A TACTILE COMMUNICATION SYSTEM FOR NAVIGATION

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Abstract

A vibrotactile display for use in navigation has been designed and evaluated. The arm and the torso, which offer relatively large and flat surface areas, were chosen as locations for the displays. The ability of subjects to identify patterns of vibrotactile stimulation on the arm and torso was tested in a series of experiments using the vibrotactile displays. A variety of patterns of stimulation was evaluated to determine which was most effective, and the efficacy of two types of motors (pancake and cylindrical) was compared. The arm display was tested with sedentary subjects in the laboratory, and the torso display was tested both in the laboratory with sedentary subjects and outdoors with active subjects. The results indicated that identification of the vibrotactile patterns was superior on the torso as compared to the forearm, with subjects achieving 99-100% accuracy with seven of the eight patterns presented. The torso display was equally effective for both sedentary and active subjects.

Thesis supervisor: Lynette A. Jones
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1. Introduction

Most communications devices rely on the senses of sight and hearing. As a result, these senses are often overwhelmed with data, and it is difficult to transmit additional information to a person who must already process a great deal of visual and auditory input. This overload of information can cause injury, or even death, when a person is not able to process stimuli quickly enough to avoid an accident (Rupert et al., 1993). The sense of touch offers an additional channel of communication that bypasses the overtaxed senses of vision and audition. With a tactile display, the user may be able to interpret information intuitively that is sent in the form of vibrotactile stimulation on the skin.

This thesis focuses on the development of tactile interfaces that are capable of sending directional information using small vibrating motors (tactors) mounted on the arm or torso. There are a variety of reasons to create a tactile interface that can be worn on the arm or the torso rather than on a more common site such as the hand or finger. The hand is required for a variety of tasks, and a device that provides input to the hand during the performance of a task could interfere with the user's ability to perform the task. Although other parts of the body, such as the torso, are generally less sensitive than the hand, using more stimuli that are spread over a larger surface area can compensate for this decreased sensitivity. The torso offers a large and flat surface that is rarely used as a medium for receiving transmitted information, so it is a good location for a tactile display. Since the effectiveness of such devices depends on the user's ability to identify reliably stimuli on the arm and torso, experiments were performed to develop a set of vibrotactile commands that were easily recognized at both sites.

2. Background

2.1 Neural Basis for the Sense of Touch

There are two types of skin on the body. The palms of the hands and the soles of the feet are covered with glabrous skin, which is ridged and hairless. The remainder of the body is covered with hairy skin. All skin is divided into two main layers; the epidermis, a thin outer layer, which contains skin cells and mechanoreceptors called Merkel receptors, and the dermis, a thick inner layer, which contains blood vessels, nerves, and other mechanoreceptors that are responsible for cutaneous sensation.

The somatosensory system regulating the perception of touch is composed of receptors sensitive to mechanical stimuli, known as mechanoreceptors, each type of which is sensitive to different properties of mechanical stimuli. Each mechanoreceptor has a receptive field on the skin; when this receptive field is stimulated, the mechanoreceptor transmits information to the central nervous system via its afferent nerve fibers. The sensory ability of the skin depends on the first order reactions of these afferents (Merzenich & Harrington, 1969; Harrington & Merzenich, 1970). The five types of receptors that are found in hairy skin can be classified into two broad groups – rapidly adapting (RA) and slowly adapting (SA) (Merzenich & Harrington, 1969; Harrington & Merzenich, 1970).

2.1.1. Rapidly adapting receptors

Rapidly adapting receptors are most sensitive to vibrating stimuli. They discharge at the onset and offset of the vibrating stimulus, and activation of RA receptors is associated with a feeling of vibration or flutter (Merzenich & Harringon, 1969; Bolanowski et al., 1994). In a study by Vallbo et al. (1995), the structures of the receptive fields associated with each mechanoreceptor on the hairy skin of the forearm were mapped. The fields were characterized by measuring the response of the afferent fibers while the skin was scanned with a probe that lightly indented the skin. The receptors that Vallbo et al. (1995) referred to as hair units, field units, and Pacinian-type units were all identified as rapidly adapting.

Hair units could be identified by their response to the movement of a hair or to a light puff of air against the receptive field. The receptive fields of field units were found to be oval-shaped or irregularly shaped. Within the field there were multiple high sensitivity spots. These high sensitivity spots were well defined, but fairly diffuse in the field. Field units were highly sensitive to mechanical indentation of the skin, with a median threshold of about 0.1 mN. However, they were not sensitive to hair movements or to remote taps. Like the receptive fields of the hair units, those of field units were also oval or irregularly shaped. The receptive fields contained high sensitivity spots that were less well defined than those of the hair units, but closer together within the responsive field (Vallbo et al., 1995).

Pacinian units were identified by the presence of a spot of maximum sensitivity in the receptive area and by their strong response to remote taps on large areas of the forearm. The size of their receptive fields was on the order of 100 mm^2, as were the receptive fields of the hair units and field units (Vallbo et al., 1995). In the area of hairy skin studied on the forearm, 12 hair units (22% of the total), 5 field units (9%), and 2 Pacinian units (4%) were found (Vallbo et al., 1995).

The organization of the receptive fields of the RA fibers on the hairy skin of the forearm in Vallbo et al. (1995) was substantially different from that of the fields mapped in a similar experiment performed on the hairy skin on the back of the hand (Järvilehto et al., 1981). Vallbo et al. (1995) concluded that the difference in results may indicate that the afferents in the hairy skin on the back of the hand function differently from those in the skin of the arm. They suggested that the hairy skin on the rest of the body bears more resemblance to that on the forearm than to that on the back of the hand and on the cheek, so that the results from their experiment can be applied to the hairy skin on other parts of the body, including the torso.

According to Bolanowski et al. (1994), two kinds of RA channels are involved in the perception of stimuli in hairy skin. The Pacinian channel (P_h) most effectively transmits rapid stimuli with frequencies between 40 and >500 Hz for hairy skin. It has a neural substrate of Pacinian Corpuscles (PC), which have a large receptive field size, and produce a sensation of vibration when stimulated. Frequencies between 3-40 Hz activate the non-Pacinian I (NP I) channel, which is best stimulated by light taps on the skin and produces a sensation of flutter (Bolanowski et al., 1994).

2.1.2. Slowly adapting receptors

Slowly adapting receptors are most sensitive to skin stretch. The two types of SA receptors, SA I and SA II, differ slightly in their response to stimuli. In hairy skin, it is difficult to distinguish between the activity of the SA I fibers and the SA II fibers (Bolanowski et al, 1994). As a result, the process of identifying the SA I and SA II fibers is somewhat more complex than the process of identifying RA fibers, and involves the measurement of features such as spontaneous firing, discharge pattern, and stretch sensitivity (Vallbo et al., 1995).

When stimulated, SA II receptors initially discharge with a high frequency onset transient. The discharge frequency soon stabilizes to a constant rate that is a direct function of the degree of skin indentation (Harrington & Merzenich, 1970). Stimulation of SA II receptors in hairy skin has been associated with a sensation of buzzing, possibly as a result of their highly regular rate of discharge (Bolanowski et al., 1994). Receptive fields associated with SA II receptors usually have a single responsive area. The borders of the responsive area are less distinctive than those of the SA I receptor. When a probe approaches an SA II receptor, nerve firings gradually increase, indicating that the SA II receptors are likely triggered by skin stretch (Vallbo et al., 1995).

The SA I receptors also discharge with a high frequency onset transient when they are stimulated. However, they adapt more slowly, gradually reaching a constant rate of discharge that is less regular than that of the SA II fibers (Harrington & Merzenich, 1970). In SA I receptive fields, there are multiple spots where a light indentation of the skin produces intense firing. These spots, which are distinct and well defined, are thought to correspond to the touch spots and domes of Merkel cells. SA I receptive fields are generally better defined and less diffuse than those of SA II receptors. Vallbo et al. (1995) found 38 SA I units (38% of the total) and 27 SA II units (27%) in the area of hairy skin on the forearm that was studied. SA I and SA II receptors both have receptive fields of roughly 11 mm^2, roughly one order of magnitude smaller than those of RA receptors.

Bolanowski et al. (1994) suggest that in hairy skin, SA II receptors, which are most sensitive in the range of 0.4-3 Hz, govern sensation at low vibration frequencies. They refer to this non-Pacinian channel as $NP_{h\ low}$. Its substrate is presumed to be composed of Ruffini endings and it is best stimulated by stretching of skin or joint movement. Although SA I receptors are found in hairy skin, Bolanowski et al. (1994) were unable to find any evidence that they are involved in perception.

2.2. Sensory Properties of the Arm and Torso

A variety of factors influence the human interpretation of tactile stimuli on the skin. These factors can be used to create stimuli that can be distinguished from one another. In addition to stimulation frequency, the factors include stimulus duration, temporal order, amplitude, and area of stimulation (Verrillo & Gescheider, 1992). Although it should theoretically be possible to utilize all of these factors in the design of an effective tactile communication device for the torso, in reality, there are fewer options. Humans can generally distinguish between high frequency and low frequency stimuli on the torso, but their ability to distinguish between frequencies is generally poor (Merzenich & Harrington, 1969). The ability to discriminate the distance between stimuli is also extremely poor (van Erp & Werkhoven, 1999), and although humans are able to distinguish between stimuli of different amplitudes (Weisenberger, 1986), it can be difficult to control the amplitude of stimuli on the skin, especially in a tactile device worn by a moving user. The area of the skin stimulated and the mechanism producing the stimulus both affect thresholds for perceiving a vibratory stimulus (Verrillo, 1963).

To interpret correctly patterns of vibrotactile stimuli presented to the torso, subjects must be able to distinguish between stimuli and to localize the stimuli on the body. The ability to discriminate between stimuli can be measured by the two-point threshold and by tests of localization on that part of the body. The classic study by Weinstein (1968), which was performed with static stimuli, states that the two-point threshold of the torso, that is, the minimum spacing between points at which the points are perceived as two separate stimuli, is around 40 mm. However, the perception of vibrotactile stimuli is substantially different from the perception of static stimuli. Eskildsen et al. (1968) found that the torso's two-point threshold for vibrotactile stimuli is significantly smaller, around 11 mm. This number is more relevant than the two-point threshold in the design of a torso-based tactile navigation display.

Several studies have been performed to increase our understanding of the human ability to interpret vibrotactile stimuli on the arm and torso. In a series of experiments, Cholewiak and Collins (2000, 2003) studied the influence of tactor position and the spacing between tactors on subjects' ability to localize vibrotactile stimuli on the arm. Seven tactors spaced 25 mm apart were placed in a linear array on the volar surface of the forearm. In a preliminary experiment, the vibrotactile threshold was measured at each of the sites at frequencies of 100 and 250 Hz, and it was found that the threshold did not vary significantly across the sites tested (Cholewiak & Collins, 2003). In a subsequent experiment, one tactor was activated and subjects were asked to identify which tactor had produced the stimulus by pressing the corresponding key on an isomorphic keyboard. The experiment was performed with stimulus frequencies of 100 and 250 Hz. The ability to localize stimuli was superior at the ends of the array, with around 70% of responses correct, whereas near the center of the array, only 30-40% of stimuli were correctly localized. Among younger subjects, the stimulus frequency of 250 Hz resulted in slightly better localization than the frequency of 100 Hz, but the effect was weak, and was not present at all for older subjects. Since there was no significant difference between vibrotactile thresholds at the test sites, but there was a significant difference in localization, Cholewiak and Collins (2003) concluded that localization must depend on something other than thresholds.

The next experiment tested the hypothesis that the joints of the forearm act as anchor points that aid in localization. To test this hypothesis, the experiment was repeated with the 7-tactor array centered on the elbow, with half of the tactors on the upper arm and half on the forearm. The localization responses for the tactors that stayed in the same position did not change significantly; however, tactors clustered around the elbow were localized with significantly higher accuracy. Another study showed that false anchor points could be created by activating selected tactors at different frequencies. However, the difference in frequency had to be large for the subject's localization ability to improve significantly. In another attempt to improve localization, the spacing between the tactors was changed from 25 mm to 50 mm. The increased spacing significantly improved localization, from an average of 46% to an average of 66% correct. Nevertheless, placement of the tactors was still a significant factor; tactors near joints were localized far more accurately than those in the middle of a limb. Clearly, both the placement of the tactors on the body and the spacing between tactors are significant factors affecting localization (Cholewiak & Collins, 2003).

