# Control Space of Apparent Haptic Motion

Ali Israr, Ivan Poupyrev

Disney Research, Pittsburgh

**ABSTRACT**

In this paper, we present three experiments to measure the control parameter space of apparent haptic motion using variety of stimulation attributes and body sites. In Exp. 1 we measured the range of Stimulus Onset Asynchrony (SOA) that created continuous motion between two vibrating points on the dorsal forearm and on the back by varying the frequency, intensity and duration of stimulation. The SOA space for apparent motion varied with duration and body site but not with frequency and intensity of stimulation. In Exp. 2, we measured the SOA space for moving sensations when direction of motion and spacing between actuators were varied. On the forearm, the SOA space was influenced by both the direction and spacing, however at the back; it was only affected by the direction of actuation. Finally, in Exp. 3 we measured the SOA space using four or more actuation points creating two-dimensional apparent motion. The results of the present study are discussed in context of designing haptic contents for movies, rides and video games.

**KEYWORDS:** Apparent haptic motion, psychophysics, haptic displays, entertainment.

**INDEX TERMS:** H.5.2 [Information Interfaces & Presentation]: User Interfaces—Haptic I/O; H.1.2 [Models & Principles]: User/Machine Systems—Human information processing

## 1 INTRODUCTION

Touch is a dominant part of our daily interactions and we feel rich and myriad variations in sensations when we touch objects around us and when these objects touch us back. It enables us to explore surfaces and textures, to manipulate objects, to feel and understand our surroundings, and to create personal connections with objects and individuals. Developing control schemes that artificially produces realistic touch sensations is not only a major research challenge but it also enables to create immersive and absorbing user experiences [12]. Our research is focused on developing such tools and control schemes that enhances user experiences in a wide range of environmental settings, e.g. while driving a car or watching a movie.

This paper investigates control schemes for producing continuous moving sensations on the skin. Moving tactile sensations is a common and effective way to communicate, express, alert and direct user's attention [5]. For example, Israr et al. utilized motion cues on the fingers to translate varying formant features of speech segments [7] and Tan et al. displayed moving tactile sensations on the back to provide directional and attentional cues [14]. In addition, moving tactile sensations evoke rich and variety of real life user experiences. Gibson listed such common sensations as stroking, rubbing, caressing, the crawling of an insect, scratching, rolling and the brushing of a leaf, etc. [6]. Combining these moving sensations with coherent visuals and audio creates engaging and believable multisensory contents, thus devising a new generation of user experiences for entertainment and interactive scenarios. These experiences, however, would require high-resolution and multi-dimensional haptic displays that stimulate the skin at various locations with high fidelity stimulations.

Research in developing high resolution haptic displays has an immense historic background. One of the smallest displays is the Optacon system, developed as a reading aid for the blind [10]. This system consists of an array of 144 tiny pins, measures 1.1 cm by 2.7 cm and fits under the fingertip of an index finger. One of the largest and historically significant is the TVSS system [2]. The TVSS systems consists of an array of 20×20 vibrators, covers almost the entire back of a user and displays images and shapes to the user. The purpose of these displays were to represent text and images to the skin with high granularity, however, they were ineffective due to the poor and limited capabilities of the skin and due to high cost, maintenance, size, weight and power requirements. In order to overcome these technical challenges, we proposed a control architecture that utilized sparse set of actuators in a grid topology and produced high resolution, continuous moving sensations on the skin [8]. The architecture and its corresponding control algorithm were based on psychophysical modeling of sensory illusions in touch, such as apparent haptic motion and phantom tactile sensations [1, 13]. The algorithm was optimized for a small set of stimulation parameters. For the algorithm to create wide variety of sensations on different body sites, there is a need to fully understand the physical and parameter space of apparent motion using a wide range of stimulus attributes, such as variations in frequency, intensity, duration, body site, direction and spacing of actuators. Moreover, how this parameter space changes for multiple actuation points that extends to two dimensional skin surface is not known in full extent.

In this paper, we measure the control parameter space for producing reliable continuous moving patterns on the skin by evoking apparent haptic motion illusions. In Experiment 1, we measure thresholds of a control parameter that would allow creating a non-simultaneous and non-discrete vibratory pattern between two actuation points using a variety of stimulation conditions and body sites. We measure the effect of frequency, intensity and duration of stimulation on two body sites: the volar forearm and the back. After establishing the baseline control space of the apparent haptic motion, we determine the influence of direction of illusory motion and spacing between two actuation points on the forearm and on the back in Experiment 2. In Experiment 3, we further investigate the apparent motion when the moving pattern extends from two points to the entire width of the back and two-dimensional moving patterns.

