the group that started with Experiment 2a, there were two errors in Experiment 2a, then two errors in Experiment 2b. In the group that started with Experiment 2b, however, there were six errors in Experiment 2b, and zero errors in Experiment 2a. The subjects who began with the more difficult experiment had perfect accuracy on the pattern recognition task afterward.

# 5. Discussion

For an effective navigational display, the identification of patterns should be near 100% correct. In hazardous situations, such as during military exercises or fire rescue, the reliability of perceiving commands is particularly important. Employing the sense of touch may be advantageous in situations in which visual displays are inconvenient or unavailable. Both experiments were conducted on stationary subjects in a quiet laboratory. In a field experiment, it would be expected that a lower percentage of patterns would be identified correctly.

In the first experiment with the torso-based tactile display, there was 100% accuracy in identifying patterns while wearing the IBA vest. Piateski (2005) showed the same accuracy without the IBA vest. The results also indicate that the spacing between the motors and the activation frequency were appropriate for the lower back and that the design of the torso display was effective for a range of body sizes. Although it has significant mass, the IBA vest probably did not influence the perception of vibrotactile stimuli because it was not in direct contact with the tactors. There was a gap between the rigid IBA and the tactile display that conformed to the torso. It would be of interest to see whether the same level of performance is achieved when subjects are moving outdoors while wearing the vest.

In Experiment 2a, subjects were able to identify correctly patterns presented on a one-dimensional tactile display with 98-100% accuracy. The errors made involved confusing the direction of a navigational cue (right and left, up and down). In Experiment 2b, in which subjects had to identify the location that was activated on the waist belt tactile display, an accuracy of 94-100% correct was achieved. This identification rate

indicates that although pattern recognition is superior, the belt display could be used in its current form to present target location information. It is logical to assume that identifying an individual motor is a much more difficult task than identifying a pattern. Since the motor only vibrates once, there is no redundancy in the command as with the patterns, and the duration of the stimulus is shorter. Other experiments have verified that eight or fewer motors is best for a waist belt display. By reducing the number of tactors around a waist belt from twelve to eight, Cholewiak et al. (2004) found that localization accuracy improved from 74% to 92% correct. A future experiment could explore whether increasing the duration or pulsing of activation of each individual motor (like the alert signal in Experiment 1 and 2a) would be a more effective way to display location cues.

The vest was a superior tactile display to the belt when comparing the pattern recognition results (Experiment 1 and 2a), particularly as there were more patterns (8) to choose between for the vest as compared to the belt. These experiments focused on identification of vibrotactile patterns and not in the precise location of these inputs (Experiment 2b). Studies of vibrotactile localization on torso have shown that localization is best for tactors placed near ends of an array for those close to anatomical landmarks such as the elbow or spine (Cholewiak et al., 2004).

The two-dimension tactile array on the torso had a greater number of tactors than the one-dimension tactile array on the waist. As a result, there was a greater redundancy in the signal when the torso was stimulated. In addition, since the belt was not in contact with the skin as the vest was, it was possible that the strength of the signal was diminished. For both displays, the waveform, frequency, and amplitude of vibration of

tactors cannot be independently controlled. Only the spatial location and temporal parameters of tactor application can be used to generate tactile patterns.

These results indicate that a torso-based tactile array is effective in displaying navigational information in a laboratory setting. Future work will determine whether an array is successful in conveying directional cues when the user is mobile and active. In the next phase, these displays will be tested on mobile subjects outdoors. The feasibility of any tactile display in the field is limited by the range of Bluetooth wireless technology, which is approximately 100 m. Finally, improvements could be made to the design of the bag holding the wiring, WTCU box, and battery, as they are somewhat bulky and not very robust.

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