Determining Appropriate Parameters to Elicit Linear and Circular Apparent Motion Using Vibrotactile Cues

Masataka Niwa[1] Robert W. Lindeman[2] Yuichi Itoh[1] Fumio Kishino[1]

[1]Graduate School of Information Science and Technology, Osaka University
[2]Department of Computer Science, Worcester Polytechnic Institute

ABSTRACT

This paper reports on two experiments we conducted to look at how to design effective linear and circular apparent-motion displays. Using a two-tactor array on the upper arm, the first study found that a time interval of greater than 400ms before repeating the directional sequence is required for subjects to achieve 95 % proficiency of direction identification over a range of Duration of Stimulus (DOS) and Stimulus Onset Asynchrony (SOA) values. The second study looked at the number of tactors necessary in a circular tactor array on the upper arm for people to correctly identify the direction of the rotation. We found that subjects could achieve a proficiency approaching 100 % across a large range of DOS and SOA values with four tactors, using a circuit-completion time of 400ms or longer. These findings can be used by interface designers to realize information displays that either stand on their own, or work in combination with visual and/or audio displays.

KEYWORDS: Apparent motion, phantom sensation, vibrotactile, DOS, SOA.

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

1 INTRODUCTION

One can provide additional information to visual and audio displays using vibrotactile stimulation. Alternatively, vibrotactile stimulation can be used in situations where visual or audio displays are inappropriate. The use of vibrotactile stimulation is especially useful in conditions where the user is attending to other tasks or displays, as it stimulates the skin, which has a much larger stimulation field than the eyes or ears. Finally, vibrotactile stimulation is useful in situations where information should be displayed in a private manner, such as in public spaces.

With regard to vibrotactile displays, much research has been done in the area of sensory substitution, but often these devices are large in size, such as TVSS [1]. More recently, many consumer devices, such as mobile phones and video-game controllers, incorporate simple DC-motor-type vibration units (*tactors*) that are readily available, inexpensive to purchase, and relatively easy to control using straightforward circuitry. Because of these factors, there has been a resurgence of research into the use of vibrotactile stimulation. For example, Rupert [2] used a vest with tactors sewn into it to relay gravity information to pilots performing aerial maneuvers. Piateski & Jones [3] used tactor arrays on the arm and torso to aid users in navigation tasks. Brown *et al.* [4] used rhythmic patterns and changes in amplitude to explore the use of multiple vibration attributes to relay information to the fingertips.

Our own previous work [5] suggests that information displays using apparent motion could be a feasible approach for presenting multiple types of information through the manipulation of various apparent-motion parameters. Apparent motion is a phenomenon that a stimulus appears to move smoothly, even though the individual display units are discrete. Though there is space between each unit, by employing appropriate time intervals, the stimulus appears to be continuous. Examples of apparent motion in the visual domain are quite common. For example, old-style movie marquees used strings of lights that would blink using such a pattern that the light seemed to be moving along the length of the string. Road-construction sites, or curves on the highway, often use this same technique. Sherrick [6, 7] and Kirman [8] performed studies of apparent motion using vibrotactile stimulation on the skin, and showed that this phenomenon can elicit feelings of continuous motion.

In [9], Sherrick also reports that the feeling of apparent motion is controlled by two factors (Figure 1). The Duration of Stimulus (DOS) is the amount of time an individual tactor is vibrating. Stimulus-Onset Asynchrony (SOA) is the time difference between one tactor turning on and the next tactor in the sequence turning on. Using three rings of tactors mounted on the arm, we previously measured the ability of users to identify (1) the speed of apparent motion, and (2) individual patterns of apparent motion, including clock-wise/counter-clock-wise movement, and up/down movement from ring to ring [5].

Based on this research, the current study looks at determining the proper timing values (DOA, SOA, *etc.*) to produce linear apparent motion. In addition, we attempt to determine the sufficient number of tactors necessary to elicit circular apparent motion around the arm.

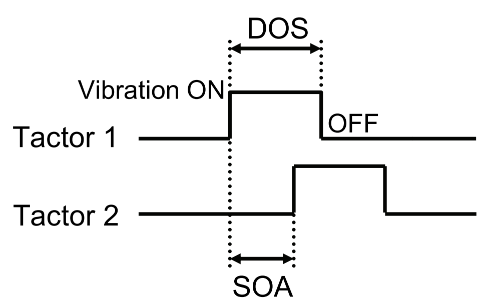

Figure 1: Duration of stimulus (DOS) and stimulus onset asynchrony (SOA).

