VIBROTACTILE PATTERN RECOGNITION ON THE TORSO: EFFECTS OF CONCURRENT ACTIVITIES

by

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ABSTRACT

Vibrotactile displays have been created to aid vision or hearing through the sense of touch. These displays communicate with the user to provide information. The focus of this thesis was to determine how concurrent activity affects vibrotactile signal recognition. An overall accuracy recognition rate of 90% or greater was desired from each of the signals in the each of the tasks. The first experiment asked subjects to wear the tactile display and walk while responding to signals. The results indicated that most of the subjects were able to recognize the patterns. The overall mean correct response rate was 92% and then when the subjects were asked to jog, they correctly identified the patterns 91% of the time. After determining the success rates from the first experiment, a second set of subjects were asked to concentrate on an internet game while responding to signals. The data from this experiment had an overall mean correct response rate of 93%. The results from this experiment further indicate that subjects can still receive communications while participating in other activities. The results also lead to specific conclusions about the patterns used and their ability to be identified with concurrent activity where some patterns are more easily received than others. By understanding how these patterns are recognized by humans, we can better develop patterns to communicate through tactile devices.

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1. Introduction

Current navigation systems usually require a visual display to transmit information about location, directions, and distance. Systems like the Global Positioning System (GPS), which require a display, are often not practical for pilots flying in an aircraft, deep sea divers, boat operators traveling the open seas, and astronauts in space. People in these situations can experience impaired vision due to weather conditions and intense vibrations can disturb the visual display that assists in navigation. These problems are not easily remedied and so other solutions have been sought.

Spatial orientation is one of the most crucial requirements when flying an aircraft and disorientation due to high gravitation forces or misperceived visual cues can result in accidents. In fact, extended periods of time spent in the clouds can cause a pilot to lose control of the aircraft. Various techniques and equipment have been used to aid pilots so that they can maintain spatial orientation. Different engineering solutions have been proposed to provide instrumentation that creates an artificial horizon for pilots to use as a reference. The artificial horizon eventually became mandatory for all aircraft but was not sufficient to prevent accidents. Further technology needs to be developed to help pilots fly safely and maintain spatial orientation. One solution to this problem has been to provide navigation assistance using the sense of touch. (Rupert 2000)

In the last twenty years, many experiments have been conducted to test different vibrotactile systems and to try to create the most efficient display to assist in navigation. Van Erp et al. (2005) conducted a study on pedestrians, a helicopter pilot and a boat driver in which the subjects successfully navigated through a course with the help of a tactile device. The pedestrian subjects wore a waistband with eight tactors (small motors providing the vibrations) positioned around the waist and were directed through a route using vibrotactile clues. The tactile clues were successful in aiding navigation in this situation. In a further experiment, a pilot and boat driver were able to successfully navigate the course laid out despite the vibrations in the vehicles they were controlling and were able to pilot their vehicles using the signals conveyed by the vibrations they felt on their backs.

Vibrotactile displays use the sense of touch to provide information. These displays come in a variety of shapes and sizes and can be made for different parts of the body to aid vision or hearing. Not only can these types of devices be used by pilots but they can also assist soldiers in the field. Verbal distribution of commands can be difficult when soldiers are moving about or concentrating on other tasks. A tactile display could assist in the communication process by allowing soldiers to communicate without requiring that they see or hear the source of the information. A command to take cover or to stop movement could be issued to all of the squad's members simultaneously regardless of whether the soldiers could see the staff sergeant or not.

One important aspect of a tactile device in these applications is that it is hands-free so users can use their hands for other activities. In addition it is important that the user not be distracted by directing his or her eyes to the device. Various environmental situations have been described in which audio cues are hard to follow. In situations in which it is not possible to present information through the visual or auditory channels or in which these channels are overloaded, the sense of touch can be used as a medium for communication. (Gemperle et al. 2001)