The rest of the paper is organized as follows: In Section 2, we present a brief historical overview of apparent haptic motion. In Section 3, we present the hardware and software interfaces, methods and results of three psychophysical experiments that measure the control space of the apparent motion. We present a usability evaluation of the measurements in Sec. 4. Finally we conclude

4615 Forbes Ave. Pittsburgh PA 15213, USA
{israr, ivan.poupyrev}@disneyresearch.com

the paper with a brief discussion on applications and implications of the measured data in Section 5.

## 2 Apparent Haptic Motion

Apparent tactile motion, also known as the phi-phenomena, has been studied for more than a century, when Harond Burtt observed that two vibrotactile stimuli placed in a close proximity on the skin and their actuation times overlapped, would not perceive as two actuators but rather a single actuator moving between them [4]. Early studies on apparent haptic motion failed to produce robust movements and only partial movements were observed by the participants [3]. As a result of this instability it was impossible to isolate control variables and conditions that would produce reliable tactile motion.

Neuhaus in 1930 demonstrated that the variables producing robust apparent tactile motion were (a) stimuli duration and (b) stimulus onset asynchrony (SOA), i.e. time between onsets of subsequent actuations [13] (see Fig. 1). A number of follow-up studies confirmed Neuhaus' observations and presented relations for "optimal" values of SOA as functions of stimuli duration [9, 13]. Using these relations, there have been a few attempts to design haptic displays primarily based on apparent haptic motion. However, they were mostly limited to producing motion along one dimensional arrays of actuators (e.g. [11, 16]).

The challenge in designing tactile displays based on apparent tactile motion is that there is insufficient understanding of the parameter space where the motion exists. Previous studies have focused on identifying variables that control the illusion by demonstrating an *instance* of control values [11, 13, 16]. How these values would change for different signal frequencies, intensities or directions, and how far they can deviate without breaking the illusion of motion, is not clear. Designing robust tactile displays based on apparent haptic motion requires deep understanding of the perceptual mechanism and measurement of *optimal parameter space* where such illusory motion is clearly perceived.

## 3 Psychophysics of Apparent Motion

In this section, we measure the control space of haptic apparent motion. Stimuli onset asynchrony (SOA) is a critical variable for controlling apparent haptic motion: when SOA is too small (Fig. 1a), subsequent stimuli overlap and are felt together as a single stimulus. Alternatively, if SOA is too large (Fig. 1c), the user feels a series of successive stimuli. Between these is a range of SOA values where the stimuli are integrated in space and time and felt as continuous directional motion (Fig. 1b).

We have conducted three psychophysical experiments to determine the optimal space of apparent motion for a wide variety of stimulus attributes. We measured the upper- and lower-thresholds of SOA that define the space of SOA for reliable apparent motion between two or more actuation points, and then use this space to control the illusion for continuous movement on the skin with a wide variety of sensations.

### 3.1 Hardware Platforms and Software Interface

Two hardware platforms were developed to stimulate a series of vibratory points on the skin of the forearm and back. Point stimulations were provided by C2 tactors (www.eaiinfo.com). These tactors have a near linear response in the range of vibrotactile perception, i.e., 80-500 Hz, and a resonance around 200-300 Hz coinciding with the most sensitive frequency of human operator [15]. Each tactor was calibrated and individually controlled by a multichannel audio card with tactile waveforms generated in Pure Data (www.puredata.info) sound design environment. A custom control board amplified the current and voltage of individual

