Towards Effective Information Display Using Vibrotactile Apparent Motion

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Abstract

In this paper, we explore the use of tactile apparent motion at different speeds for information display. A prototype vibrotactile tactor array was constructed, consisting of three rings of five voice-coil tactors each, and mounted on the upper arm of test subjects. The results of two experiments are presented: a study on the sensitivity to differences in apparent motion speed, and a study on users' ability to differentiate four motion patterns at three different speeds. Users had little trouble with pattern identification, but found absolute speed recognition difficult. Several ideas for future exploration of tactile apparent motion for general-purpose information displays are presented.

CR Categories: H.5.2 [User Interfaces]: Haptic I/O; H.1.2 [User/Machine Systems]: Human factors; I.3.6 [Methodology and Techniques]: Interaction techniques.

Keywords: haptics, vibrotactile, information display, apparent motion

1 Introduction

In many situations in life, we must receive information without distracting or notifying those around us. Sometimes this information is of an urgent nature. This is particularly true in certain kinds of occupations. For example, factory workers who work in loud settings where their hearing is impaired, and to whom providing emergency information often requires visual attention, could use cutaneous displays to alert them of incoming messages. Military personnel and firefighters may be placed into environments where both vision and hearing are impaired due to loud or smoky conditions. In a hospital environment, the everyday activity of administering medication to patients has been cited as a major cause for medical accidents [13]. If a nurse is about to erroneously give (or has already given) a patient a drug that would interact with another drug the patient has taken, the nurse needs to be informed immediately. However, it is undesirable to inform the patient, as this would increase the risk of complications arising from panic. Informing the nurse via a visual display may be less than ideal because it requires that the nurse's visual attention be divided between the display and the patient.

In all of these cases, we want to provide relevant and often urgent information, but it is not always possible through traditional means [17]. The skin surface provides a large area for displaying information to a user, but remains underutilized for human-computer interaction [1, 3]. Until recently, tactile feedback technology had not been sophisticated enough to allow adequate exploration of this domain, but technological advances have made the cutaneous sense feasible as a medium for information display.

2 Background

There are several ways to provide tactile feedback. In this work, we are primarily concerned with using vibrotactile cues, which employ vibration for displaying information to users. Research has shown that a variety of interesting sensations can be provided through vibrotactile feedback. Many commercial game systems already use vibration to give users the sense that a collision has occurred, or to give a feel for other game attributes. However, several questions remain regarding the effectiveness of using vibrotactile feedback for information display. The set of useful parameters for vibration is still very much an open research area.

Vibrotactile feedback is not a new area of research, however. Several decades ago, Geldard discussed using the skin as a display surface by varying several vibrotactile parameters, including intensity, duration, frequency, locus, and waveform [4].

There has been a recent push to explore the parameter space of vibrotactile feedback further. There are a number of parameters that can be used to vary the characteristics of a vibrotactile stimulus [8]. For a single tactor, these include *frequency*, *amplitude*, *temporal delay*, and *pulse patterns*. For groups of tactors, both regularly-spaced [10, 14] and non-regularly-spaced layouts [9, 19], *tactile movement patterns*, *body location*, and *interpolation method* can be identified. MacLean & Enriquez [11] introduced the notion of haptic icons (*hapticons*) and performed empirical analysis of the design space of these vibration characteristics. Using a haptic knob held by the thumb and index finger, they found that frequency and *stimulus shape* (*i.e.*, sinusoid, square, sawtooth) were the most orthogonal properties. Frequencies in the range of 3-25 Hz provided the best distinguishability, and a sinusoidal waveform was found to be easily distinguishable from waveforms with discontinuities, such

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as square or sawtooth waveforms, at least at low frequencies. Brewster & Brown [1] explored the notion of tactile icons (*tactons*), structured, abstract messages that can be used to communicate information non-visually. Similar to previous work, they outlined the possible parameters for distinguishing tactons, adding *rhythm* to those previously listed. They define more-complex tactons consisting of compositions of simple stimuli, as well as hierarchical structures that vary different signal parameters of a common tacton to differentiate, for example, an underflow error from an overflow error; both are errors, so they share a common portion of the tacton, but have a unique portion as well. They outline some interesting possible approaches for off-loading the visual channel, such as using motion around an array of tactors around the waist to display a "progress bar" for such tasks as downloading files.