Cholewiak and Collins (2000) also tested the perception of vibrotactile patterns generated by a linear array on the finger, arm, and torso. An array of seven tactors was used to present a line on the subject, and the subject was asked questions about the quality of the line: its perceived length, smoothness, spatial distribution, and straightness. The pattern was displayed in two modes: veridical mode, in which the seven tactors were activated one by one in a sequence, and saltatory mode, in which only three tactors were activated, but each tactor was activated several times, creating the illusion of movement using the property of sensory saltation. The burst duration (BD) and inter-burst interval (IBI) of the stimuli were also varied, to gauge the influence of these factors on the quality of the line. All tactors were activated at a frequency of 230 Hz (Cholewiak & Collins, 2000).

The experimental results for the veridical and saltatory modes of stimulation were nearly the same. Subjects were not able to distinguish between veridical and saltatory stimuli 63% of the time. The inability of subjects to distinguish between these types of stimuli suggests that it may be possible use sensory saltation to create the illusion that more tactors are present than actually are. In addition, it may be possible to use the phenomenon of sensory saltation to increase the resolution of vibrotactile displays on parts of the body with poor resolution (Cholewiak & Collins, 2000).

Although Weinstein (1968) and Wilska (1954) report that the vibratory and two-point thresholds of the arm and torso are substantially different, the optimal temporal parameters for the two sites were essentially the same when they were both tested using the same array (Cholewiak & Collins, 2000). Cholewiak and Collins (2000) infer from this result that the features of the peripheral nervous system are not the most important factor in the ability to interpret the stimuli. In more general terms, these results suggest that if a set of vibrotactile patterns is tested on one body part, the results from the test should be valid for other body parts that are covered with similar types of skin, even if the two-point and vibratory thresholds are different.

Van Erp and Werkhoven (1999) performed a set of experiments on the spatial sensitivity of the torso. In their experiments, they tested the ability to localize stimuli and perceive spatial intervals on the torso. Most of the experiments were performed on the back. Tactors were taped to the upper back 4 mm apart and driven at a frequency of 250 Hz and an amplitude of 1 mm. In the localization task, one tactor was activated, then after a pause, 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. The inter-stimulus interval was varied to study its effect on localization accuracy. The results revealed that inter-stimulus intervals are a significant factor in the correct localization of a stimulus. Longer inter-stimulus intervals resulted in more accurate localization. There was no significant difference between vertical and horizontal localization, but the locus of stimulation had a moderate effect on the results. Localization was best in the center of the torso and worst on the left side. Furthermore, localization was better on the ventral side of the torso than on the dorsal side. Van Erp and Werkhoven (1999) and Cholewiak et al. (2004) hypothesize that localization ability is optimal at the body's central axis because when the body is stimulated on both sides of this axis, the stimuli are processed in both hemispheres of the brain, leading to improved localization.

The next task tested subjects' ability to discriminate spatial intervals between stimuli presented to the torso. In the interval discrimination task, the tactors were positioned as in the localization task. Two tactors were activated, then after a pause, two others were activated. The subjects were asked to determine whether the distance between the second pair of tactors was larger or smaller than that of the first. The results indicated that the ability to detect the distance between two tactors is best at the spine, where the mean threshold is about 6.8 cm. The mean threshold on the left side was about 12.5 cm, and that on the right side was about 15.5 cm. These results suggest that the human ability to discriminate the distance between two activated tactors is poor (van Erp & Werkhoven, 1999).

Localization ability on the torso was further studied by Cholewiak et al. (2004), who tested subjects' ability to localize vibrotactile stimuli on the torso. A band with tactors attached at equidistant intervals was wrapped around the subject's torso. Tactors on the band were activated, and subjects were asked to identify which tactor had been activated by typing the button corresponding to that tactor on a cylindrical keyboard. A nose and ears were placed on the keyboard to prevent mapping errors. Tactor bands with 6, 7, 8, and 12 tactors were tested. The band with eight tactors produced the best overall performance with 92% correct responses. Localization was most accurate when there were tactors located at the spine and navel, further supporting van Erp and Werkhoven's results (1999). In a preliminary experiment, Cholewiak et al. (2004) had determined that vibrotactile thresholds at frequencies between 25-320 Hz did not vary significantly around the torso where the display was worn. Therefore, it may be assumed that variations in localization ability at the different sites around the torso are not a result of changing thresholds (Cholewiak et al., 2004).

2.3. Arm-based Tactile Displays

There have been relatively few reports on the performance of arm-based tactile displays. Arm-based devices have been used to assist in understanding speech (Weisenberger & Percy, 1995) and to aid users of virtual reality systems with collision detection (Bloomfield & Badler, 2003). In Weisenberger and Percy's study, a device was designed to assist hearing-impaired individuals in speech comprehension. Seven vibrating tactors placed on subjects' arms were used to display phonemes. The frequency range of human speech was divided into seven parts, and each tactor acted as a channel to display a given range of frequencies. The lower frequencies were closer to the wrist, and the higher were closer to the elbow. The tactors were placed on the right volar forearm of each subject, equidistant from one another. In the experiment, combinations of vowels and consonants were spoken by a reader and displayed on the subjects' arms using the tactile device. The subjects' ability to distinguish between phonemes using the tactile display was tested both with and without speech reading. Since each phoneme used in speech produced a different pattern of activation of the tactors, with training, the subjects could distinguish between phonemes using tactile input. The subjects were able to discriminate between phonemes most accurately when the tactile device was used in conjunction with speech reading, although use of the tactile display alone also improved performance. The ability of subjects to discriminate between phonemes improved with training, although some combinations of vowels and consonants were consistently easier to distinguish than others, regardless of training (Weisenberger & Percy, 1995).

A more common use of arm-based tactile displays has been to present collisions in a VR environment (Bloomfield & Badler, 2003; Lindeman et al., 2004). Bloomfield and Badler (2003) tested users' ability to maintain a collision-free posture in space, using a visual VR display and an arm-based tactile display of virtual collisions. Users were asked to reach into a virtual box to retrieve a sphere. The ability to perform the task without colliding with the box was tested using a visual display alone, and with a visual display combined with tactile collision feedback. The tactile display was composed of 6 rings of 4 tactors each, evenly spaced on the arm, with three rings on the forearm and three on the upper arm. In the event of a virtual collision, the tactors at the site of the collision were activated. Bloomfield and Badler (2003) found that when the task was performed with the tactile display, there were significantly fewer collisions than when the user relied solely on visual input. Arm-based tactile devices for virtual environments are often combined with tactors on other parts of the body, especially the torso, for displaying collisions over the whole body (Lindeman et al., 2004).

2.4. Torso-based Tactile Displays

Torso-based tactile devices have been built and evaluated for a variety of uses. They have been used as communication systems that provide situational information to pilots and astronauts. These situational cues have been used to decrease, ameliorate, or eliminate problems associated with spatial disorientation (Rupert et al., 1993; Rochlis & Newman, 2000; van Erp et al., 2002). Another application of these devices is as a source of feedback of body tilt to prevent falls in people with balance disorders (Wall et al., 2001). Torso-based devices have also been studied for use in directional cueing (Rochlis & Newman, 2000; Tan et al., 2003; Cholewiak et al., 2004).

Torso-based tactile devices for communication generally fall into one of three categories. In the first category, tactors can be placed around the torso, either as a single row or multiple rows (Yang et al., 2002; Cholewiak et al., 2004). A tactor or a column of tactors is activated and the user must localize the site of stimulation to interpret the information sent. The number of tactors must be carefully chosen, since these devices rely on accurate localization. Cholewiak et al. (2004) found that for an array of 12 equidistant tactors wrapped around the torso, localization was only 74% accurate. Accuracy could be improved to 97% when the number of tactors was reduced to 6.

Yang et al. (2002) wrapped tactors around the torsos of subjects and used them to display virtual objects intersecting with the subjects' bodies. Five rows of twelve tactors each were wrapped around the body, with the tactors equidistant from one another. When a virtual object passed through the subject's body, the tactors which the virtual object passed through were activated. The subjects used an arrow to report the perceived trajectory of the moving object. The objects used were a sphere, a 1D line, and a 2D plane, and the objects moved at two different speeds. The subjects most accurately reported the direction of movement of the 1D line moving at the slower speed. The directions of motion were more accurately reported at the directions orthogonal to the body (12, 3, 6, and 9 o'clock) than at diagonal directions. The average error angles ranged from about 9 degrees for the 1D line to about 14 degrees for the 2D plane (Yang et al., 2002).

In the second category of devices, a grid of tactors is used to send information to the user by vibrating the skin on their lower back. The tactors can be attached to the body or mounted on a chair, allowing the user to feel the stimuli when sitting in the chair (Tan et al., 2003). Tactors are usually activated sequentially. To interpret the command, the user must localize the beginning of the activation sequence and perceive the direction of the motion. Several studies have been performed using a torso-based grid of tactors.

Tan et al. (2003) used a three by three array of tactors attached to a chair to display attentional and directional cues to subjects. In the first part of the experiment, the activation of a tactor was used to cue the subjects' attention to a change in a visual scene. The tactile cue was an effective way of reducing the subjects' response times when identifying which part of the scene had changed. In the second part of the experiment, the tactors were activated in patterns to provide directional cues. Tactors were activated in succession to give the illusion of horizontal, vertical, or diagonal movement on the subjects' lower backs. Tests were performed using activations of single tactors to draw a line across the back, and columns or rows of tactors to draw a wide band. Each tactor in the sequence was activated multiple times to generate the tactile illusion of movement. The subjects performed the experiment using both absolute identification (i.e. choosing a pattern from a list) and open responses (i.e. drawing a diagram of the perceived pattern) to record their perceptions of the stimuli. There was no significant effect of response method on accuracy of identification of the patterns. Subjects' perceptions of the signals were much more accurate for activations of single tactors in succession than for bands of tactors, especially for the diagonal directions. However, this effect disappeared after an additional experiment, indicating that training and an absolute identification paradigm were helpful in improving response accuracy. There was a significant effect of body size and tactor spacing on the accuracy of responses. Those subjects with larger torsos benefited from an increase in inter-tactor spacing.

In the final type of torso interface, a number of tactors are placed at various locations on the torso; for example, on the shoulders, waist, and back (Rupert et al., 1993; Lindeman et al., 2004). When the tactors are activated, the user must localize the stimuli to interpret the commands. In general, fewer tactors are used and the distances between them are much greater than in the previous categories. It is generally easier to localize these stimuli than to localize those in a ring around the torso, due to the smaller number of tactors, the significantly increased distance between the tactors, and the fact that the tactors are often positioned near joints, facilitating localization. Rupert et al. (1993) have been quite successful with their use of this type of torso display to prevent spatial disorientation in pilots by displaying information about the orientation of an aircraft. They have studied the use of tactors at various locations on the torso for presenting information relating to the orientation, airspeed, and direction of an aircraft. In the experiments, pilots wore a harness with vibrating tactors. Experiments were performed with various configurations of the tactors, various types of tactors, and with both fixed wing and rotor wing aircraft.

In the first experiment, a matrix of 254mm-diameter electromechanical speakers (i.e. tactors) was mounted on a stretch Lycra suit. The tactors were mounted on the torso in eight evenly-spaced columns. Experiments were performed with three tactors per column and with five tactors per column. The tactile device was primarily used to convey information about the orientation of the aircraft to the pilot. The direction of the gravity vector was presented to the pilot by activating the tactors in the location on the torso where the pilot would feel pressure if strapped in normally. The experiment was performed both in a flight simulator and in a real aircraft. In the experiment, pilots were able to fly the plane in simple acrobatic maneuvers while blindfolded, only using tactile information for cues regarding the aircraft's attitude.

In another experiment, the electromechanical speakers previously used as tactors were replaced with pager motors mounted inside 254-mm nylon casings. In this experiment, an activation frequency of 90 Hz was chosen to ensure that stimuli could be felt in the noisy and vibratory environment of the aircraft. Four columns of five tactors were mounted on the front and back of the torso, and on the left and right. Two additional tactors were included to convey information about pitch and roll. It took pilots about 20 minutes to learn how to interpret the stimuli. In this experiment, pilots flew a T-34 airplane without any kind of visual cues. Some of the maneuvers performed by the pilots were ground controlled approaches, climbing and descending turns, simple acrobatics such as loops and aileron rolls, and recovery from unusual attitudes.