[1] e-mail: {niwa.masataka, itoh, kishino}@ist.osaka-u.ac.jp
[2] e-mail: gogo@wpi.edu

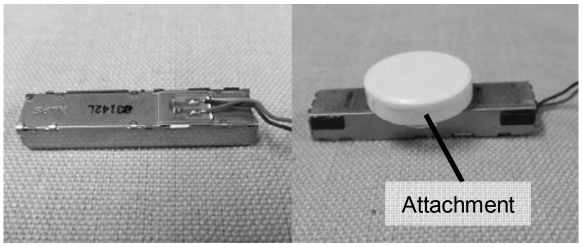

Figure 2: Tactor and attachment.

2 Tactors Used in Our Work

The current study uses the Force Reactor tactors (ALPS AF-Series, Type L) shown in Figure 2. These are the tactors found in the Rumble Pak of the Nintendo DS handheld game system. The technology is similar to voice-coil-type tactors, and provides a faster response time than DC-motor-type tactors. They provide a solid platform for studies of apparent motion where very fine-grained control of DOS and SOA is required. The vibration frequency of the Force Reactor tactors is in the range of 200-300Hz, which is the range of the underlying mechanoreceptors in the skin that sense vibration of this kind [10, 11]. In this experiment, we will use 300Hz as the vibration frequency.

As Figure 2 shows, this tactor has a long, thin form factor, which would produce a stimulus field on the skin that is long in one direction, and narrow in another. Therefore, we mount each tactor onto a rigid, ceramic disk (17mm diameter x 4mm height), similar in dimension to previous work [12], which used a voice-coil tactor (NEC/Tokin MMA-33). Using the disk makes a smaller, symmetric stimulus field.

3 Experiment 1: Continuous, Linear Motion Display

3.1 Objectives of Experiment 1

When multiple tactors are used in a linear array, and the tactors are triggered in order, apparent motion can be displayed. However, if the sequence is continuously repeated, and the time interval between successive sequences is too short, the stimulus can be felt to be moving back and forth (Figure 3). Therefore, this experiment attempts to identify the minimum time interval for users to perceive the motion as being linear in a single direction, as opposed to back and forth.

3.2 Method of Experimentation

As shown in Figure 4, the tactors were affixed on the upper arm using double-sided tape. A single tactor was placed on the front of the bicep 50mm from the "elbow crease." In addition, a second tactor was mounted 150mm from the elbow crease in line with the first tactor. Subjects were seated with their hands in their laps, and wore headphones playing white noise to block out any audio cues.

The stimuli were delivered to allow subjects to sense continuous apparent motion in one direction. Two stimulus sequences were used. Referring to Figure 4, movement in a DOWN direction was delivered using the sequence of Tactor A followed by Tactor B. For an UP motion, the sequence was Tactor B followed by Tactor A. To reduce the possibility that subjects would use the first tactor in the sequence to determine the direction, the tactor in a given sequence that was triggered first was varied. For example, even if the DOWN sequence was displayed, sometimes the sequence would begin with Tactor B. Because the sequence was repeated until the subject declared the direction, this approach seems valid.

Four pairs of DOS/SOA combinations (*i.e.*, movement speed of the stimulus point across the tactors) were used: 100/100, 200/200, 400/300, and 800/400msec. The DOS values have been shown to be good candidates for eliciting apparent motion [12]. In addition, the time interval between sequences varied over 11 levels: 0, 100, 200, ..., 1000msec.

Subjects were given a choice as to whether they felt the stimulus point was moving UP or DOWN. Ten subjects (nine male, one female) in age from 20-29 took part in the experiment. In summary, each subject experienced four DOS/SOA combinations, two directions, two different starting points, and eleven time intervals, giving a total of 176 combinations. Each subject received each combination four times, giving a total of 704 data points per subject. The combinations were displayed in random order.