We can draw a differentiation between the *aspect* that a given parameter is used for. We identify at least two aspects to the information we are displaying: *kind* and *value*. Kind refers to the type of information (*e.g.*, message from work, message from home), and value refers to some quantitative measure (*e.g.*, importance). Our current system attempts to combine these two aspects of displaying information using vibrotactile cues.

3 Apparent Motion

One attribute of vibrotactile cues that could be used to allow users to better disambiguate stimuli is the *sense of movement* produced across a field of tactors. By way of illustration, and borrowing from the visual domain, moving pictures and television are made up of a set of *discrete images* showing a *scene* that *changes over time*. Apparent motion is produced when, for example, the position of an object within a sequence of frames, displayed at sufficient speed, changes such that the visual-brain system determines that the object is moving. If the sequence is played back too slowly, then the illusion breaks down, and we perceive the object as occupying discrete positions instead of moving.

Apparent motion in the cutaneous domain follows the same principle. If a vibrotactile stimulus can be displayed to a sequence of tactors with the correct speed characteristics, the user perceives the stimulus moving across the field. Though the vibrational signal is not actually moving on the surface of the skin, the perception felt by the user is that of motion. Regardless of the stimulus domain, apparent motion gives the illusion of a *continuous* signal using a *discrete* signal.

What this work is attempting to better understand are the characteristics of the discrete signal in the haptic domain that are necessary for subjects to perceive motion. To return to the visual domain, it is generally agreed that 30 frames-per-second is sufficient for humans to perceive motion in pictures. What are the equivalent parameters for the haptic domain? An additional question is how well users can differentiate between various *speeds* of apparent motion in the haptic domain. Homing in on the answers to these questions will allow us to design more effective information displays using the haptic channel.

The two main parameters that describe signals used to elicit apparent motion are the duration of stimulus (DOS) and the stimulus onset asynchrony (SOA) (*a.k.a.* the interstimulus onset interval or ISOI [7, 15]). Looking at three tactors mounted in a line, we can illustrate these two parameters (Figure 1).

The DOS is simply the amount of time a tactor is in the ON state. The SOA is the time difference between one tactor turning ON and the next tactor in the sequence turning ON. If the SOA is 0, then all tactors are ON at the same time. If the SOA is equal to the DOS, then one tactor is turned OFF at the same time the next tactor is turned ON. If the SOA is greater than the DOS, then there is some delay between one tactor turning OFF, and the next tactor turning ON. It is therefore crucial to choose the proper values for these two parameters in order to create the illusion of apparent motion. Our current focus is on selecting values for these that allow us to define expressive vibrotactile cues that are unambiguous.

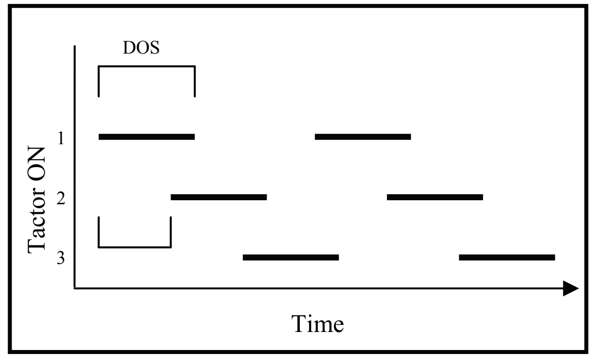

Figure 1: The duration of stimulus (DOS) and stimulus onset asynchrony (SOA)

4 Our Approach

Previous work has found that it is possible to display apparent motion using cutaneous stimuli [7, 12, 15, 16, 18]. Here we explore the use of sequences of tactors deployed in rings around the upper arm as an information display. The high-level attributes of apparent motion we compare are the *direction* and *speed* of the motion. We foresee the direction of the motion as a differentiator of one type of information from another (*e.g.*, a message from home versus a message from work), and the speed to denote the urgency of the message.