Tactile displays have also been used as sensory substitution aids. Blind persons can use these devices to navigate throughout their homes and deaf persons have used tactile displays to aid their impaired hearing. Vibrotactile displays can be used to send signals through the skin in place of other senses such as vision. (Kaczmarek et al. 1991) Tactile displays can be worn on the shoulder, around the waist, or placed on the arms. A number of experiments have shown that subjects can learn to use these displays quickly, without extensive training. Cardinal directions and instructions have been successfully transmitted to subjects ranging from the average college student to Army pilots. (Rupert 2000, Jones et al. 2006) Many aspects of the tactile devices have been analyzed to improve their communication capabilities. The distance between motors (Van Erp 2005), the type of motors (Jones et al. 2006), placement of the motors (Cholewiak et al. 2004), and the timing of the vibrations (Van Erp 2005) have all been studied to determine what configuration and properties of the vibrotactile stimuli are optimal. Experimental tests have not yet been run to determine the feasibility of comprehending tactile signals while concentrating on something different.

In a series of recent experiments, vibrotactile displays have been shown to be useful in navigation. Patterns were sent to the tactile display worn on the lower back to guide the subjects to move in various directions such as go left, right, forward and backward. Other patterns were also presented to the subjects to analyze their ability to distinguish different patterns. In one experiment, the subjects had to identify the patterns in a laboratory setting, and then in a second experiment, subjects were taken outdoors and given the task of using the vibrotactile cues to instruct them as to which direction they should walk. Tactile signals were also sent to the subjects that indicated simple commands such as hop and raise the arm to parallel to the floor (Jones et al., 2006). In order to be beneficial in navigation, tactile patterns should be identified with an accuracy exceeding 90% correct. Without near perfect identification, accidents can occur which in hazardous environments could be disastrous. In the experiments run with students between the ages of 21 and 32, almost 100% correct identification of tactile patterns was found. Subjects tested in both the laboratory and outdoors could successfully identify the patterns. This suggests that the vibrotactile displays may be useful for navigation. (Jones et al 2006)

The focus of this thesis is to further the development of tactile displays, by studying how concurrent activity affects tactile pattern recognition. Tactile displays will often be used by people actively engaged in other tasks in order to determine what effect concurrent activities have on tactile pattern recognition.

2. Experiment 1: Pattern Recognition using the Torso-Based Display

2.1 Apparatus

2.1.1 Tactors

The motors used is in the display are pancake motors (Sanko electric, Model 1E120) which are 1.39 cm in diameter and .34 cm thick. In order to increase the surface area available for contact and to make the motor more robust each individual motor is encased in plastic.

2.1.2 Torso-Based Display

Sixteen tactors in a 4x4 matrix were attached to a spandex waist band. The display can be seen below in Figure 1. The waistband fits snuggly on the back of the subject and is secured in the front with two Velcro straps and a snap-in strap.

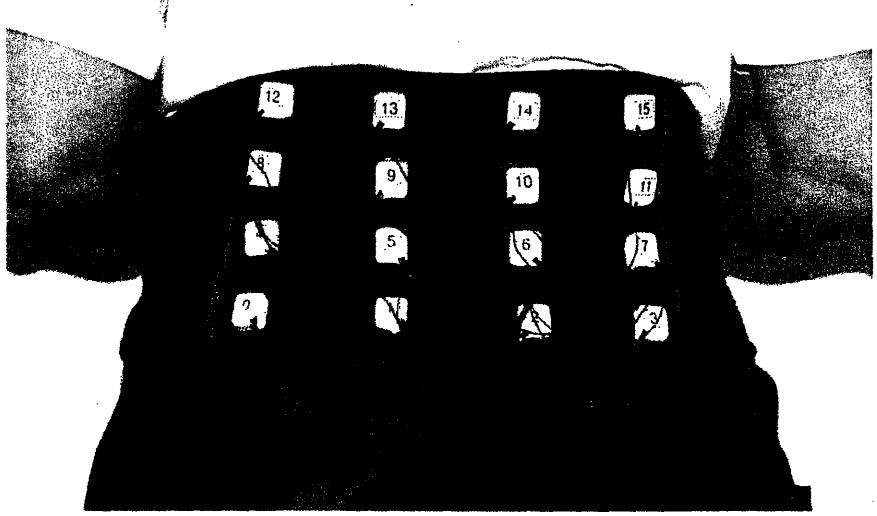

Figure 1: Image of the waistband used displaying the 4x4 matrix of motors.