In a third experiment, a tactor system was designed to enable the pilot to fly an H-60 helicopter using tactile stimuli. A grid of eight columns with two tactors per column was attached to an inflated vest. The purpose of the inflated vest was to maintain better contact between the tactors and the body. However, due to the limited size of the vest, fewer tactors per column were used in this experiment than in previous experiments. Pneumatic tactors were used, and vibrated at a frequency of 50 Hz, in pulse patterns with frequencies of 1, 4, and 10 Hz. The frequency of the pulses was used to indicate drift. In addition, there were tactors on the shoulder and wrist to present information about airspeed, and also on the left and right thighs to show the aircraft's heading. The pilots who participated in the experiment indicated that the tactor system effectively increased their ability to control the aircraft.

Of the three types of torso-based tactor systems, the system of affixing a grid of tactors to the lower back of the subject seems the most promising for use in a navigational interface. When tactors are positioned around the torso, localization is poor and users are unable to accurately interpret the commands (Yang et al., 2002; Cholewiak et al., 2004). Tactors dispersed over the trunk have been proven to be effective (Rupert et al., 1993), but they are most useful for displaying situational data such as attitude and airspeed intuitively, rather than displaying commands that the user must consciously interpret. A grid of tactors attached to the lower back has already been shown to be effective for sending directional commands (Tan et al., 2003). With further testing outdoors and an empirically-based set of patterns, it should be possible to achieve almost perfect identification. A display on the lower back occupies a relatively small part of the body surface, leaving room for other vital equipment.

3. Experimental Equipment

3.1. Selection of tactors

The selection of tactors for the tactile display was guided by a number of factors. The tactors had to be small and light enough that the combined weight of the tactors, the mounting, and the electronics would not impede movement or excessively burden the user. The tactors had to be quiet when activated, since excessive noise could annoy or even endanger the user. The amplitude of vibration had to be high enough to surpass the skin's threshold for sensation, but not so high that the user would feel discomfort. Power requirements were another important issue, since the power supply for the tactor array had to last a reasonably long time, and the tactile display and associated electronics had to be portable.

Some of the technologies used for tactors in related studies have been vibrating pneumatic membranes, piezoelectric speakers, pager motors, and vibrating units specifically designed for use as tactors. The decision to use pager motors as tactors was a fairly easy one. The pneumatic membranes, though highly effective, are not very portable due to their need for an air supply. The piezoelectric speakers, though they are conveniently small and lightweight, are noisy and do not always vibrate at a high enough amplitude that the user can reliably detect the vibration. Many of the tactors designed for specific applications are excessively heavy or bulky. The pager motors, which are lightweight, cheap, and available with diverse specifications, were therefore chosen for use. The experiments were performed used two types of tactors – pancake motors and cylindrical motors.

3.2. Characterization of Tactors

Five vibrating tactors (Fig. 1) were tested for possible use in the experiments: three cylindrical-type tactors (identified here as "cylindrical tactor", "R1 rototactor", and "waterproof tactor") and two disk-shaped pancake-type tactors (identified here as "pancake tactor" and "coin-shaped tactor"). Both types of tactors produce vibrations by rotating a mass. The crucial difference between these tactors is the axis of rotation. The pancake-type tactors rotate a mass in a plane parallel to the surface on which the tactor is mounted. The cylindrical-type tactors produce vibrations in a plane normal to the mounting surface. The characteristics of the tactors are listed in Table 1.

Table 1. Properties of tactors

Tactor	Diameter	Length	Operating Range	Supplier	Part Number
Coin-shaped	10 mm	--	2.5-4.0 V	JinLong Machinery	C1234L-38
Cylindrical	5 mm	12.8 mm	2.0-4.0 V	JinLong Machinery	4TL1-0201B
Pancake	14 mm	--	2.5-8.8 V	MP Jones & Assoc.	12820 MD
R1 Rototactor	6.5 mm	25.45 mm	1.5-4.0 V	Steadfast Technologies	--
Waterproof	7.8 mm	21.9 mm	1.1-1.6 V	JinLong Machinery	6CL-5472A

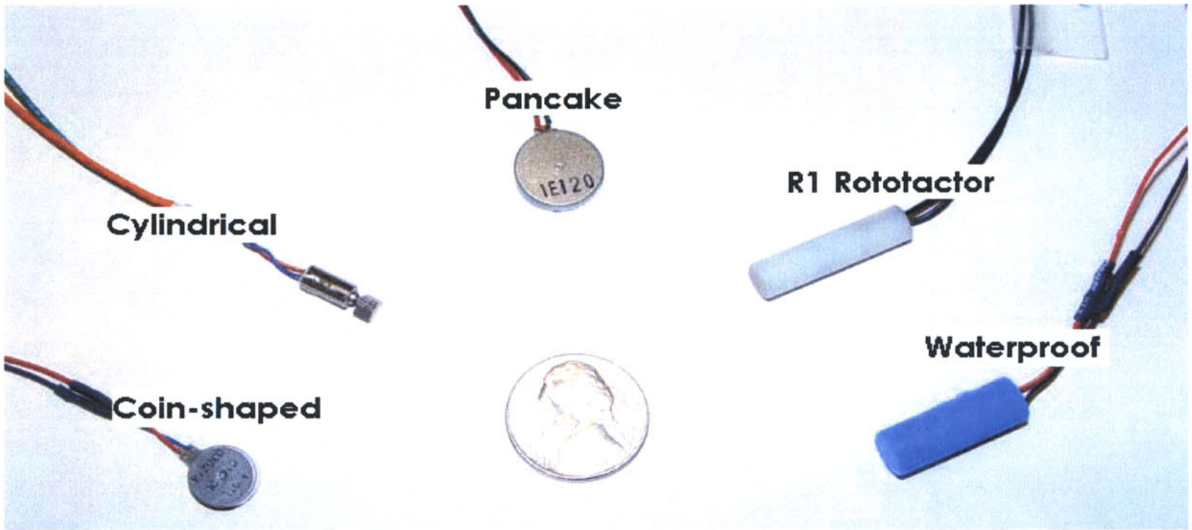


Fig. 1. Tactors characterized during tactor selection

To help in the selection of suitable tactors for the wearable tactile displays, the voltage to frequency curve of each tactor was characterized using a Brüel and Kjaer impedance head (Type 8001) attached to a charge amplifier (Type 2635) and an oscilloscope. Each tactor was glued to the impedence head, which was secured in a clamp, and tested at input voltages spanning its range, in 0.1V increments (see Fig. 2). At each input voltage, the amplitude was recorded in millivolts, the period in milliseconds, and the current drawn by the tactor in amperes. The period was used to calculate the vibration frequency.

Since the tactors do not vary widely in size, tactor performance is the characteristic that governed the selection of tactors for use in the experiment. In addition, one cylindrical-type and one pancake-type tactor were chosen in order to compare their effectiveness for use in tactile displays. The primary characteristics considered in the selection of tactors were high amplitude and low current draw when vibrating at a frequency between approximately 100-500 Hz, for which hairy skin has high sensitivity (Bolanowski et al., 1994).

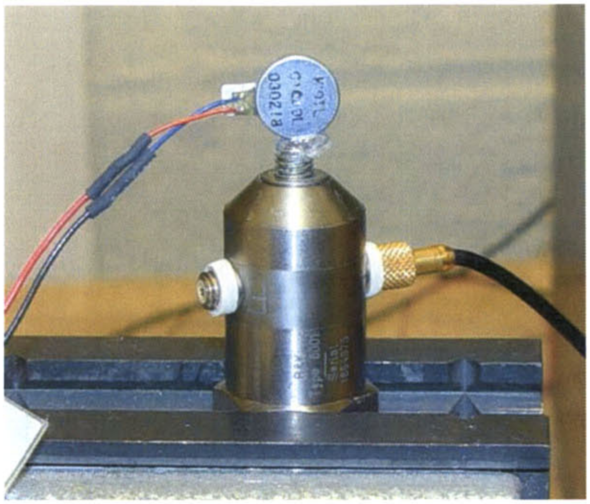


Fig. 2. Impedance head and charge amplifier used for motor characterization

The most important of these attributes is the current draw. The WTCU, the circuit board used to control the tactors in the experiment, can only withstand 1 A of current drawn by the tactors without risking damage (Lockyer, 2004). Since the Wireless Tactor Control Unit (WTCU) may need to operate up to 16 tactors simultaneously, the current drawn by a single tactor should not exceed about 0.06 A at the operating voltage of 3.3 V DC. The full results of the tactor characterization can be seen in Appendix 1. The relationship between voltage and frequency (see Fig. 3) and between amplitude and frequency is essentially linear for all five of

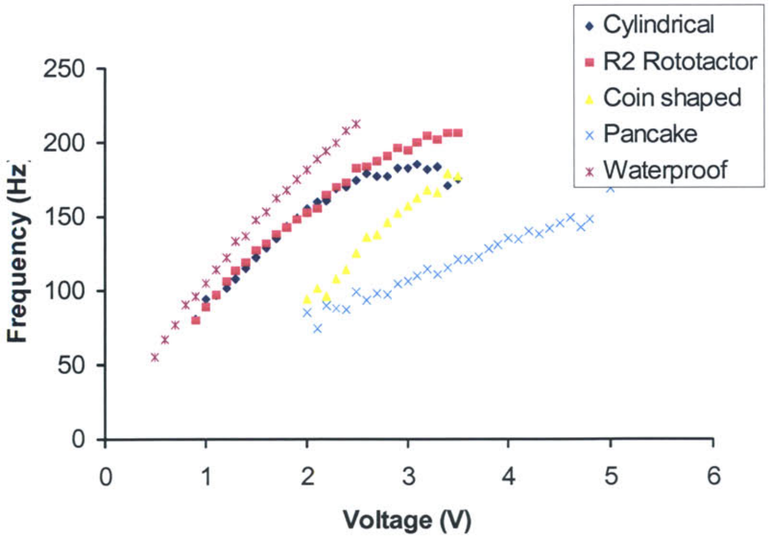


Fig. 3. Comparison of tactors – Frequency as a function of input voltage

the tactors tested. The current drawn by the various tactors at the operating voltage varies widely, from 0.034 A (pancake tactor) to 0.093 A (coin tactor). The waterproof tactors vibrate at an amplitude that is an order of magnitude higher than that of the other tactors, but also drew the most current – more than twice as much current as that drawn by the pancake tactor. However, within the range spanned by the other tactors, the cylindrical tactors vibrate with the smallest amplitude at the operating frequency, with a value about half that of the R1 rototactors, which are at the top of the range of the main group of tactors.

Based on these data, the pancake tactor and the cylindrical tactor were chosen for use in the tactile displays. The pancake tactor, though it vibrates at a low frequency compared to the others, draws little current and vibrates at a sufficiently high amplitude. The cylindrical tactor was inferior to the R1 rototactor in many respects; it vibrates at a slightly lower frequency above 3V, draws more current, and vibrates at a lower amplitude. However, the cost of the cylindrical tactors is less than a tenth of the cost of the R1 rototactors, and they can be obtained much more easily. In addition, the operating frequency, amplitude, and current of the cylindrical tactor are within acceptable limits.

3.3. Tactors used

In order to make the tactors more robust and increase the contact area between the tactor and the skin, the tactors were encased. Two different types of mountings were used for the pancake tactors – a rigid mounting and a flexible mounting. For the rigid mounting, each pancake tactor was sealed with glue, and then molded in a plastic block 18.4 mm long, 17 mm

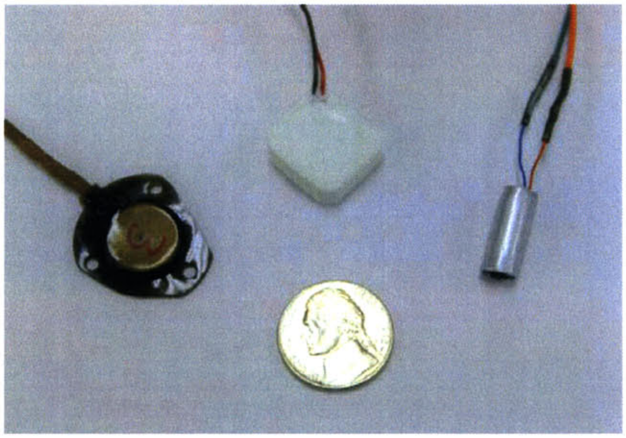


Fig. 4. Mounted tactors used in experiments: (l to r) R2 rototactor, pancake motor, cylindrical motor

wide, and 6 mm thick. The tactors with flexible mountings were the R2 rototactors (Steadfast Technologies). The tactors were coated in a layer of plastic that was 0.4mm thick, and attached to a flexible flange with a diameter of 27 mm and a width of 1.3 mm. The flange was trimmed into a roughly triangular shape to enable the close tactor spacing required for the arm array. The rigidly mounted pancake tactors will hereafter be referred to as "pancake tactors", and the flexibly mounted pancake tactors will be referred to as "R2 rototactors" (not to be confused with the R1 rototactors mentioned above). The mounted tactors are pictured in Figure 4. Each cylindrical tactor was glued into a section of aluminum tube with a diameter of 7 mm and a length of 15 mm. The aluminum tube was used to prevent the cloth of the tactile display from interfering with the rotating mass on the tactor.