We have chosen to concentrate on the upper-arm as the location of stimulus, as we would like the display to be as unobtrusive as possible. The current prototype can be mounted so that it is concealed under the short sleeve of a shirt. Also, mounting the apparatus on this area of the body will not encumber a worker's typical motions. Other groups have also suggested this location as a candidate site for wearable displays [6].

4.1 Hardware

In this work, vibrotactile stimuli were presented using 15 voice-coil-type tactors (model MMA-33 by NEC Tokin Corp., Figure 2, left). These tactors were chosen for their low-latency response time, and are controlled by custom hardware. A waveform generator provides a signal to drive the tactors, and a bank of analog switches controls whether each tactor is ON or OFF. The analog switches and timing are controlled via a PIC16F876 microcontroller (Microchip Inc.). Commands are sent to the microcontroller from a PC using an ASCII protocol over an RS-232 connection.

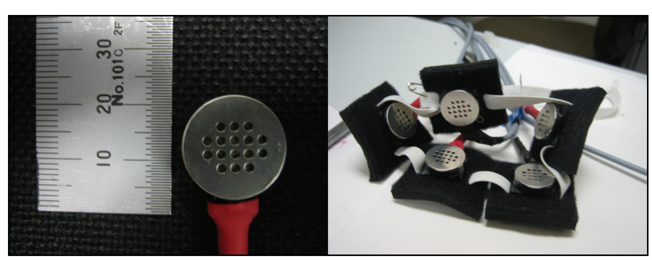

Figure 2: Left, voice-coil tactor; right, five-tactor ring

Initially, a ring of five tactors was constructed and placed around the upper arm (Figure 2, right). Each tactor was attached to a small Velcro pad using adhesive-backed Velcro, and each pad was connected using a strip of elastic. This configuration allows the distance between tactors to be easily adjusted to accommodate different arm sizes. A ring topology also allows the apparent motion of a cycle around the arm to be created.

5 PILOT STUDY

Before running any experiments, it was necessary to determine an approximate range of SOA values that would result in a sense of apparent motion. Several studies on tactile apparent motion have related SOA to this sensation [7, 12], so there is a solid basis for comparison. However, we needed to ensure that we chose a good set of values for our particular tactor configuration. In an informal pilot study, using the five-tactor ring placed on the upper arm, we delivered stimuli with various DOS/SOA combinations, and collected subject responses as to whether they perceived the stimulus as a continuous cycle, discrete activations, or simultaneous activations. Based on their responses, we selected values for a slow, a medium, and a fast apparent motion (Table 1).

Table 1: Apparent motion SOA ranges

DOS	Low SOA (fast)	Medium SOA (medium)	High SOA (slow)
100ms	30ms	110ms	190ms
200ms	100ms	220ms	340ms
400ms	200ms	320ms	440ms

6 EXPERIMENT 1: SPEED DISCRIMINABILITY

Given ranges within which to explore more deeply, we investigated users' sensitivity to speed differences of apparent motion in our system. We were interested in determining the just-noticeable difference (JND) of changes to the SOA. The five-tactor ring was once again used for this experiment, and white noise was played through headphones to mask tactor noise.

The ranges of SOAs given in Table 1 were evenly divided to give nine SOA values for each DOS value. This allowed fine-grained comparisons across the range of apparent motion (Table 2).