Below the waistband, a small pouch is attached that holds the wireless tactile control unit (WTCU) and the battery.

2.1.3 Wireless Tactile Control Unit (WTCU)

The tactile display is connecte3d to a WTCU, which was designed and fabricated in the BioInstrumentation Laboratory (see Figure 2). The circuit board communicates via a 2.4 GHz Bluetooth Class 1 Device, and is programmed with the patterns for tactor activation. (Lockyer, 2004) A Visual Basic interface running on an IBM laptop computer sends the signals to the WTCU that controls the pattern of motor activation.

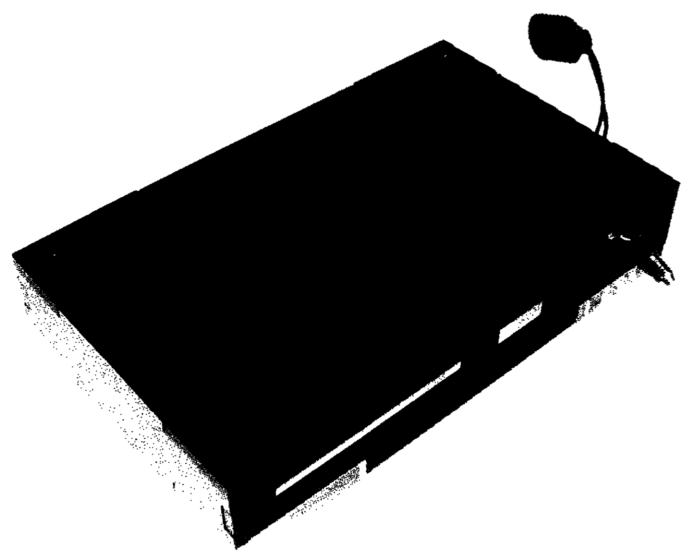

Figure 2: Image of the wireless control unit used.

2.2 Method

The goal of this experiment was to measure the accuracy of vibrotactile pattern recognition as subjects either walked or jogged. The intensity of the physical activity was greater during the jogging condition and so it was hypothesized that subjects would have more difficult identifying tactile patterns when jogging as compared to walking.

2.2.1 Subjects

The first experiment was performed on a group of nine subjects, all of whom were students attending the Massachusetts Institute of Technology. All subjects were between the ages of twenty and twenty-two years old. Three men and six women were tested.

2.2.2 Stimuli

The patterns used in Experiment 1, as shown in Figure 3, were tactile versions of military commands. In developing these tactile icons or tactons an attempt was made to maintain some intuitive meaning of the Army hand and arm signals (Jones, Kunkel & Torres, 2007). Patterns B, E and H were chosen to represent the corresponding motion of the arm. "Move to the right" is represented by the motors being activated in sequence across the subject's back from left to right. The other patterns describe the motion to be followed by the hand but are slightly less intuitive.