3.4. Design of an Arm-based Tactile Display

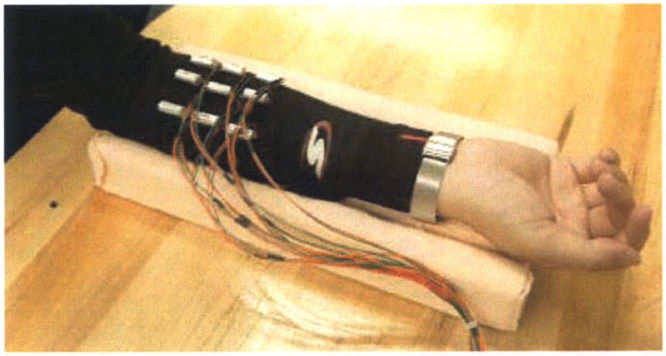


Fig. 5. Arm array with cylindrical tactors

One tactile display was constructed for each type of tactor used in the experiments. The tactors were mounted in a 3x3 grid on a spandex sleeve (Fig. 5). The vertical and horizontal spacing between the center points of the tactors was 24 mm. This spacing was chosen to maximize the distance between tactors, while keeping the array small enough so that it could be used on people with smaller arms. The horizontal and vertical spacing between the tactors was the same in order to determine whether subjects would be able to discriminate between horizontal patterns and vertical patterns, equally well. The center of the tactors in the top row was 124 mm from the cuff of the sleeve. A red stripe was glued on the cuff to indicate the location of the middle of the array. This stripe was used to center the array on the subject's arm and to ensure the same placement for all subjects. Two Velcro straps were sewn on the sleeve to allow the sleeve to be tightened or loosened.

3.5. Design of a Torso-based Tactile Display

In the design of the tactile display for the torso it was necessary to avoid the spine, which sits in an indentation, in order to maintain close contact between the tactors and the skin. Therefore, the grid was a four-by-four array of tactors instead of a three-by-three array, in order to maintain symmetrical placement while avoiding the spine. The tactors were glued on a spandex waist band (Fig. 6). The vertical spacing between the center points of the tactors was 40 mm and the horizontal spacing was 60 mm. The spacing was not equal, as it was in the arm experiment, but it was considerably greater than the threshold for localizing vibrotactile stimuli on the back, which can be as small as 11 mm (Eskildsen et al., 1969). Velcro straps were used to attach the band to the torso of the subject.

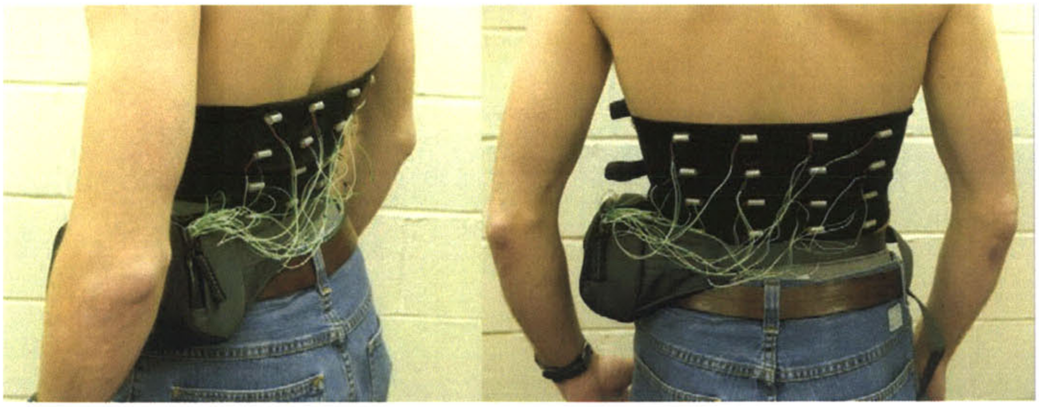


Fig. 6. Profile and back view of torso display with cylindrical tactors

3.6. Wireless Tactile Control Unit

The tactile displays were connected to a custom-designed circuit board, the Wireless Tactile Control Unit (WTCU), which communicated wirelessly with the computer using a 2.4 GHz Bluetooth Class 1 device (Lockyer, 2004). The microcontroller on the WTCU is an AT90LS8535, from the Atmel AVR family. The board was programmed with the patterns of tactor activation. During the experiments, a Visual Basic interface was used to send signals wirelessly to the control board, activating the desired patterns.

The WTCU was designed to apply a voltage of 3.3 V to each activated tactor. For the pancake tactor and Rototactor, this input voltage produced a vibration frequency of approximately 115 Hz; this value varied by about ±5 Hz, depending on the tactor. For the cylindrical tactor, the input voltage produced a vibration frequency of approximately 182 ± 4 Hz. Both of these vibration frequencies lie within the range of approximately 100-500 Hz, for which hairy skin has high sensitivity (Bolanowski et al., 1994).

The tactor activation patterns used in the experiments were chosen to be easily distinguishable from one another. Each pulse of the tactors lasted approximately 0.5 s, and the pulses were separated by a gap of 0.5 s. Care was taken to ensure that the time required to display each pattern was equalized.

4. Experiments

Four experiments were performed to test subjects' ability to interpret vibrotactile information sent by a torso- or arm-based device. Two experiments were performed with a three-by-three array of tactors on the forearm. These experiments were used to determine which tactor activation patterns could be reliably identified by the subjects. The results of these arm experiments were used to formulate a set of patterns to be tested using a four-by-four torso array, attached to the lower back. The first torso experiment was performed to determine the efficacy of these patterns, and a second torso experiment was then undertaken to test subjects' ability to navigate outside using the tactile cues from the array.

4.1. Experiments 1 and 2 – Pattern Recognition on the Forearm

4.1.1. Subjects

Each experiment was performed on a group of ten subjects, who were mainly MIT students. All subjects, none of whom participated in both experiments, were between the ages of 21 and 32. Both experiments were performed 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 following dimensions of each subject were measured: the circumference of the wrist, the length of the forearm from the wrist to the elbow, and the circumference of the forearm just before the elbow. In addition, after the tactile display was attached to the subject's arm, the distance between the edge of the display and the wrist was measured, to ensure uniform placement for each display that was tested.

4.1.2. Stimuli

The patterns used in Experiments 1 (Fig. 7) and 2 (Fig. 8) were chosen to represent possible navigational commands that had intuitive meaning. Patterns A, B, C, and D represent possible directions of motion. Patterns G and H represent possible warning or stop signals. In Experiment 1, Patterns E and F represent possible navigational commands. When the results of

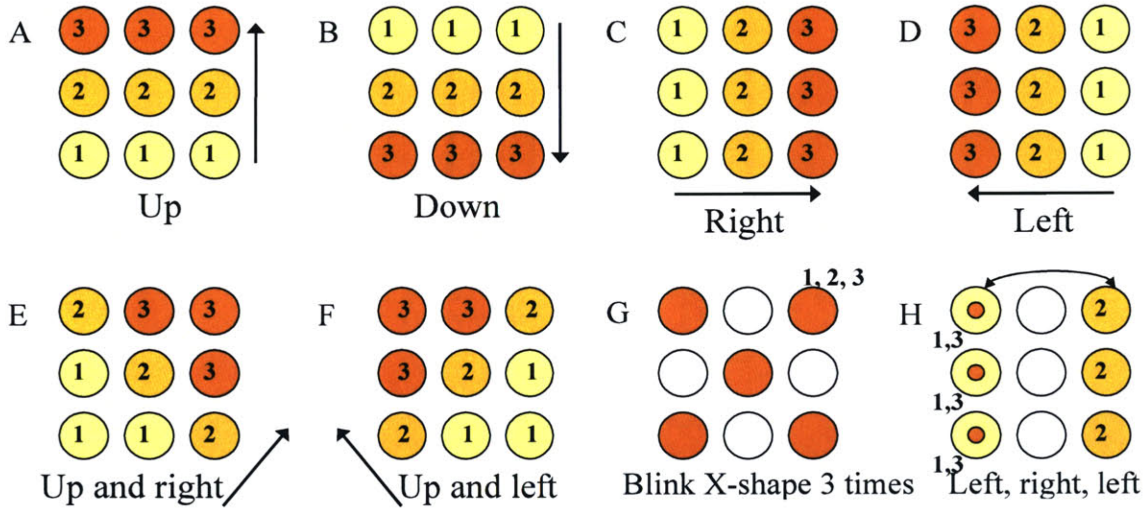


Fig. 7. Visual representation of tactor activation patterns – Experiment 1

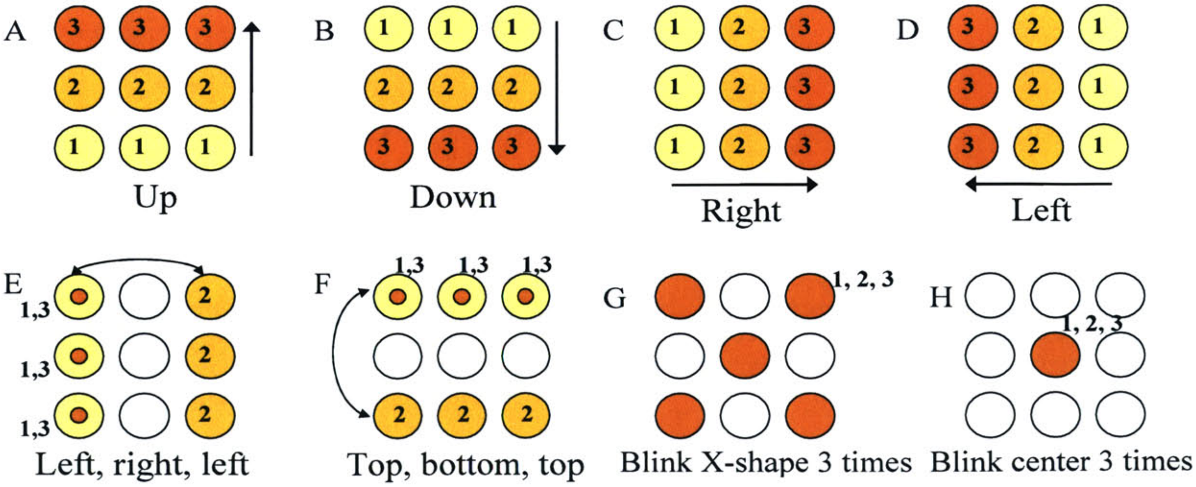


Fig. 8. Visual representation of tactor activation patterns – Experiment 2

Experiment 1 showed poor rates of correct identification of Patterns E and F, they were replaced. In Experiment 2, Patterns E and F test the ability to identify the direction of motion of a stimulus.

4.1.3. Procedure – Experiment 1

Subjects were told that the experiment would test their ability to discriminate between various patterns. They were shown a diagram of the possible patterns (Fig. 7). The arrows, the numbers, and the colors are three different ways of showing the patterns of tactor activation. The numbers indicate the order of activation. Tactors with the same number are activated at the same time. The colors reinforce this information, and the arrows show the direction of the wave of activations. After the notation of the diagram was explained to the subjects, the tactile sleeve was placed on the volar surface of the forearm, and tightened so that the tactors all made good contact with the skin. The sleeve was adjusted on the arm to ensure that the array was placed on the widest part of the forearm, without overlapping the elbow. The array was centered on the arm by aligning the red strip on the cuff with the center of the wrist. Subjects were required to wear headphones during the experiment to ensure that their responses were based solely on tactile cues, and not on visual or auditory information. Subjects were instructed to rest their arms on a foam cushion during the experiment in order to minimize arm movements. After the subjects had put on headphones, they then sat down at a table and placed their arm on a foam cushion, as shown in Fig. 5. Once the subject's arm was resting on the cushion in the proper position, a plastic enclosure (not pictured) was placed over the arm to ensure that their responses were not influenced by visual cues.