Table 2: DOS & SOA combinations in ms (boldface SOAs = reference SOAs)

DOS	SOAs used
100	30, 50, 70, 90, **110**, 130, 150, 170, 190
200	100, 130, 160, 190, **220**, 250, 280, 310, 340
400	200, 230, 260, 290, **320**, 350, 380, 410, 440

6.1 Procedure

Four people, ages 20-23, participated in this study (2 males, 2 females). All participants were students at Osaka Institute of Technology and were paid ¥3000 (US$30) for their participation.

The experiment followed a 2-alternative, forced choice design (2-AFC) using the method of constant stimuli and proceeded in two phases: training, and trials. During the training phase, we explained to participants that they would sequentially be presented two signals on their arm, and that they would need to select which felt faster: first or second. Participants were then given five sample trials to get a sense of what the task was and how to use the graphical interface. In each trial, the stimuli consisted of a cycle at some SOA_1 for three seconds, followed by a pause of 1.5 seconds, and finally a cycle at some SOA_2 for three seconds. In every case, SOA_1, SOA_2, or both were the reference stimulus for the selected DOS. As each cycle was presented, participants were also given a visual indication of whether they were feeling the first signal or the second signal.

After the training session, participants began the trial phase. Over the course of the experiment, each participant performed 270 trials: 10 trials for every DOS/SOA combination, five of which presented the reference stimulus first, and five of which presented it second. Each participant received the same randomized trial order. Because of the repetitive nature of the task, the trial phase was divided into three sessions of 90 trials each. Participants were allowed to rest for 30 minutes between sessions. The experiment took approximately two hours to complete per participant. Data was collected on how many times participants chose the reference stimulus as being faster.

6.2 Results

Figure 3, Figure 4, and Figure 5 show the mean percentage of times participants chose the reference stimulus instead of the test stimulus. Functions were also fit to the data for the purposes of JND computation. We fit logistic sigmoid curves to the data for the 100ms and 200ms DOS conditions. In the case of 400ms DOS, a linear function was a better fit for the data. This may be because a wide enough range of values was not tested, or the stimuli were too short in duration because such large SOA values only allowed 1-2 cycles to complete.

JND values were determined using psychometric functions fitted to mean subject data. We compute the JND as $(SOA_{75\%} - SOA_{25\%}) / 2$; Table 3 shows the computed JND values. It should be emphasized that this was a preliminary experiment used to guide the design of the second experiment. More participants and trials are needed to arrive at more precise values for the JND. In more rigorous future studies, it may be useful to compute the JND by averaging the JNDs determined from each individual participant's psychometric function.

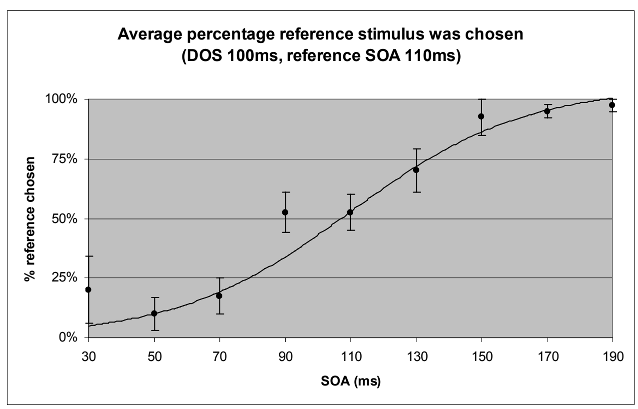

Figure 3: Plot of user responses for DOS = 100ms and reference SOA = 110ms (error bars represent standard error of the mean)