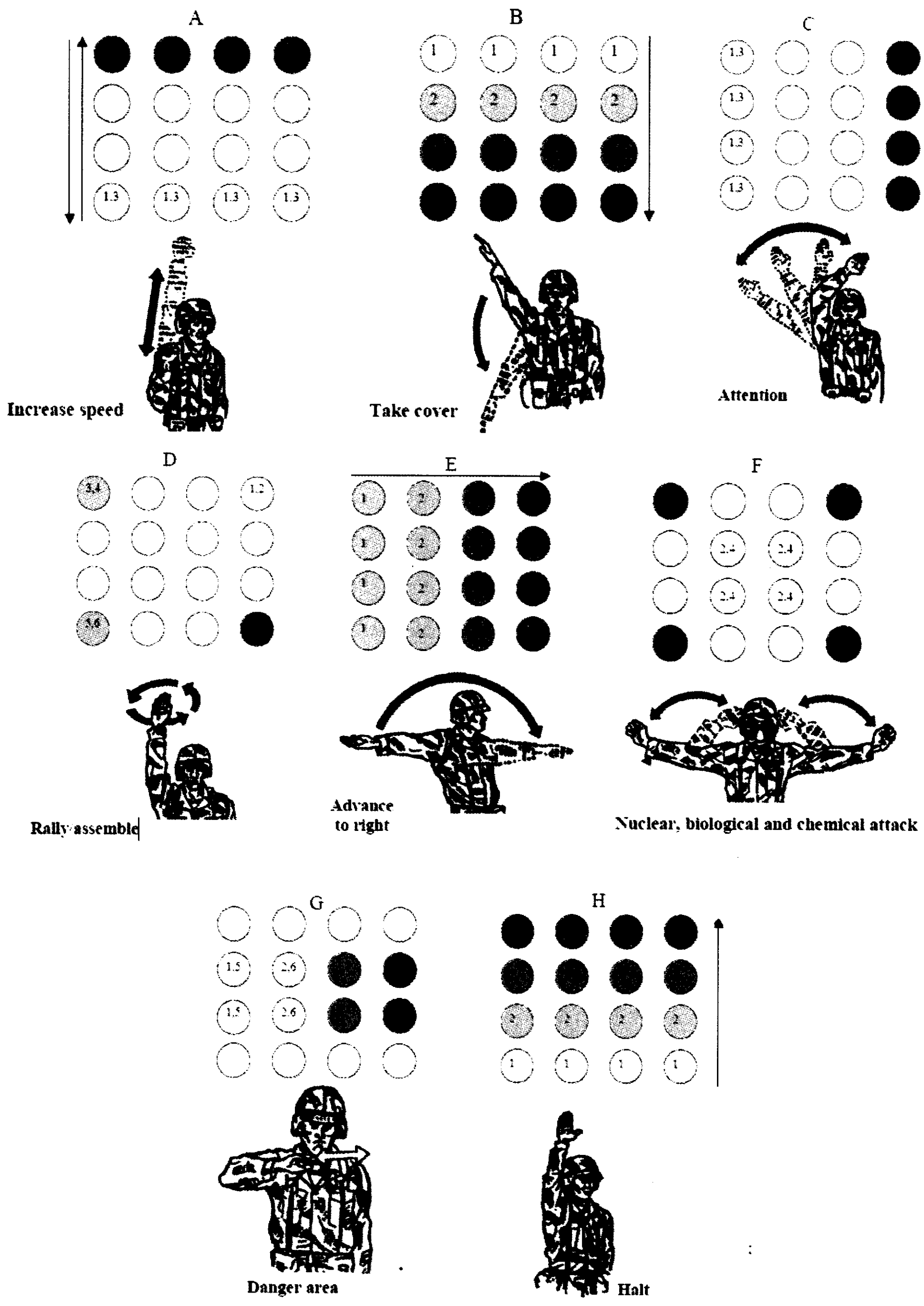

Figure 3: Patterns used in experiment 1 and 2 designed to resemble common military hand signals. The numbers signify the order of which the motors are vibrating. Separate motors vibrate simultaneously if they have the same number. The colors are used to reinforce the order of activation and the arrows indicate the direction of tactor activation.

2.2.3 Procedure

The experimental procedure was first explained to the subjects. The objective of the experiment was explained to each individual and consent forms were presented and signed. The vest was placed on the back of each subject so that he or she would become comfortable wearing the display. The subject was then asked to remain standing throughout the training period and the actual experiment.

Subjects were given a training period to become familiar with the eight patterns used and this lasted between five to eight minutes. Diagrams of the possible patterns identical to those illustrated in Figure 4, were shown to the subjects. It was pointed out that the numbers refer to the order of activation (if the tactors have the same number, they are activated simultaneously), the colors were meant to reinforce the order, and lastly the arrows indicate the direction of tactor activation. The images below the tactor representation are a visual representation of the movements that correspond to the tactile signals. During this training period, the experimenter identified the patterns by name, corresponding letter and signal. The tactile stimuli were activated via the WTCU which was controlled by the notebook computer. After the third presentation of the set of patterns, the subjects were permitted to ask that patterns be repeated for clarification. Once the training period came to a conclusion, the subjects were no longer permitted to look at the visual representation of the patterns.