3.3 Results and Analysis of Experiment 1

The results are shown in Figure 5. The horizontal axis shows the time interval, and the vertical axis is the percentage of correct answers, calculated from all the responses from all the subjects. Each plot shows a different DOS/SOA combination. As shown in the figure, among all DOS/SOA combinations, when the time interval is 0 msec, the percentage of correct answers is lowest. As the time interval increases, the percentage of correct answers also

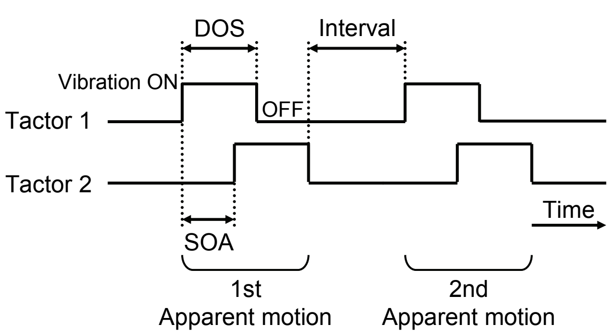

Figure 3: Time interval between sequences.

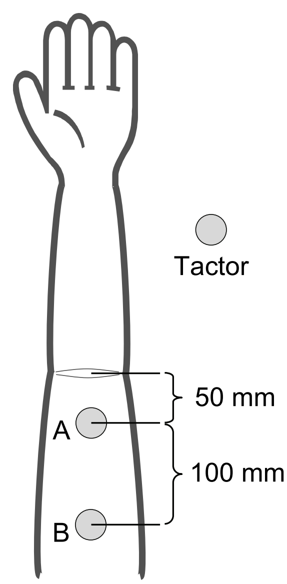

Figure 4: Tactor placement for Experiment 1.

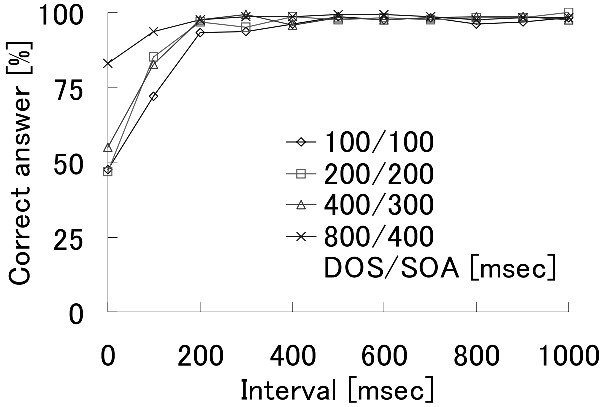

Figure 5: Correct-answer percentage of all subjects by stimulus.

increases. Furthermore, when the DOS/SOA are 800/400msec, a percentage of greater than 90 % was achieved for time intervals greater than 100msec. In the other three DOS/SOA combinations, greater than 90 % was achieved for time intervals greater than 200msec. A correct-answer percentage of greater than 95 % was achieved for time intervals greater than 400msec, regardless of DOS/SOA levels.

We also found very strong evidence that the starting point for the sequence has a dramatic influence on recognition rates. For example, in the DOWN cases, when the starting point was Tactor A, recognition rates for increasing DOS/SOA combinations were 73 %, 73 %, 88 %, and 96 % when the time interval was 0msec. When the time interval was 100msec, these rates jumped to 95 %, 95 %, 98 %, and 99 %, respectively. Comparing these values to the overall numbers shown in Figure 5, we can confirm that subjects used the sequence starting point to help determine the direction of the stimulus movement.

In summary, when one provides continuous, linear stimulus in a single direction, people should be able to correctly identify the apparent motion direction more than 95 % of the time with a time interval greater than 400msec. When subjects correctly sense the initial stimulus point of the sequence, they can achieve similar results with even shorter time intervals.

4 EXPERIMENT 2: NUMBER OF TACTORS REQUIRED FOR CIRCULAR MOTION DISPLAY

4.1 Objectives of Experiment 2

In order to display circular apparent motion around the upper arm, tactors can be deployed in a ring around the arm. However, space on the upper-arm is limited, and placing many tactors on the upper arm makes the system more cumbersome. Ideally, we would like to use as few tactors as possible, while still retaining high correct-identification rates. Therefore, this experiment aims to determine the appropriate number of tactors needed to support effective circular apparent motion perception.