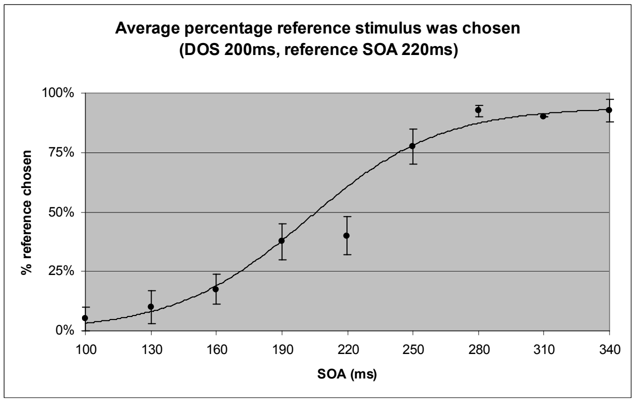

Figure 4: Plot of user responses for DOS = 200ms and reference SOA = 220ms (error bars represent standard error of the mean)

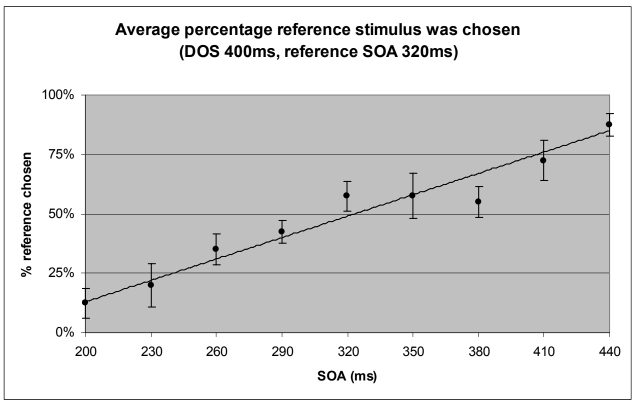

Figure 5: Plot of user responses for DOS = 400ms and reference SOA = 320ms (error bars represent standard error of the mean)

Table 3: Computed JND for reference stimuli

DOS	Reference Stimulus SOA	JND
100ms	110ms	~27ms
200ms	220ms	~36ms
400ms	320ms	~83ms

7 Experiment 2: Signal Identification

When we began, our primary goal was to evaluate whether the speed of tactile apparent motion, as well as movement patterns, would be valuable parameters for an information display. In designing an information display, it is important to devise signals that are distinct enough that users can differentiate them. The speed of these signals might be particularly useful for evaluating the intensity or priority of incoming information. In this experiment, we tested users' ability to distinguish between signals created by varying two parameters: apparent motion *pattern*, and apparent motion *speed*.

Ten people participated in this study (8 males, 2 females, 1 left-handed). All participants were volunteers and were ATR employees between the ages of 20 and 31.

7.1 Equipment

Because we wanted to incorporate a vertical motion in this experiment, we constructed two more rings like the one used in Experiment 1. Three rings were placed around the upper arm, creating an array of 15 tactors with which to present signals (Figure 6).

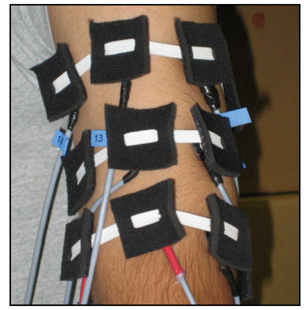

Figure 6: The three-ring, 15-tactor array

7.2 Design

Previous research [7, 12, 15, 16] has shown that tactile apparent motion is a strong cue and that users are fairly good at identifying different motion patterns. Four patterns were chosen: counter-clockwise (CCW), clockwise (CW), down (DOWN), and up (UP). The CCW and CW patterns went around the arm continuously. The UP and DOWN patterns had a 400ms pause in between successive repetitions (three tactors would be activated in sequence, followed by a 400ms pause, and then the sequence would repeat). In pilot tests, these motion patterns were found to be relatively easy to identify with our system. We view the pattern parameter as addressing the *kind* aspect of information display described in the introduction.