Subjects were then asked to walk up and down a corridor responding to the stimulus received. The 24 stimuli were presented in a random order, in groups of eight and each stimulus was presented three times. The subjects' responses were recorded by hand by the experimenter. The subjects were permitted to identify the signal by letter name, name or hand signal. They were also permitted to indicate that they were unsure of the stimulus if they could not identify the pattern. The three sets of eight trials took approximately ten minutes to complete. After the 24 trials, subjects were asked to jog up and down the corridor and respond to 24 additional signals. These signals were again presented in random order and the subjects were asked to identify the stimuli. Subjects were given an unlimited amount of time to respond to each stimulus. The second part of the experiment took approximately ten minutes to complete.

2.2.4 Results

The pattern of responses averaged across subjects is shown in Table 1. The overall mean correct response rate was 92% and ranged between 78% and 100% while subjects walked. Highlighted within the table are the percentages of correctly identified signals. All nine subjects were able to identify signals B, D and G with 100% accuracy. Signal H was identified incorrectly by one subject during one of the trials, and signals A and F were occasionally misidentified and subjects were unsure when these patterns were presented. Patterns C and G were occasionally confused. Pattern C alternates between the left and right motors with four simultaneously vibrating at once, whereas pattern G uses activates two motors simultaneously across the back and then repeats the pattern. Both patterns send signals from the left side of the back to the right which could explain the misidentification. Patterns F and C were also confused although these patterns are considerably different from one another. Possible confusion could be if the user could not process all of the motors that were vibrating and perceived pattern F to activate the motors in the first row, then the third, and then repeated to sense pattern C.

Table 1: Mean Subject Response while walking during Experiment 1. The percentages of correct pattern recognition are highlighted.

	Subject Response								
Actual Pattern	A	B	C	D	E	F	G	H	Unsure
A	85%	0%	0%	0%	0%	7%	4%	0%	4%
B	0%	100%	0%	0%	0%	0%	0%	0%	0%
C	0%	0%	81%	0%	0%	0%	19%	0%	0%
D	0%	0%	0%	100%	0%	0%	0%	0%	0%
E	0%	0%	7%	0%	93%	0%	0%	0%	0%
F	4%	4%	11%	0%	0%	78%	0%	0%	4%
G	0%	0%	0%	0%	0%	0%	100%	0%	0%
H	4%	0%	0%	0%	0%	0%	0%	96%	0%

The ability to identify a tactile pattern when jogging was tested after the walking condition. In this situation, the overall mean correct response rate was 91% with a range between 78% and 100%. The results from subjects while they were jogging are shown in Table 2. As was the case in the first part of the experiment, both B and D were perceived with 100% accuracy, and only one of the trials with pattern G was misidentified. Similar to results obtained while walking, pattern F was the hardest to identify. While jogging, subjects were more likely to be unsure of the pattern as compared to misidentifying it which they did more frequently while walking. The error in pattern F is misleading as the uncertainty level rose while jogging.

Table 2: Mean Subject Response while jogging during Experiment 1. The percentages of correctly identified patterns are highlighted.

	Subject Response								
Actual Pattern	A	B	C	D	E	F	G	H	Unsure
A	85%	0%	0%	0%	0%	7%	0%	4%	4%
B	0%	100%	0%	0%	0%	0%	0%	0%	0%
C	0%	0%	89%	0%	0%	0%	11%	0%	0%
D	0%	0%	0%	100%	0%	0%	0%	0%	0%
E	0%	0%	0%	0%	93%	0%	7%	0%	0%
F	4%	7%	0%	0%	4%	74%	0%	0%	11%
G	0%	0%	4%	0%	0%	0%	96%	0%	0%
H	0%	0%	0%	0%	4%	4%	0%	93%	0%

3. Experiment 2: Effect of Concurrent Concentration Intensive Activity on Recognition

3.1 Apparatus

3.1.1 Torso-Based Display and WTCU

The same display and WTCU that were utilized for experiment 1 were also used for experiment 2.