4.2 Method of Experimentation

As shown in Figure 6, a ring of tactors was placed around the bicep 150mm from the elbow crease. The ring consisted of 3, 4, or 5 equally spaced tactors. Subjects were seated with their hands in their laps, and wore headphones playing white noise to block out any audio cues.

Each sequence was repeated five times (*i.e.*, five loops around the ring) for each trial. The speed of the stimulus movement varied based on two factors: SOA and the number of tactors. Eight

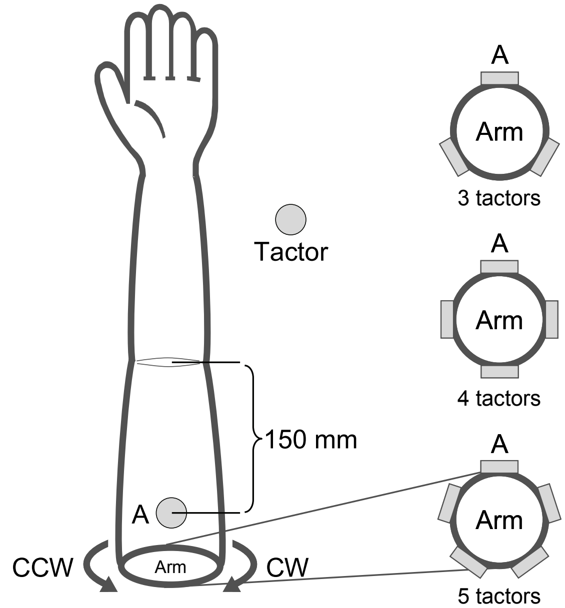

Figure 6: Tactor placement for Experiment 2.

Table 1: Combinations of DOS and SOA for Experiment 2.
(Circuit-Completion Time = SOA × Number of Tactors)

Number of Tactors	Circuit-Completion Time (msec/r)							
	100	200	300	400	500	600	800	1000
3	50/ 30	50/ 70	100/ 100	100/ 130	100/ 170	200/ 200	200/ 270	400/ 330
4	50/ 20	50/ 50	100/ 70	100/ 100	100/ 120	100/ 150	200/ 200	200/ 250
5	50/ 20	50/ 40	100/ 60	100/ 80	100/ 100	100/ 120	200/ 160	200/ 200

DOS/SOA [msec]

different circuit-completion times were used. In order to properly compare results from different numbers of tactors, the time for one circuit around the ring can be computed as SOA * number of tactors. As shown in Table 1, the stimulus was provided by combining DOS and SOA. If the time of one circuit was not evenly divisible by the number of tactors, the SOA was adjusted to get as close as possible to the target circuit-completion time.

Subjects had to answer with either CLOCKWISE or COUNTER-CLOCKWISE following each trial. Ten male subjects in age from 20-29 took part in the experiment. In summary, each subject experienced eight different circuit-completion times and two directions, with 5 repetitions, giving 80 combinations, which were displayed in random order. Also, each subject performed the experiment with a 3-, 4-, and 5-tactor rings.

4.3 Results and Analysis of Experiment 2

The results are shown in Figure 7. The horizontal axis shows the circuit-completion time, and the vertical axis shows the percentage of correct answers. Each plot shows the number of tactors in the ring. As the figure shows, using the fastest circuit-completion time (100 msec/r), regardless of the number of tactors, the percentage of correct answers is about 50 %, meaning the

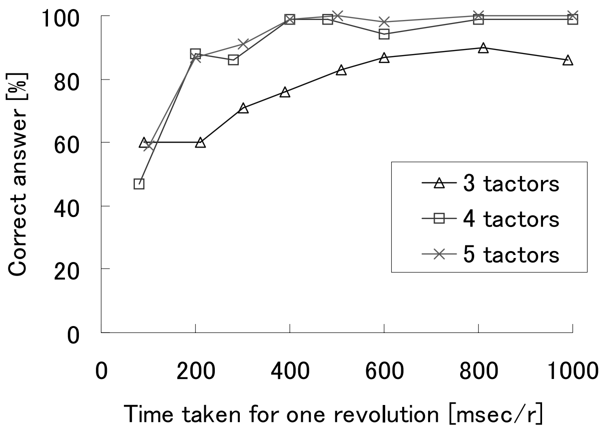

Figure 7: Correct-answer percentage of all subjects by number of tactors.

answers were basically random guessing. Based on these numbers, we can conclude that this speed is below the threshold of what humans can use for direction recognition.