To address the *value* aspect, we use the speed of the motion. The results from Experiment 1 give some idea of how well users can distinguish signals of different speeds from one another. However, in general, absolute identification is far more difficult than relative identification (*e.g.*, intensity, frequency, *etc.*) [2, 4]. Accordingly, three different SOA values were chosen that were likely to be different enough for users to identify. The reason for the choice of a 100ms DOS is that the range of valid SOAs is lower than the range for the other DOS values, thus allowing us to create signals that complete in less time and provide information more quickly. The three chosen SOA values were 64ms (FAST), 110ms (MEDIUM), and 190ms (SLOW). The 110ms SOA was selected for the MEDIUM speed because it was the reference stimulus in Experiment 1. In order to get maximum variability between our signals, 190ms SOA was selected for the SLOW speed. We initially intended to choose 30ms SOA for the FAST speed, but pilot tests indicated that while it was clear that some motion was occurring, allowing speed judgments, it was very difficult to determine which direction a cycle was moving (perhaps due to temporal aliasing), making pattern judgments difficult. We therefore increased the FAST SOA until we were reasonably confident about signal directions, and settled on 64ms. Thus, 12 different signals were implemented, resulting in the 3x4 matrix of treatments shown in Table 4.

One additional exploratory variable was also included: *stimulus width*, which could be either ONE_LINE or ALL_LINES. In ONE_LINE, signals consisted of either one horizontal ring of five tactors around the arm (in the CCW and CW cases) or one vertical line of three tactors along the arm (in the DOWN and UP cases). In ALL_LINES, all three horizontal rings were used for

CCW and CW, and all five vertical lines were used for DOWN and UP. This condition was included to evaluate if signals were more identifiable if they were more emphasized, and to determine if users had a preference for one or the other.

Table 4: 3x4 design

	CCW	CW	DOWN	UP
FAST	CCW+ FAST	CW+ FAST	DOWN+ FAST	UP+ FAST
MED.	CCW+ MED	CW+ MED	DOWN+ MED	UP+ MED
SLOW	CCW+ SLOW	CW+ SLOW	DOWN+ SLOW	UP+ SLOW

7.3 Procedure

Experiment 2 also had both a training phase and a trial phase. The training phase consisted of a free training mode, and a training test mode. In free training, participants were shown two sets of radio buttons: one set for pattern, and one set for speed (Figure 7).

Our system presented the selected signal combination when users chose a pattern and a speed. Participants were instructed to try all combinations until they felt comfortable with the signals and felt confident that they could tell them apart. After free training, participants were given a training test, consisting of 24 trials (each of the 12 treatments was presented twice, in random order). In each trial, participants were presented with some signal for three seconds, and they then had to select which pattern and speed they thought they felt. If the selection was incorrect, participants were told to try again and were presented with the same signal again.

Once training had been completed, participants began the trial phase. Each trial was as described for the training test, except participants were not informed whether they were correct or incorrect. The trial phase consisted of 60 trials in randomized order (five trials of each pattern/speed combination). Data was collected on which choices were made.

The training and trial phases were done once for the ONE_LINE condition, and once for the ALL_LINES condition. Since the stimulus width variable was not of primary interest, these trials were not intermixed. However, the ordering of each set of trials was counterbalanced between participants. After the experiment, we asked participants via an open-ended discussion if they had any comments or suggestions about the system.