3.1.2 Use of "WEBoggle" as concurrent activity

For this experiment, the same protocol of introducing the display to the subject was followed. In addition the subject was asked to play two rounds of boggle using the web interface found on http://weboggle.shackworks.com/4x4/. The objective of this game is to score more points than the opponents by discovering words from the letters presented. Based on the subjects' placing among the players of the game, they were asked to place ± 5 spots from their average in the first two games to introduce competition. Each game of boggle lasted three minutes with a thirty second break between the games. No signals were given during the thirty second break.

3.2 Method

The goal of this experiment was also to measure the accuracy of vibrotactile pattern recognition while performing a task that required attention and thought. More specifically, the experiment looked at the accuracy with which subjects could identify patterns while they were engaged in a cognitive task requiring concentration.

3.2.1 Subjects

The second experiment was performed on a second set of eight subjects, none of whom participated in the first experiment, all students attended the Massachusetts Institute of Technology and were between the ages of nineteen and twenty-two years old. Five men and three women participated in this experiment.

3.2.2 Stimuli

The stimuli used in Experiment 1 (as seen in Figure 3) were also used in this experiment.

3.2.3 Procedure

The introduction to this experiment was identical to that of Experiment 1. The same training protocol was followed: the subjects were shown the diagram and introduced to the signals. Then the subjects were asked to play a round of boggle and the signals were presented again. After the trial period, the subjects were asked to play boggle while three trials of eight stimuli were given. The subjects were permitted to respond to the signal by either reciting the signal name or giving the appropriate arm signal. These responses and the subjects' placing in the game were recorded by the experimenter.

3.2.4 Results

The overall mean correct response rate was 93% with a range of 83% to 100% while subjects were playing boggle. The results are shown in Table 3. Patterns B, D, and E were all perceived with 100% accuracy. In this experiment, patterns A and C had the lowest response rates with an average of 83% correct.

Table 3: Mean Subject Response during Experiment 2. The percentages of correctly identified patterns are highlighted.

	Subject Response								
Actual Pattern	A	B	C	D	E	F	G	H	Unsure
A	83%	0%	4%	0%	0%	8%	0%	0%	4%
B	0%	100%	0%	0%	0%	0%	0%	0%	0%
C	0%	0%	83%	0%	0%	0%	17%	0%	0%
D	0%	0%	0%	100%	0%	0%	0%	0%	0%
E	0%	0%	0%	0%	100%	0%	0%	0%	0%
F	4%	0%	0%	0%	0%	92%	0%	0%	4%
G	0%	0%	0%	0%	4%	0%	92%	0%	4%
H	8%	0%	0%	0%	0%	0%	0%	92%	0%

A comparison of the results obtained in the two experiments indicates that there was little difference in the ability of subjects to identify the signals as a function of the nature of the concurrent activity. In Figure 4, the correct response rates for the three tasks are displayed. Overall, patterns B, D, and G were identified correctly most of the time. Patterns A, C and F were identified poorest throughout the three experiments. Pattern C was confused with pattern G. All those who incorrectly identified pattern A confused this signal for pattern F. Pattern F is the most confusing of the signals as it was only correctly identified 78% of the time while walking and even less frequently (74%) while participating in more strenuous physical activity. Pattern F is a somewhat ambiguous signal as the tactors are not activated in a simple pattern such as from left to right or up to down. The motors are activated on the outer edges and then the middle four are activated. If all of the tactors are not felt subjects could easily misidentify the signal.