When the number of tactors is three, the correct-answer percentage is lower than when the number of tactors is four. Furthermore, when the number of tactors is greater than four, if the circuit-completion time is 400 msec or longer, subjects achieved close to a 100 % correct-answer percentage. In contrast, when the number of tactors is three, the best correct-answer percentage was 90 % across all circuit-completion times. Therefore, in order to display circular motion correctly, at least four tactors are necessary, and the time to complete one circuit needs to be 400 msec or longer.

Almost the same results were obtained using five tactors versus four. Some subjects commented after the experiment that when comparing three tactors versus four, it was easier to determine direction when there were four, but between four and five, there was not much difference. Based on these findings, in order to display circular motion on the upper arm, four tactors are sufficient, and the addition of one more tactor is probably not necessary.

5 CONCLUSION

These studies built on results obtained by ourselves and others on determining appropriate DOS and SOA values for vibrotactile stimuli. We determined the necessary time interval between stimulus sequences in order to correctly identify continuous linear apparent motion on the upper arm. The results show that a 400 msec or longer time interval leads to 95 % or better correct direction identification.

Next we attempted to determine the minimum sufficient number of tactors to correctly identify the direction of circular apparent motion on the upper arm. The results show that four or more tactors should be used, and the circuit-completion time should be 400 msec or longer.

These findings can be used by interface designers to realize information displays that either stand on their own, or work in combination with visual and/or audio displays. In addition, these findings can be used to deliver motion-following or navigation information for applications such as sports training [13]. In the future, we would like to investigate whether the same results are obtained from tactors placed on other parts of the body.

REFERENCES

[1] P. Bach-y-Rita, C.C. Collins, F.A. Saunders, B.W. White, L. Scadden. Vision substitution by tactile image projection. *Nature* 221, pages 963-964, 1969.

[2] A.H. Rupert. An instrumentation solution for reducing spatial disorientation mishaps. *IEEE Engineering in Medicine and Biology 2000*, pages 71-80, 2000.

[3] E. Piateski, L. Jones. Vibrotactile pattern recognition on the arm and torso. *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 90-95, 2005.

[4] L.M. Brown, S.A. Brewster, H.C. Purchase. A first investigation into the effectiveness of tactons. *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 167-176, 2005.

[5] L. Kohli, M. Niwa, H. Noma, K. Susami, K. Hosaka, Y. Yanagida, R.W. Lindeman, Y. Kume. Towards effective information display using vibrotactile apparent motion. *Proceedings of the 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 445-451, 2006.

[6] C.E. Sherrick, R. Rogers. Apparent haptic movement. *Perception & Psychophysics*, Vol. 1, pages 175-180, 1966.

[7] C.E. Sherrick. Bilateral apparent haptic movement. *Perception & Psychophysics*, Vol. 4, pages 159-160, 1968.

[8] J.H. Kirman. Tactile apparent movement: The effects of interstimulus onset interval and stimulus duration. *Perception & Psychophysics*, Vol. 15, No. 1, pages 1-6, 1974.

[9] C.E. Sherrick. Studies of apparent tactual movement. In D.R. Kenshalo (Ed.), *The Skin Senses*, pages 331-344. Springfield, IL: C.C. Thomas, 1968.

[10] C.E. Sherrick. Variables affecting sensitivity of the human skin to mechanical vibration. *Journal of Experimental Psychology*, 45, pages 273-282, 1953.

[11] G.D. Goff. Differential discrimination of frequency of cutaneous mechanical vibration. *Journal of Experimental Psychology*, 74, pages 294-299, 1976.

[12] M. Niwa, Y. Yanagida, H. Noma, K. Hosaka, Y. Kume. Vibrotactile apparent movement by DC motors and voice-coil tactors. *Proceedings of ICAT 2004*, pages 126-131, 2004.

[13] J. Kume, M. Konuki. Sports training using vibrotactile stimulation. *Proceedings of the 10th Annual VRSJ Meeting*, (in Japanese), pages 50-54, 2005.