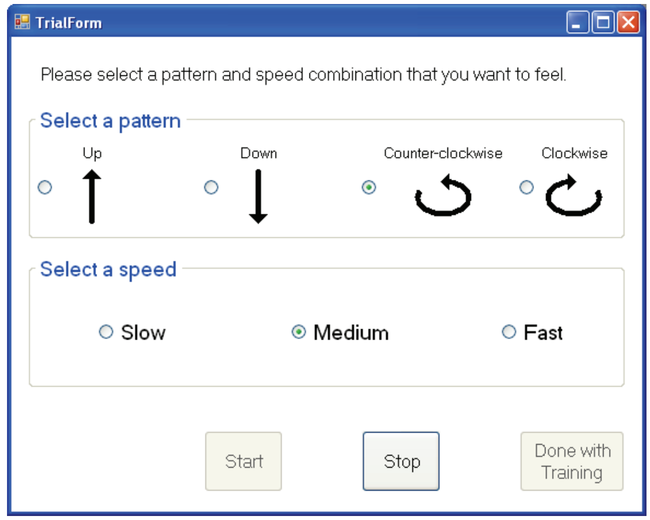

Figure 7: The user interface for free training

7.4 Results

Figure 8 shows the mean identification rate for all users and signals in the ONE_LINE condition. The minimum mean identification rate was 72%, for the DOWN+FAST and UP+MEDIUM treatments. The maximum was 100% for the DOWN+SLOW treatment. In order to understand what could cause the errors in identification, we looked at the data in terms of the mean identification rate of just the pattern across all treatments (Figure 9), and the mean identification rate of just the speed (Figure 10).

Pattern identification was very high across all treatments: 94% for DOWN+MEDIUM, 98% for DOWN+FAST and CW+MEDIUM, and 100% for all others. This implies that participants had little trouble identifying patterns correctly.

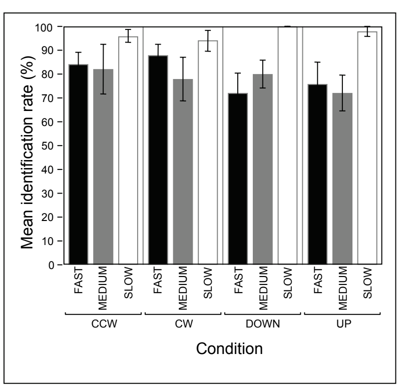

Figure 8: Mean identification rate of pattern & speed across all subjects (ONE_LINE condition)

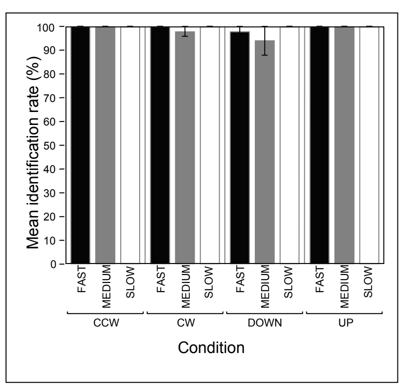

Figure 9: Mean identification rate of pattern across all subjects (ONE_LINE condition)

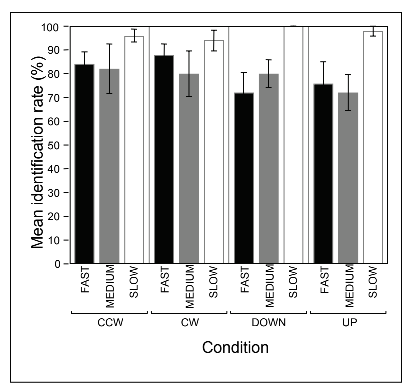

Figure 10: Mean identification rate of speed across all subjects (ONE_LINE condition)

Speed identification rates, on the other hand, were not as high or consistent. The minimum mean identification rate was 72%, in the DOWN+FAST and UP+MEDIUM treatments. The maximum mean identification rate was 100.0%, in the DOWN+SLOW treatment. Across all patterns, participants correctly identified SLOW patterns more consistently than patterns at other speeds. Table 5 categorizes the errors that participants made in speed identification.

The table's main diagonal values show the percentage of times participants chose the correct speed across all patterns. The remaining table cells show participant errors. In the case of SLOW, there was little error. The vast majority of errors, shown in the grey cells, were between the FAST and MEDIUM speeds. This mirrors several participants' comments that they had difficulty distinguishing the FAST and MEDIUM speeds. The results for the ALL_LINES condition were very similar, so they have not been included here.