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

For each type of tactor, 40 stimuli were presented: there were 8 patterns, and each was repeated 5 times in a random order. After each stimulus, the subject told the experimenter which pattern had been detected, and the experimenter recorded the response. Subjects were given an unlimited time to respond after each stimulus. All subjects were tested using all three types of tactors. Testing was performed with the pancake tactor array first, then the cylindrical array, and finally with the rototactor array.

4.1.4. Results – Experiment 1

Table 2. Percentage of correct responses for each pattern presented by each type of tactor

	Pancake	Cylindrical	Rototactor
A	34%	58%	58%
B	64%	74%	72%
C	82%	78%	68%
D	80%	92%	70%
E	46%	62%	50%
F	30%	54%	36%
G	70%	96%	78%
H	90%	100%	72%

Table 2 shows the percentage of correct responses for each pattern, for each type of tactor. Table 3 shows the mean percentage of correct responses for each vibrotactile pattern, averaged across subjects and tactor types. Similar tables, separated by motor, can be seen in Appendix 2.

Table 3. Group mean responses for each pattern averaged across the three tactors

	Subject response							
Actual Pattern	A	B	C	D	E	F	G	H
A	**50%**	**0%**	**3%**	**4%**	**6%**	**37%**	**0%**	**1%**
B	**3%**	**70%**	**11%**	**5%**	**3%**	**1%**	**3%**	**3%**
C	**1%**	**1%**	**76%**	**0%**	**18%**	**1%**	**1%**	**1%**
D	**1%**	**7%**	**0%**	**81%**	**1%**	**5%**	**3%**	**2%**
E	**13%**	**1%**	**22%**	**1%**	**53%**	**3%**	**3%**	**4%**
F	**7%**	**3%**	**1%**	**43%**	**2%**	**40%**	**3%**	**1%**
G	**2%**	**5%**	**2%**	**4%**	**1%**	**1%**	**81%**	**3%**
H	**1%**	**1%**	**3%**	**2%**	**1%**	**1%**	**3%**	**87%**

There was a statistically significant difference in the pattern recognition rates as a function of the tactor used (F(2,18)= 10.280, p=0.001). The mean percentage of correct answers was 62.0% for the array of pancake tactors, 76.7% for the cylindrical tactors, and 60.5% for the rototactors. Post hoc tests indicated that there was a significant difference between the cylindrical tactors and the pancake tactors and the rototactors, but there was no significant difference between the pancake tactors and the rototactors. Since the recognition rates for the cylindrical tactors were higher than those of the pancake tactors and rototactors the post hoc tests indicate that the performance of the cylindrical tactors is superior to that of the pancake tactors and rototactors.

There was also a significant difference between the results for different patterns ($F(7,63)=14.75$, $p<0.0001$). Patterns D (left), G (blinking X) and H (left, right, left) had the highest rates of recognition, as seen in Table 1. Patterns A (up) and B (down) should have very similar recognition rates, but the recognition rate of B was significantly higher than that of A. The presence of Patterns E (diagonally up and right) and F (diagonally up and left) may have had a negative effect on the recognition rates for Pattern A (up). Post hoc tests performed on the data confirmed the existence of a significant difference between the results from Patterns A, E, and F and the remaining patterns. In particular, the tests indicated that with the exception of one comparison (Patterns B and E), Patterns A, E, and F were always identified less accurately than the other patterns, and were not significantly different from one another. There was no significant interaction between tactor type and pattern. In addition there was no significant effect of sex or arm dimensions on the percentage of correct answers, nor were there any significant interactions between these variables.

4.1.5. Procedure – Experiment 2

The experimental procedure for the second arm experiment was essentially identical to that for the first. However, only two kinds of tactors were used – the pancake tactors and the cylindrical tactors. The rototactors were eliminated because the pancake motors used in that tactor are the same as the pancake tactor that was encased in our laboratory, and the results were statistically the same for both tactors. In addition, users reported that it was more difficult to identify patterns presented with the rototactors than with the pancake tactors. A further change in the protocol was that the two diagonal patterns, “up and right” and “up and left”, were eliminated from the experiment due to their low identification rates in the first experiment. They were replaced by an “up, down, up” pattern and by a pattern with a single blinking dot. These choices were made based on the success of the “left, right, left” and “blinking X” patterns from the first experiment. Half of the subjects were tested with the cylindrical array first, and half were given the pancake tactor array first. Each subject was given a 5-minute break between the two parts of the experiment.

4.1.6. Results – Experiment 2

Table 4 shows the mean percentage of correct responses for each pattern as a function of the type of tactor. Table 5 summarizes the responses given by subjects. The data are averaged over all subjects and both tactor types. Similar tables, separated by motor, can be seen in

Table 4. Percentage of correct responses for each pattern presented by each type of tactor

	Pancake	Cylindrical
A	76%	84%
B	80%	92%
C	94%	96%
D	96%	84%
E	92%	100%
F	74%	98%
G	74%	94%
H	94%	100%

Table 5. Group mean responses for each pattern averaged across the two tactors

	Subject response							
Actual Pattern	A	B	C	D	E	F	G	H
A	**80%**	**0%**	**1%**	**8%**	**2%**	**1%**	**8%**	**0%**
B	**1%**	**86%**	**6%**	**3%**	**0%**	**1%**	**3%**	**0%**
C	**2%**	**0%**	**95%**	**0%**	**2%**	**1%**	**0%**	**0%**
D	**0%**	**8%**	**0%**	**90%**	**2%**	**0%**	**0%**	**0%**
E	**0%**	**0%**	**1%**	**1%**	**96%**	**2%**	**0%**	**0%**
F	**1%**	**4%**	**0%**	**1%**	**5%**	**86%**	**2%**	**1%**
G	**0%**	**5%**	**3%**	**3%**	**0%**	**3%**	**84%**	**2%**
H	**0%**	**1%**	**0%**	**1%**	**0%**	**0%**	**1%**	**97%**

Appendix 3. There was a statistically significant difference in the pattern recognition rates as a function of the tactor used (F(1,9)= 5.090, p=0.05). The mean percentage of correct answers was 93.5% for the cylindrical tactors and 85% for the array of pancake tactors. There was also a significant difference between the results for different patterns (F(7,63)=2.319, p=0.04). Pattern H (a single tactor blinking) was highly distinctive and, as a result, had the highest rate of recognition, as seen in Table 4.

In general, Patterns C(right), D(left), and E(left, right, left), which moved across the width of the arm, were easier to identify than patterns A(up), B(down), and F (top, bottom, top), that moved along the length of the forearm. There was significant interaction between pattern and type of tactor (F(7,63)=2.507, p=0.02). For patterns moving along the length of the forearm, the percentage of correct responses was often 10-20% higher for the cylindrical tactors than for the pancake tactors. In contrast, for the patterns moving across the width of the arm, the percentage of correct responses of the cylindrical tactors was only slightly higher than that of the pancake tactors. The correct response rate for the pancake tactors even surpassed that of the cylindrical tactors for Pattern D (left). This result may be a consequence of interaction between scale factors and tactor geometry. The array of tactors spans almost the entire width of the forearm, although it spans only about one fourth of the length. The sides of the arm may serve as markers that facilitate localizing stimuli that move across the arm. In contrast, only part of the length of the forearm is stimulated by the array, so there are probably fewer cues to help localize stimuli that are moving up the arm, hence the patterns are more difficult to identify. However, the cylindrical tactors have an oblong shape and are oriented on the display so that the length of the cylinder is parallel with the forearm. Since there is less space between the cylindrical tactors along the length of the forearm than along the width, the stimuli may seem more continuous and therefore easier to localize. For the pancake tactors, which are approximately square, there is not a significant difference between the distance between the stimuli for the two axes of the forearm. Since the spacing between them is roughly the same for both axes of the arm, the perception of the stimuli is governed only by the geometry of the arm. Although there was a main effect of pattern type in the overall ANOVA, post hoc tests performed on the data did not indicate a significant difference between any of the patterns. There was no significant effect of sex, tactor tested first, or arm dimensions on the percentage of correct answers, nor were there any significant interactions between these variables

4.1.7. Comparison of Experiments 1 and 2

A repeated-measures ANOVA was performed on the results recorded for the six patterns that were tested in both experiments: A (up), B (down), C (right), D (left), G (blink X shape) and H/E (left, right, left). The analysis revealed that this set of patterns led to significantly higher recognition rates in the second experiment than in the first (F(5,45)= 9.863, p<0.0001). This result indicates that the removal of the patterns "up and right" and "up and left" from the first experiment, and replacement with the patterns "top, bottom, top" and "blink center 3 times) dramatically improved recognition rates for the remaining patterns. Clearly, the "up and right" and "up and left" had a deleterious effect on the recognition rates of other patterns. The analysis also showed a significant interaction between experiment and pattern (F(1,9)=1.651, p=0.0035) and between tactor type and pattern (F(5,45)=3.810, p=0.0153). Post hoc tests indicated significant differences in the recognition rates for patterns A (up) and B (down) in the two experiments.

4.2. Experiments 3 and 4 – pattern recognition on the torso

4.2.1. Experiment 3 – Pattern recognition in sedentary subjects

The goal of the torso experiments was to measure vibrotactile pattern identification using a similar set of patterns to those used on the arm. The patterns used in Experiment 2 had higher identification rates than those used in Experiment 1. Therefore, the set of patterns used in Experiment 2 (Fig. 8) was modified for display on a four-by-four grid.

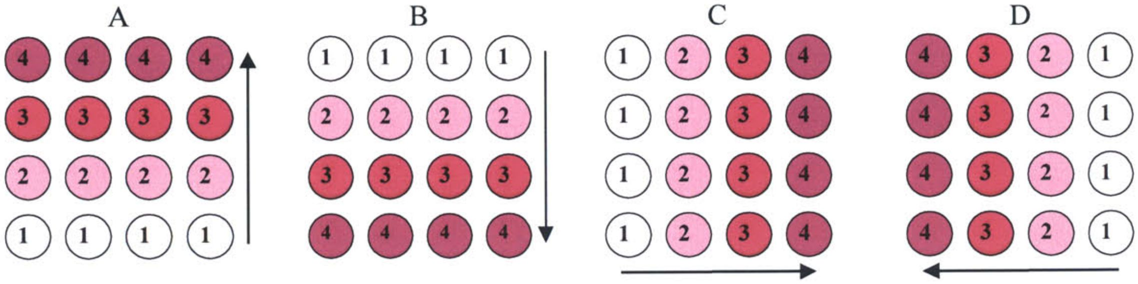
4.2.2. Subjects

Experiment 3 was performed on a group of ten subjects, who were mainly MIT students. Five of the subjects had participated in one of the previous experiments involving stimuli on the arm. All subjects, none of whom participated in both Experiment 3 and Experiment 4, were between the ages of 22 and 26. None of the subjects reported any sensory difficulties. The experiments were approved by the local ethics committee, and all subjects signed informed consent forms.

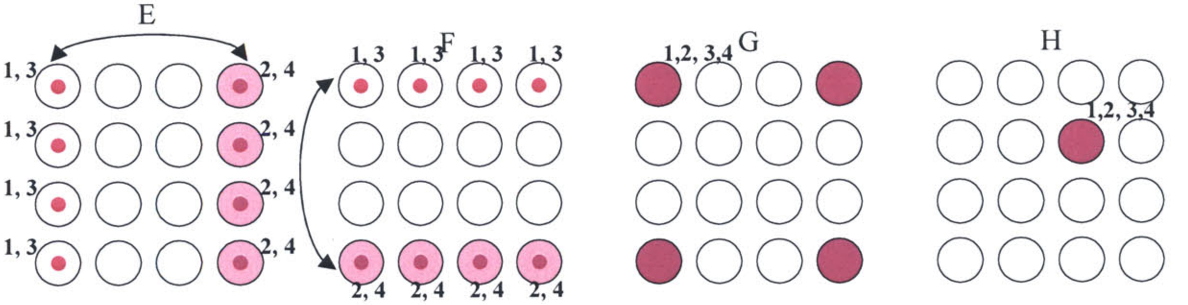
In Experiment 3, the following dimensions of the subject's torso were measured: the circumference around the waist and below the breast. The self-reported height and weight of the subject were also recorded.