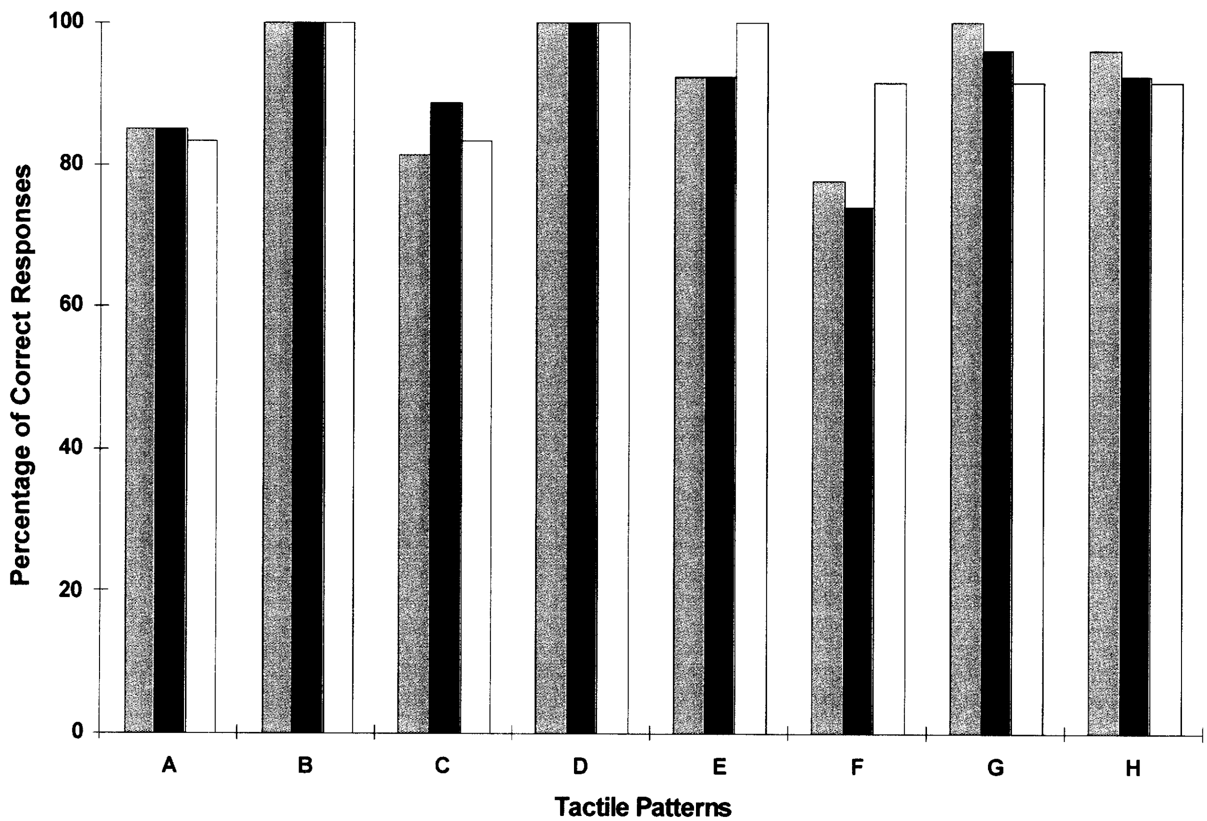

Figure 4: Comparison of the number of correctly identified signals (27 possible) while walking (blue) and while jogging (red) and of the correctly identified signals (24 possible) while playing boggle (cream).

4. Discussion

Tactile displays should be identified with 90% accuracy rate if they are to be useful as navigation aids. Five of the patterns met this criterion while walking and jogging, and six of the patterns reached 90% correct response rate while subjects played a computer game. Throughout the two experiments, patterns B and D were identified with perfect accuracy. Patterns E and G met the 90% cutoff rate with each of three distractions and each were perfectly identified under one condition. Three of the eight patterns were harder to distinguish. Patterns A and C were misidentified the most frequently throughout the three experiments, and were identified with an average response rate of 80%. While performing a physical activity, pattern F was the least accurately recognized with an average response rate below 80%. When the subjects were asked to concentrate on a game, pattern F was perceived with an accuracy rate of 92%.

The responses for each pattern help to identify easily distinguishable signals. Patterns F and C were confused because they both involved activating the tactors from left to right and were repeated twice and differed in the middle part of the pattern. Pattern C, which alternates between the four motors on the left side of the vest and the four on the right, was also misidentified as signal F. It is unclear as to whether these motors were not felt as a result of inattention or inability to distinguish the number of motors concurrently active. It is also unclear as to whether 2, 3, or 4 motors active can be differentiated contributing to the possible confusion between patterns G and C as well as between C and F.