Table 5: Mean percentages of chosen speeds (ONE_LINE condition)

		User-chosen Speed		
		FAST	MEDIUM	SLOW
Actual Speed	FAST	80%	20%	0%
	MEDIUM	21%	78.5%	0.5%
	SLOW	0%	3%	97%

8 Discussion

The results of Experiment 2 are encouraging. Overall signal identification rates were high. However, speeds were more difficult to identify than patterns. We believe that the primary reason for this difficulty is that our selected SOAs for MEDIUM and FAST are too close to one another. We chose SOA values for SLOW and FAST that were far enough away to be distinguishable from the MEDIUM SOA as per our results from Experiment 1, but shifting the MEDIUM SOA closer to the SLOW SOA may yield better results in an absolute identification scenario.

Another possible reason for any difficulties in identification is that participants may not have undergone enough training. For example, three participants made five or fewer identification errors for the entire signal in the ONE_LINE condition, while two participants made greater than 15 identification errors. Repeated training may improve these results.

The data seem to indicate that participants had some difficulty identifying the speed of signals in the DOWN and UP conditions. In our particular system setup, three sites may not be enough to establish a sense of linear speed. Using the sensory saltation effect (where multiple pulses are delivered to each tactor site successively, leading to the illusion that the pulses are equally distributed in space between the first and last tactor sites) may improve the identification rate of different DOWN and UP speeds [5, 16].

Post-experiment discussion with participants yielded some interesting thoughts and comments. One participant noted that it was easier to tell which direction a cycle was going when it first started, but after it became a continuous loop on the arm, it was more difficult to determine the direction. This may explain the reason why using an SOA of 30ms in pilot tests caused difficulties in determining cycle direction. It may be useful to also include a pause between successive CCW and CW cycles, as we did with the DOWN and UP patterns.

Several participants indicated that they felt more confident about their answers in the ALL_LINES condition instead of the ONE_LINE condition. The results do indicate a slight increase in identification rate, but further study will be required to determine if ALL_LINES is better. It may be valuable to investigate participants' reaction time to signals as a measure of performance.

One participant commented that in the ONE_LINE case, the DOWN and UP patterns seemed personal in nature, as if someone were moving a finger along the arm. This could be an interesting way to map stimulus width to different kinds of abstract information (*e.g.*, incoming personal message or business message).

9 Conclusions and Future Work

We have presented a study into users' sensitivity of tactile apparent motion speed. It is our hope that our results will provide a baseline for future work using speed as a parameter to tactile apparent motion displays. We have also conducted an evaluation of using tactile apparent motion patterns and speeds as parameters to signals in a tactile information display on the upper arm. Our results indicate that using different patterns of motion is a promising direction to follow, as participants' pattern identification rate was very high (94% - 100%). However, absolute speed was somewhat more difficult to identify (72% - 100%). In our current system, at least two speeds were easily distinguishable, and we feel that with further tuning of the parameters and with more training, three speeds would be identifiable.

One caution is that in this work, we did not map our signals to abstract concepts (such as an incoming personal call vs. an urgent call from work), as would be necessary in a true information display. Adding this layer of complexity will necessitate further training, and finding motion patterns and other signals that map well to abstract concepts is key.

There are several possible avenues of future research. Relative speed differentiation is easier than absolute speed identification. It may be possible to create a set of signals that sequentially present patterns of different speeds. We may also be able to create signals by ramping speeds up or down over time.

Another possibility is to have one ring on each arm. This would allow us to map signals to different sides of the body, and may make it easier to map spatial locations to abstract concepts. We could also use a difference in cycle direction on each arm as a signal. Informal tests indicate that this is feasible on two arms, but two cycles on the same arm going in opposite directions is a very difficult signal to identify.

With our current tactor array configuration, informal tests also indicate that it is possible to discriminate when one, two, or three cycles are being presented simultaneously. This may allow us to incorporate an additional way to encode emphasis or priority information. We may also be able to employ a more temporal encoding scheme which involves an alternating sequence of horizontal and vertical signals.

Acknowledgements

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