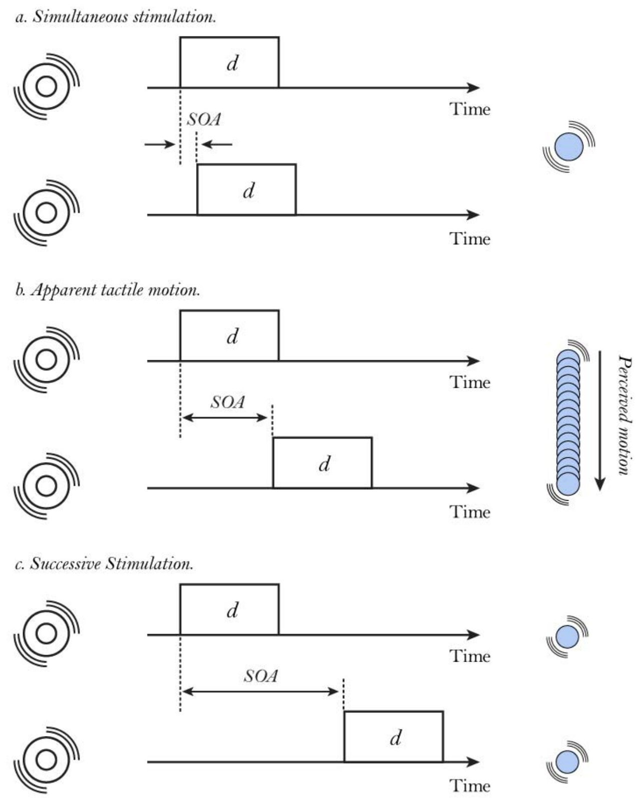



Figure 1. Apparent Haptic Motion as a function of SOA

waveforms and sent it to the actuators. Custom application software controlled Pure Data patches over UDP protocol.

Interspacing of tactors was fixed in each platform. On the arm sleeve, the tactors were embedded in a foam pad and fastened to the dorsal forearm using Velcro strips. Three tactors were placed equidistance along the length of the forearm. A fourth tactor was placed on the left lateral direction of the most proximal tactor. Inter-tactor spacing was 2.35″. To stimulate the skin of the back, the tactors were placed in a finely cut sheet of foam padding and glued to the back of a wooden chair. They were placed in a 3×4 array and spaced 2.5″ apart in every row and column. The locations of actuators on the forearm and back are shown in Fig. 2.

### 3.2 Experimental Methods

Experimental methods and general procedures for all three experiments were the same. We measured the time thresholds of the onsets of vibration points. Each experimental condition was tested in two threshold cases: (1) the onset threshold between the total simultaneity and movement of stimulation points (lower threshold), and (2) the onset thresholds between the total discreteness of stimulation points and the motion that felt merged together as a continuous motion (upper-threshold). Small differences among the experiments are discussed in their relevant sections.

#### 3.2.1 General Procedures

We utilized a one-interval two-alternatives forced-choice (1I-2AFC) paradigm combined with one-up one-down adaptive procedure to determine both the upper- and lower-thresholds of SOA. Thresholds obtained this way corresponded to the 50-percentile point on the psychometric function.

For the runs determining the upper threshold of SOA, the start value of SOA was selected large enough such that participants could clearly feel independent stimulation points. In every trial, participants were asked if they could feel individual "discrete" actuators. They responded by pressing a button marked "yes" or "no" using a mouse with their right hand. A new trial started immediately after the response. For every "yes" response the SOA value decreased and for every "no" response the SOA value increased for the subsequent trial. Similarly, for the runs determining the lower threshold of SOA, the start value of SOA was selected small enough such that participants could feel stimulations simultaneously, i.e. they could not sense the direction of vibratory motion. In every trial, they were asked if they felt actuators "simultaneous". For every "yes" response the SOA increased and for every "no" response the SOA decreased for the subsequent trial.

The SOA value was changed initially by 16-msec and then by 4-msec after the first two reversals. A reversal occurred when the participant's response changed from "yes" to "no", or vice versa. The experimental run terminated after six reversals at the 4-msec step-size. Each run typically took 15-25 trials, which took about 2-3 minutes. Participants sat comfortably on the chair facing towards the computer screen displaying experimental protocol. In the case of illusions on the forearm, they put their left arm on the table in the upright position and the sleeve was fastened such that the tactors touch the hairy skin of the dorsal forearm. In the case of the illusions on the back, they were asked to sit back such that the actuators on the back of the chair were in complete contact with the skin of the back. Participants wore normal shirts during the experiments and asked to raise the left sleeve up to their elbows. They wore headphones playing pink noise and earmuffs to isolate environmental noise.

Before testing for main experiments, we also measured the absolute detection threshold levels of 200 Hz and 270 Hz vibration stimulated on the back and on the forearm. Only one stimulation point was tested at each body site and assumed that the threshold was the same on the adjacent points. The detection thresholds were measured by using 2IFC paradigm combined with 1-up 3-down adaptive produce. The intensity step-size was initially set to 4 dB and changed to 1 dB after 3 reversals. The run terminated after 8 reversals at 1 dB step size. The average threshold was computed by taking an average intensity levels of the last 8 reversals. This procedure ensured quick estimation of threshold levels before starting the main experiments. Each run, on average, took two to three minutes of testing and the intensity of stimulation at subsequent experiments were computed relative to the corresponding threshold of participant at each frequency and body site.