4.2.3. Stimuli

Most of the patterns used in Experiments 3 and 4 (Fig. 9) were chosen to represent possible navigational commands that had intuitive meaning. Patterns A, B, C, and D represent possible directions of motion. Patterns G and H represent possible warning or stop signals. Patterns E and F could be used to give the user some other sort of navigational information, or to prompt the user to perform an action unrelated to navigation.



Up Down Right Left



Left, right, left, right Top, bottom, top, bottom Blink corners 4 times Blink single motor 4 times

Fig. 9. Pattern diagram for Experiments 3 and 4

4.2.4. Procedure – Experiment 3

The experimental procedure for the first torso experiment was similar to that for the arm experiments. The waist band was put on the subject underneath the clothing, so that the tactor array was centered on the lower back and every tactor made firm contact with the body. The band was tightened with the Velcro straps until it was firmly attached. The experimental procedure was explained to the subjects, and then they were asked to sit on a stool and put on headphones for the training period. The WTCU used in the arm experiment was used for

Experiments 3 and 4, with new patterns programmed into it. The training session and experiment were conducted according to the same procedures outlined for the arm experiments. Following the training period, during which every pattern was displayed three times and the subject was allowed to request repetitions of the tactile patterns, the experiment began. Each pattern was displayed five times, in random order, for both tactors. The patterns used in the torso experiment (Fig. 9), which are similar to those used in the arm experiment, were modified for use with a four-by-four array. The system of notation used in the arm experiments was used to represent the patterns in the torso experiment.

4.2.5. Results – Experiment 3

Table 6 shows the average percentage of correct responses for each pattern and each tactor type. Table 7 shows the subjects' responses, averaged across subjects. Similar tables,

Table 6. Percentage of correct responses for each pattern presented by each type of tactor

	Pancake	Cylindrical
A	94%	100%
B	98%	100%
C	100%	100%
D	100%	100%
E	100%	100%
F	100%	100%
G	100%	98%
H	100%	100%

Table 7. Group mean responses for each pattern averaged across the two tactors

	Subject response							
Actual Pattern	A	B	C	D	E	F	G	H
A	**97%**	**1%**	**0%**	**0%**	**0%**	**0%**	**2%**	**0%**
B	**0%**	**99%**	**0%**	**0%**	**0%**	**0%**	**1%**	**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%**	**1%**	**0%**	**99%**	**0%**
H	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**100%**

separated by motor, can be seen in Appendix 4. As the tables illustrate, most subjects correctly identified 100% of the stimuli. Of the eight patterns presented, patterns C, D, E, F, and H produced the best results; for both tactor types, they were identified correctly 100% of the time. Patterns B and G were identified correctly 99% of the time, and pattern A was identified correctly 97% of the time. In this experiment, there was no significant effect of tactor type, pattern, tactor tested first, torso dimensions, or sex on the percentage of correct answers, nor were there any significant interactions between these variables. A ceiling effect was clearly evident in the data from the torso experiment. Since so many subjects identified the patterns with 100% accuracy, there was no difference between the identification rates of the tactile patterns used. All of the patterns were easily identified.

4.2.6. Comparison of forearm and torso results

A comparison of the results from the second forearm experiment and the first torso experiment indicated that there was a significant difference between them. In particular, the percentage of correct identifications was much higher on the torso than on the arm (F(1,9)=11.746, p=0.008), and there was also a significant difference in the recognition rates of the patterns (F(7,63)=4.644, p=0.0003). The latter reflects the lower percentage of correct responses in the arm experiment.

4.2.7. Experiment 4: Use of tactile cues on the torso for navigation

Since the subjects in the first torso experiment successfully identified most of the patterns displayed, a navigational experiment was performed using the same set of patterns. This experiment tested subjects' ability to identify and interpret correctly patterns displayed on the torso, outside the laboratory setting. The second torso experiment required subjects to navigate a path through a grid of cones outdoors, guided only by stimuli presented to the torso.

4.2.8. Subjects – Experiment 4

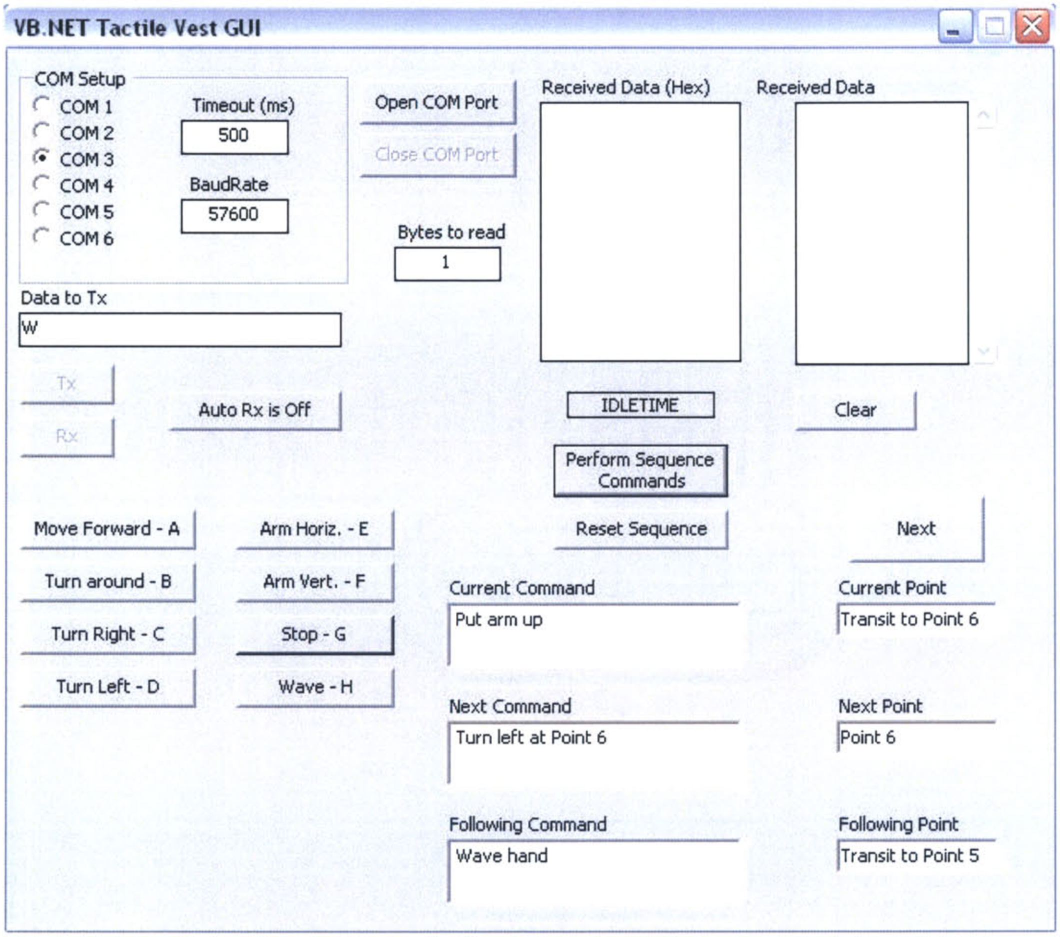
Five subjects, two female and three male, participated in this torso experiment. The self-reported height of each subject was recorded. Additional body dimensions were not measured since the results of the previous experiments did not show a significant correlation between performance and body size.

4.2.9. Apparatus – Experiment 4

Fig. 10. Outdoor Course for Experiment 4

The same torso-based tactile display used in the previous experiment was used in this experiment, with the WTCU and the same patterns of tactor activation. The experiment was performed with only one type of tactor – the pancake tactors encased in rigid plastic. Short, flexible cones were used to mark out a course comprising a three-by-three grid of points (see Fig. 10). The grid was aligned with two rows of trees, to ensure that the placement would be the same for every experiment. The trees were around 11 m apart, so each cone was roughly 5.5 m away from its neighbors. The cones were labeled with numbers to facilitate identification of grid points. An laptop computer was used to send commands to the WTCU. All experiments were videotaped using a Sony HDR-FXI high definition video camera, placed on a tripod and positioned so that the whole course was visible. Although the camera is capable of recording high-definition images, the high-definition mode was not used for this experiment, to reduce the size of the files.

One command was chosen for each pattern used in the previous experiments. Since only five patterns (forward, back, right, left, and stop) are necessary to direct a subject around the course, the remaining three patterns were associated with body movements. This enabled testing of all eight patterns by providing a way for the subject to show that the command was received and properly interpreted (i.e. by performing the movement associated with the command). These patterns of movement and actions were combined to create two paths through the grid of points (Appendices 5 & 6). These paths included the directional commands "move forward," "turn around," "turn right," "turn left," and "stop," and the action commands "raise arm horizontally," "raise arm vertically," and "hop." The path used for training the subjects was designed to include three instances of each command. The path used for collecting experimental data included five instances of each command.


VB.NET Tactile Vest GUI

COM Setup

○ COM 1
○ COM 2
● COM 3
○ COM 4
○ COM 5
○ COM 6

Timeout (ms): 500

BaudRate: 57600

Bytes to read: 1

Data to Tx: W

IDLETIME

Current Command: Put arm up

Next Command: Turn left at Point 6

Following Command: Wave hand

Current Point: Transit to Point 6

Next Point: Point 6

Following Point: Transit to Point 5

Fig. 11. GUI used in Experiment 4

The Visual BASIC program used to send the commands from the computer to the WTCU was modified to load these path files. The GUI (Graphical User Interface) used to control the experiment is shown in Figure 11. Six windows were added to the interface of the program to allow the experimenter to run the experiment using a file including the sequence of commands necessary to guide a subject on a path through the grid. In this set of six windows, the window in the upper left corner shows the current position or action of the subject. The two windows below it display the next two commands to be sent. To the right, the current position of the subject corresponding with each action is displayed, assuming the subject has correctly interpreted all commands. To send the next command to the user, the experimenter clicks "Next." The command is sent and the windows are updated. It was anticipated that subjects would not walk at the same pace and so it was not possible to automate the transmission of tactile commands, since commands could be sent too early or too late. The interface designed for this project informs the experimenter of the upcoming commands, to make it possible to send commands at the correct pace for the current subject.

4.2.10. Experimental Procedure – Experiment 4

The tactor band was put on the subject's torso underneath the clothing, in the same manner as described in the first torso experiment (see Fig. 6). The WTCU was placed in a waist pack and attached to the subject's waist, positioned so that the strap would not make contact with the tactors. The experimental procedure was explained to the subjects, and then they were given a visual representation of the patterns and their meanings (Appendix 7), and asked to memorize the patterns. The experimenter gave suggestions to subjects to help them remember the patterns. While the subject was looking at the visual representation of the patterns, each command was sent and identified by letter, to allow the subject to identify the tactile sensation that corresponded to each command.

The subjects were told that they were not to move forward for any command but "forward", and not to stop for any command but "stop." Upon receiving a command to turn left, turn right, turn around, or stop, subjects were instructed to keep walking and not perform the action until they reached the next cone. In the event that they received these commands while stationary, they were instructed to turn 90° left or right or to turn 180°, for the "turn left," "turn right," and "turn around" commands, respectively. They were told to perform the "arm horizontal," "arm vertical," and "hop" commands as soon as they received them. The subjects were reminded that the purpose of the actions was to indicate to the experimenter that the commands had been received and correctly interpreted. Consequently, they were told that they need not keep their arms up, or continue to hop through the course – an arm raised for a moment, or a single hop, were sufficient to communicate their understanding of the command.

There were two phases of training to ensure that the subjects had memorized the commands and knew how to interpret them properly. In the first phase of training, the experimenter led the subjects through the course using the tactile stimuli, correcting them when they made mistakes and repeating the commands that seemed to cause confusion more frequently. When the subjects had a good understanding of the commands, the second phase of training began. In the second phase, they were led through the course on a set path that was different from the one used for data collection. Although subjects were corrected when they made a mistake during the training period, they were notified that mistakes would not be corrected during the data collection phase of the experiment. They were informed that no command would send them beyond the borders of the course and that if they interpreted a command that led them beyond the borders of the course, they should stop and tell the experimenter which command they had perceived. The experimenter could then use the information shown in the tactile control window and tell the subject to move to another point, where the experiment could be started again from the correct position. This procedure offered a means of keeping the subject on the course, even in the event of errors, without correcting each error.