The difficulty in identifying pattern F was common to both conditions in the experiment involving physical activity. When the subjects were asked to complete the computer task, this pattern was correctly perceived 92% of the time. This is a significant increase above the 78% and 74% accuracy rates achieved while walking and jogging, respectively. Patterns may be more difficult to identify when moving as the display could change its position on the back, particularly when jogging. The waistband was designed to be comfortable and to be flexible enough to conform to the body of the user. Therefore while moving quickly it is possible that subjects could temporarily lose the ability to detect one or two motors (or sets of motors). In some cases, the subjects mentioned that they were unaware of the starting point of the pattern and often missed the first two sets of signals. For example, with pattern C, subjects mentioned that they did not detect vibrations until the third and fourth set of tactors were activated, thereby only feeling two sets making it difficult to identify the pattern. Future experiments could test if a warning cue improves the accuracy rates by alerting subjects that a signal is about to be presented. By providing a hint before the signal, the user would be able to allocate attention to perceiving the information and possibly interpret the signal better.

Jones et al. (2007) were able to achieve near perfect performance when subjects used a visual representation of the signals to identify the tactile pattern. In one experiment a 98% correct response rate was achieved and in the other 96%. The results obtained are similar in that five of the patterns achieved this success rate. However, the subjects were asked to recall the commands via memory, making their task harder from the start. The additional task of either physical activity or playing a game increases the difficulty of identifying signals and yet five of the eight patterns were correctly identified at least 90% of the time.

Overall, the results from these experiments show that this tactile display can successfully transmit information to a user while he or she participates in other activities. Specific patterns appear to be harder to identify than others which suggests that these may need to be modified to increase the identification rate.

5. Possible Design Enhancements

This vest was designed with specific design criteria in mind. These criteria include lightweight, robust, comfortable and functional. Currently, this device meets the criteria with the exception of robustness. With the current design, the motors are left exposed to the environment on the back of the vest and are therefore subject to damage. These tactors are covered in plastic but the wires to connect to the WTCU are left open and vulnerable. The wires could be cut or detached in this current configuration which would render the vest useless. The motors and wires need to be protected. One suggestion would be to overlay an additional piece of fabric across the motors and wires sewn in to protect them. This would provide extra support, but would make accessibility to the motors difficult. Accessing the tactors is important to check on the functionality of the system and troubleshoot device operational issues. If a motor is not working properly, someone would need to get to that tactor without disrupting the system and with relative ease. An approach that is similar to sewing the fabric overlay would be to attach the overlay with Velcro, similar to the way that the motors are attached. This would allow for motor access in the event that troubleshooting errors.

While these modifications can successfully accomplish the accessibility goal there are better ways to increase robustness.

A different approach to covering the motors and increase robustness would be to add a plastic slide over the back of the display. By placing runners on the vest and sliding a plastic piece in, the motors will be covered by a sturdy cover. In addition, a slide and runner system would allow for easy access. This design achieves two of the main functional requirements; however, the slide may reduce the comfort level. An additional piece of the waistband material may be placed on the outside of the runners and slide so that the plastic is not uncomfortable on the back of the user. These additional pieces will increase the weight of the device itself, but it will remain considerably lightweight if the material chosen is light.

Another aspect of the design that can be improved is the attachment of the WTCU and battery to the vest. Currently, a small pouch is placed on the back of the user which holds both the battery and WTCU. The pouch is sewn to the vest to keep the two attached. It would be more efficient to have housing for the WTCU and battery on the vest itself making it one collective piece and not two separate pieces. This housing could potentially be placed on the back of the vest, but it would have similar placement as in the current design. If the housing was placed on the front of the vest, this would be highly visible and could potentially be in the way of other equipment. A better place for housing may be vertically along the side of the body. By aligning the WTCU and battery with the side of the chest, they will not protrude from the body or interfere with other devices. The housing should not add much to the weight of the system.

6. Conclusion

Based on the results from both experiments, it becomes evident that users of the tactile display can successfully receive information while participating in other activities. As the subjects were asked to walk, they successfully identified 92% of the patterns, and while jogging, subjects had a success rate of 91%. As the subjects played the computer game, they were able to successfully identify 93% of the signals. It has been said to be successful to aid navigation a correct response rate of at least 90% is needed, and subjects reached this goal while walking, jogging and playing a computer game individually.

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