After the training session, the subjects were asked if they felt confident enough in their knowledge of commands to start the data collection for the experiment. Most subjects felt ready after around 10 minutes of training.

4.2.11. Data Analysis – Experiment 4

Following the experiments, the video created of the experiments was reviewed and compared with the path that the subjects should have followed. A checklist was used to mark which commands were correctly obeyed and which resulted in errors.

4.2.12. Results – Experiment 4

Table 8 displays the mean responses of the subjects for each pattern presented. Most subjects correctly identified 100% of the stimuli and moved through the course correctly. Only one of the five subjects made a mistake, and that subject made just one mistake. The subject interpreted the "turn left" command as a "stop" command. The misinterpreted command was sent shortly after a "hop" command, so it could be that the tactors were not making good contact when the command was sent.

As in Experiment 3, a ceiling effect was evident in the data from the outdoor torso experiment. Since so many subjects identified the patterns with 100% accuracy, there was no

Table 8. Group mean responses for each pattern

	[illegible]							
Actual Pattern	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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%	96%	0%	0%	4%	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%

difference between the identification rates of the tactile patterns used. All of the patterns were easily identified, even when the subject was in motion.

5. General discussion

The correct identification of the patterns should be near 100% for an effective navigational display. However, in Experiment 2 the mean recognition rate across tactors and patterns was 89%. This identification rate, which indicates that roughly one command in ten is likely to be misinterpreted, is too low for the arm-based display to be useful in its current form. These results were obtained in a stationary experiment in a quiet laboratory and it would be expected that in a field experiment an even lower percentage of patterns would be identified. Therefore, though the results from Experiments 1 and 2 indicate that an arm-based tactile array is somewhat effective in displaying navigational information, more research and experimentation is needed to produce a viable arm-based display.

The efficacy of an arm-based tactile display for presenting navigational cues is constrained by issues of spatial resolution and tactor placement. An effective arm-based display may require fewer tactors and simpler signals than those used in these experiments. The tactile display could also be distributed over a larger surface area on the arm as there is no change in vibrotactile sensitivity on the volar surface of the arm between the elbow and the wrist (Cholewiak & Collins, 2003). In one of the few successful applications of a tactile display on the forearm, Wiesenberger and Percy (1995) used an array of seven vibrators mounted between the wrist and elbow to enhance lip reading skills by providing tactile cues from the acoustic waveform. The results from these previous studies could be used in a future study to develop a more effective arm-based navigational display.

While an arm-based display may not be suitable for navigational purposes due to the difficulty of interpreting stimuli presented to the arm, arm-based displays are still useful for attentional cueing, which requires much simpler stimuli. The effectiveness of arm-based displays for attentional cueing has already been demonstrated for use in virtual environments (Bloomfield & Badler, 2003; Lindeman et al., 2004). An arm-based display could also be used to direct the user's attention to a given location, as in the torso-based display in the study by Tan et al. (2003).

The torso-based display was significantly more effective than the arm display. Most patterns resulted in a 100% identification rate, and the experiments showed that the torso-based display is effective in displaying navigational information both in a laboratory setting where the subject is seated and in an outdoor setting where the subject is moving from point to point. The torso display had a number of advantages over the arm-based display. Since there were 16 tactors instead of 9, there was greater redundancy in the commands. Therefore, it was less likely that the movement of the user would prevent them from perceiving the stimuli. In addition, since each pattern presented using the torso display comprised four waves of tactor activation instead of three, a longer time was needed to present patterns on the torso than on the arm. As a result, the user had a longer period of time to consider and interpret the command. The area of skin covered by the display was also a factor. Since the torso has a significantly larger area than the arm, there was a greater distance between the stimuli, so it was easier to localize the stimuli to determine the direction of motion. Finally, the patterns presented using the torso display crossed the spine, which is the body's central axis. Consequently, stimuli were processed by both hemispheres of the brain, increasing the likelihood that the user could correctly interpret the stimulus (Van Erp & Werkhoven, 1999; Cholewiak et al., 2004). The stimuli presented by the arm display, which is limited to one side of the body, would only be processed by one cerebral hemisphere.

The results from these experiments demonstrate that vibrotactile cues presented to the torso can be accurately identified both inside and outside of the laboratory, and could therefore be used to provide navigational cues to mobile operators. Given the context in which these tactile displays are to be used (i.e. navigation in hazardous environments), high accuracy is required in identifying the tactile cues, especially since the user is likely to be distracted by other stimuli. Therefore, the torso display, with 100% identification of most of the patterns presented both inside and outside the laboratory, offers more promise than the forearm display in its present configuration. The results also indicate that the spacing between the tactors 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.

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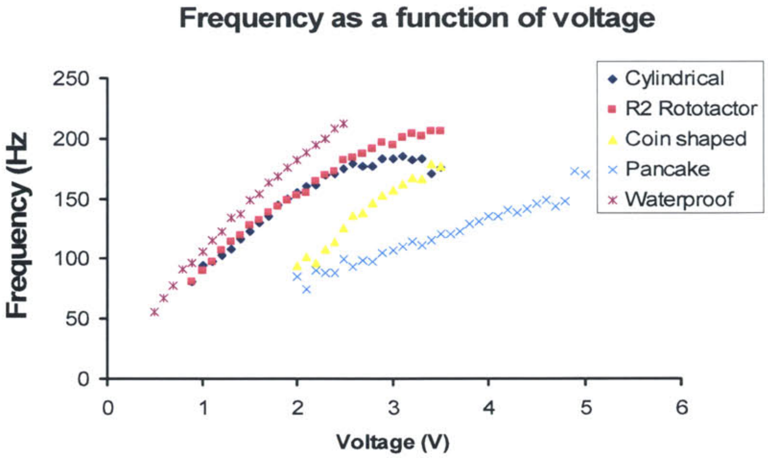
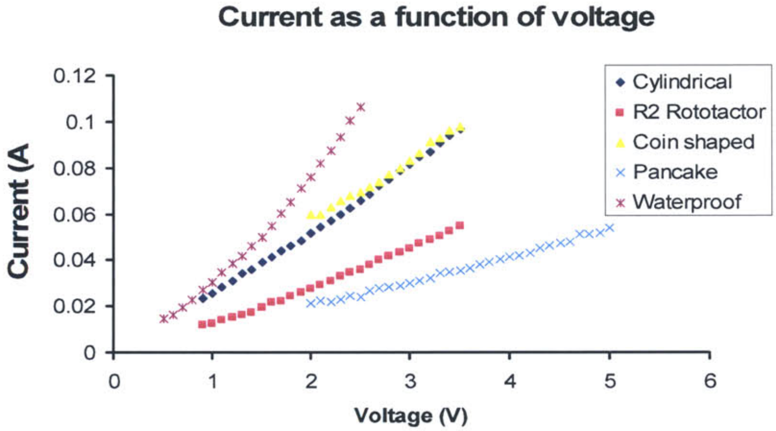
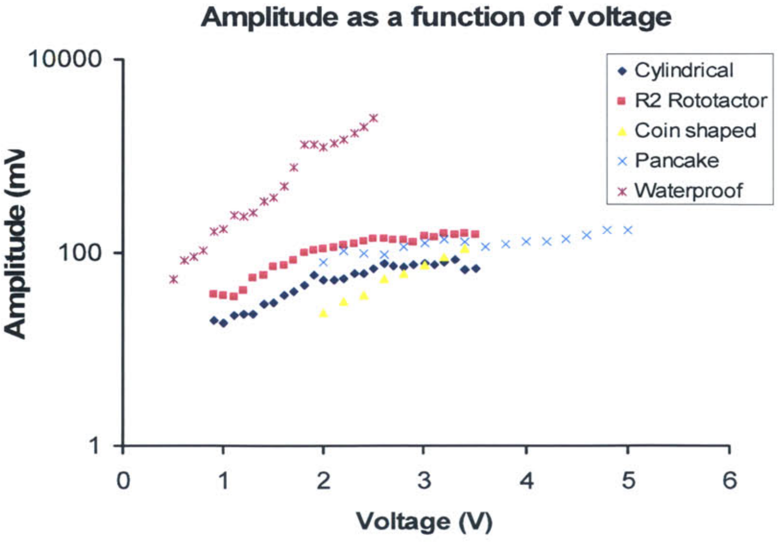
Appendix 1. Tactor characterization







Appendix 2. Group mean responses for each pattern – Experiment 1

Pancake	Subject response							
Actual	A	B	C	D	E	F	G	H
A	**34%**	0%	8%	0%	2%	54%	0%	2%
B	2%	**64%**	14%	4%	4%	0%	6%	6%
C	0%	0%	**82%**	0%	16%	0%	0%	2%
D	0%	4%	0%	**80%**	2%	8%	2%	4%
E	6%	2%	30%	2%	**46%**	2%	4%	8%
F	10%	2%	2%	48%	4%	**30%**	0%	4%
G	2%	8%	2%	6%	2%	2%	**70%**	8%
H	0%	0%	4%	2%	2%	0%	2%	**90%**

Cylindrical	Subject response							
Actual	A	B	C	D	E	F	G	H
A	**58%**	0%	0%	6%	8%	28%	0%	0%
B	8%	**74%**	6%	8%	0%	2%	2%	0%
C	0%	0%	**78%**	0%	22%	0%	0%	0%
D	0%	2%	0%	**92%**	0%	6%	0%	0%
E	22%	0%	12%	0%	**62%**	2%	2%	0%
F	2%	6%	0%	38%	0%	**54%**	0%	0%
G	0%	0%	0%	2%	2%	0%	**96%**	0%
H	0%	0%	0%	0%	0%	0%	0%	**100%**

Rototactor	Subject response							
Actual	A	B	C	D	E	F	G	H
A	**58%**	0%	0%	6%	8%	28%	0%	0%
B	0%	**72%**	14%	4%	6%	2%	0%	2%
C	4%	4%	**68%**	0%	16%	2%	4%	2%
D	2%	14%	0%	**70%**	2%	2%	8%	2%
E	10%	2%	24%	0%	**50%**	6%	4%	4%
F	8%	2%	0%	44%	2%	**36%**	8%	0%
G	4%	8%	4%	4%	0%	2%	**78%**	0%
H	2%	4%	6%	4%	2%	2%	8%	**72%**

Average	Subject response							
Pattern	A	B	C	D	E	F	G	H
A	**50%**	0%	3%	4%	6%	37%	0%	1%
B	3%	**70%**	11%	5%	3%	1%	3%	3%
C	1%	1%	**76%**	0%	18%	1%	1%	1%
D	1%	7%	0%	**81%**	1%	5%	3%	2%
E	13%	1%	22%	1%	**53%**	3%	3%	4%
F	7%	3%	1%	43%	2%	**40%**	3%	1%
G	2%	5%	2%	4%	1%	1%	**81%**	3%
H	1%	1%	3%	2%	1%	1%	3%	**87%**

Appendix 3. Group mean responses for each pattern – Experiment 2

Pancake	Subject response							
Actual Pattern	A	B	C	D	E	F	G	H
A	76%	0%	0%	4%	4%	2%	14%	0%
B	2%	80%	10%	4%	0%	0%	4%	0%
C	2%	0%	94%	0%	2%	2%	0%	0%
D	0%	4%	0%	96%	0%	0%	0%	0%
E	0%	0%	2%	2%	92%	4%	0%	0%
F	2%	8%	0%	2%	8%	74%	4%	2%
G	0%	8%	6%	6%	0%	2%	74%	4%
H	0%	2%	0%	2%	0%	0%	2%	94%

Cylindrical	Subject response							
Actual Pattern	A	B	C	D	E	F	G	H
A	84%	0%	2%	12%	0%	0%	2%	0%
B	0%	92%	2%	2%	0%	2%	2%	0%
C	2%	0%	96%	0%	2%	0%	0%	0%
D	0%	12%	0%	84%	4%	0%	0%	0%
E	0%	0%	0%	0%	100%	0%	0%	0%
F	0%	0%	0%	0%	2%	98%	0%	0%
G	0%	2%	0%	0%	0%	4%	94%	0%
H	0%	0%	0%	0%	0%	0%	0%	100%

Average	Subject response							
Actual Pattern	A	B	C	D	E	F	G	H
A	80%	0%	1%	8%	2%	1%	8%	0%
B	1%	86%	6%	3%	0%	1%	3%	0%
C	2%	0%	95%	0%	2%	1%	0%	0%
D	0%	8%	0%	90%	2%	0%	0%	0%
E	0%	0%	1%	1%	96%	2%	0%	0%
F	1%	4%	0%	1%	5%	86%	2%	1%
G	0%	5%	3%	3%	0%	3%	84%	2%
H	0%	1%	0%	1%	0%	0%	1%	97%

Appendix 4. Group mean responses for each pattern – Experiment 3

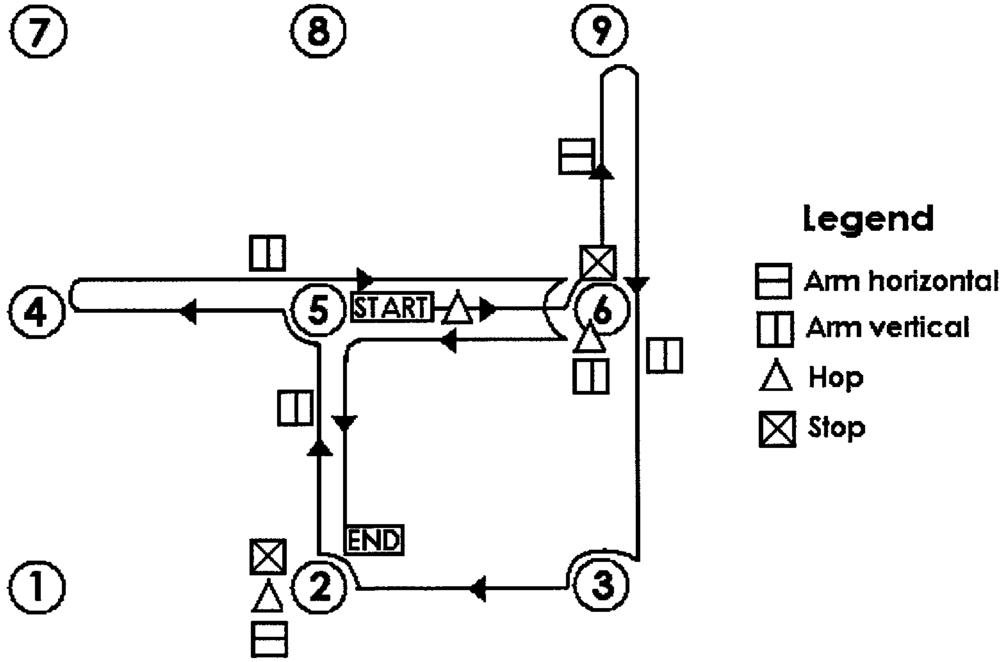
Pancake	Subject response							
Actual Pattern	A	B	C	D	E	F	G	H
A	**94%**	2%	0%	0%	0%	0%	4%	0%
B	0%	**98%**	0%	0%	0%	0%	2%	0%
C	0%	0%	**100%**	0%	0%	0%	0%	0%
D	0%	0%	0%	**100%**	0%	0%	0%	0%
E	0%	0%	0%	0%	**100%**	0%	0%	0%
F	0%	0%	0%	0%	0%	**100%**	0%	0%
G	0%	0%	0%	0%	0%	0%	**100%**	0%
H	0%	0%	0%	0%	0%	0%	0%	**100%**

Cylindrical	Subject response							
Actual Pattern	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%	2%	0%	**98%**	0%
H	0%	0%	0%	0%	0%	0%	0%	**100%**

Average	Subject response							
Actual Pattern	A	B	C	D	E	F	G	H
A	**97%**	1%	0%	0%	0%	0%	2%	0%
B	0%	**99%**	0%	0%	0%	0%	1%	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%	1%	0%	**99%**	0%
H	0%	0%	0%	0%	0%	0%	0%	**100%**

Appendix 5. Training path

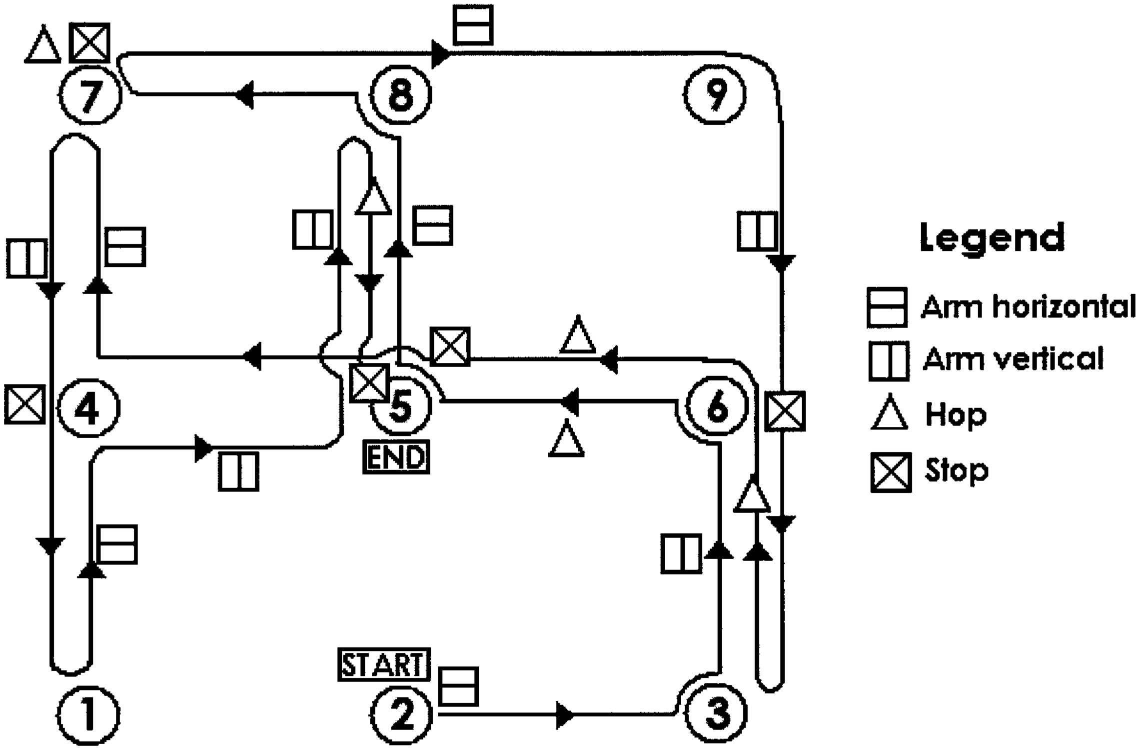
Starting position	Point 5
Turn to the right	Point 5
Move forward from point 5	Transit to Point 6
Stop at point 6	Point 6
Hop	Point 6
Put arm up	Point 6
Turn left	Point 6
Move forward from point 6	Transit to Point 9
Put arm out	Transit to Point 9
Hop	Transit to Point 9
Reverse direction at point 9	Point 9
Put arm up	Transit to Point 3
Turn right at point 3	Point 3
Stop at point 2	Point 2
Hop	Point 2
Turn right at point 2	Point 2
Put arm out	Point 2
Move forward from point 2	Transit to Point 5
Put arm up	Transit to Point 5
Turn left at point 5	Point 5
Reverse direction at point 4	Point 4
Put arm up	Transit to Point 6
Reverse direction at point 6	Point 6
Turn left at point 5	Point 5
Stop at point 2	Point 2 - End



Appendix 6a: Data Collection Path

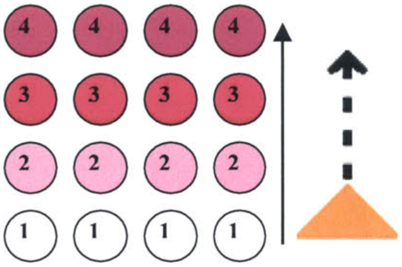
Subject at point 2	Point 2
Put arm out	Point 2
Turn to the right	Point 2
Move forward from point 2	Transit to Point 3
Turn left at point 3	Point 3
Put arm up	Transit to Point 6
Turn left at point 6	Point 6
Wave hand	Transit to Point 5
Turn right at point 5	Point 5
Put arm out	Transit to Point 8
Turn left at point 8	Point 8
Stop at point 7	Point 7
Turn 180, remain at point 7	Point 7
Move forward from point 7	Transit to Point 9
Put arm out	Transit to Point 9
Wave hand	Transit to Point 9
Turn right at point 9	Point 9
Put arm up	Transit to Point 6
Stop at point 6	Point 6
Move forward from point 6	Transit to Point 3
Reverse direction at point 3	Point 3
Wave hand	Transit to Point 6
Turn left at point 6	Point 6
Wave hand	Transit to Point 5
Stop at point 5	Point 5
Move forward from point 5	Transit to Point 4
Turn right at point 4	Point 4
Put arm out	Transit to Point 7
Reverse direction at point 7	Point 7
Put arm up	Transit to Point 4
Wave hand	Transit to Point 4
Stop at point 4	Point 4
Move forward from point 4	Transit to Point 1
Reverse direction at point 1	Point 1
Put arm out	Transit to Point 4
Turn right at point 4	Point 4
Put arm up	Transit to Point 5
Turn left at point 5	Point 5
Put arm up	Transit to Point 8
Reverse direction at point 8	Point 8
Wave hand	Transit to Point 5
Stop at point 5	Point 5 - End

Appendix 6b. Diagram of Data Collection Path



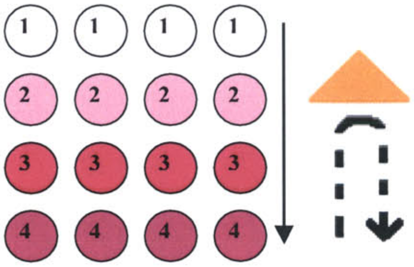
Appendix 7. Visual Representation of Patterns for Experiment 4

A



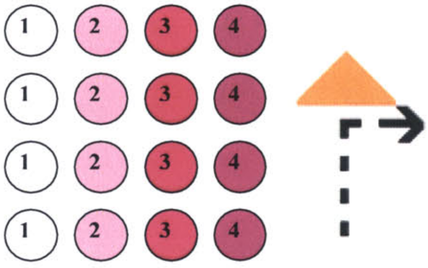
Move forward

B



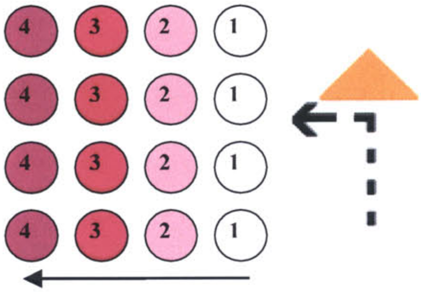
Turn around

C



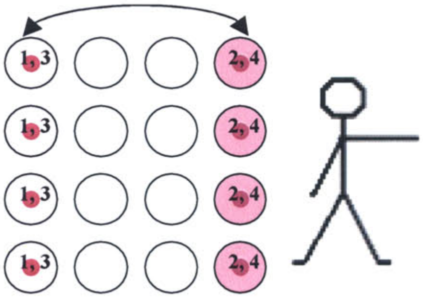
Turn right

D



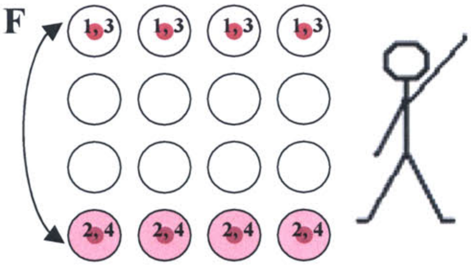
Turn left

E



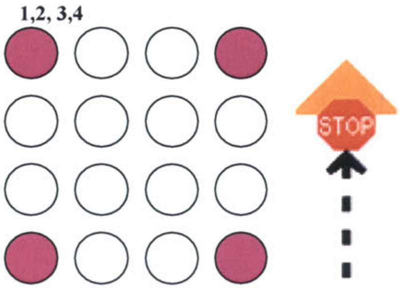
Arm horizontal

F



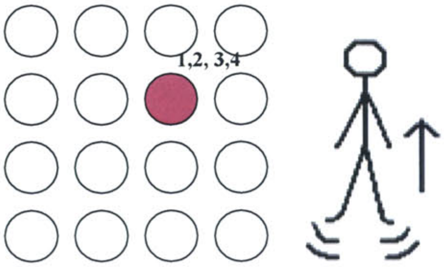
Arm vertical

G



Stop at next cone

H



Hop