### 3.2.2 Data Analysis

The average SOA threshold was computed by taking the mean value of the last six reversals of each run. Repeated measures Analysis of Variance (ANOVA) tests were utilized to determine significant effects ($\alpha = 0.05$) of test conditions and body sites.

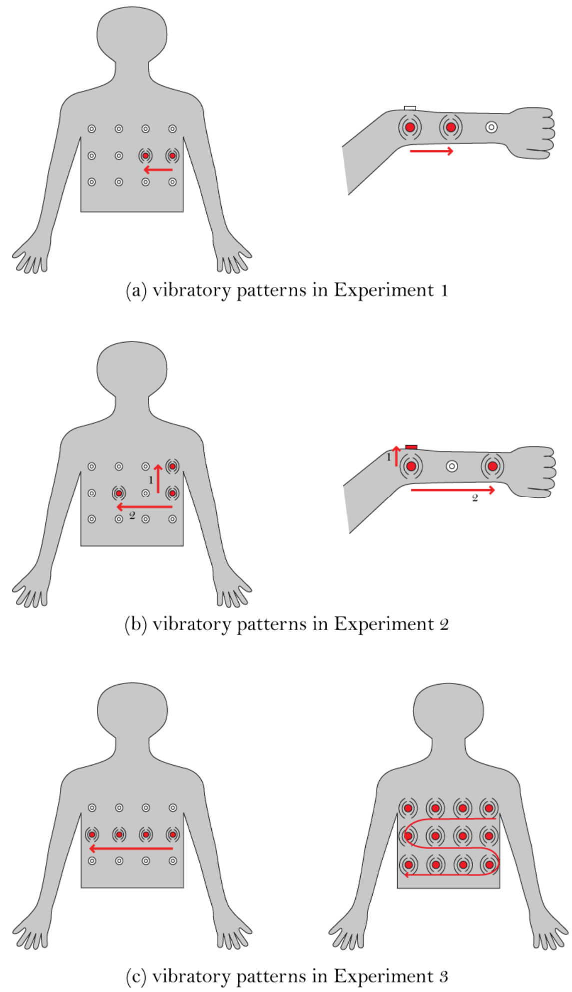
## 3.3 Experiment 1

In the first experiment, we determined SOA thresholds of apparent motion for a variety of stimulus conditions. Specifically we measured the thresholds at two body sites with different frequencies, intensities and duration.

### 3.3.1 Participants and Stimuli

Seven participants (four males and three females, average age: 28 years old) took part in this experiment. All participants were paid staff of Disney Research, Pittsburgh and had no known sensory impairments. They were right handed by self report and used a right hand mouse to enter their responses.

The SOA thresholds were measured for two pure sinusoidal tone waveforms, 200 Hz and 270 Hz, each stimulated at two intensities, 20 and 25 dB SL (sensation level, i.e., relative to the measured absolute detection threshold level), and at two durations, 120- and 240-msec, for two body sites, forearm and back. The test stimuli were ramped up and ramped down with 40-msec rise and decay times in order to reduce abrupt transient response of the actuators and corresponding skin surface. On the back, two adjacent actuators on the center row were vibrated such that they created a moving sensation from the extreme right end towards the midline of the back (see Fig. 2a). In the case of the forearm, the two adjacent points at the dorsal forearm were stimulated such that they created a moving sensation towards the distal forearm along the proximodistal axis (see Fig. 2a).



(a) vibratory patterns in Experiment 1

(b) vibratory patterns in Experiment 2

(c) vibratory patterns in Experiment 3

Figure 2. Actuator layout and vibratory patterns tested in the experiments

Each participant was tested in 16 test conditions, resulting in 32 runs of either determining the upper- or lower-threshold. Participants completed the testing for each body site in one session per day that lasted no more than 20-25 minutes. The order of body site was randomized among participants. Within each session, the frequency, intensity, duration and threshold conditions were also randomized. Participants were asked to take sufficient rest between test runs.

### 3.3.2 Results

We observed variability in SOA thresholds among participants, ANOVA analysis showed significant between-subject effects [$F(1,6)=302$, $p<0.001$], thus we pooled the data among participants and generalized the results for further analysis. Figure 3 shows the upper and lower thresholds of SOA space for tested

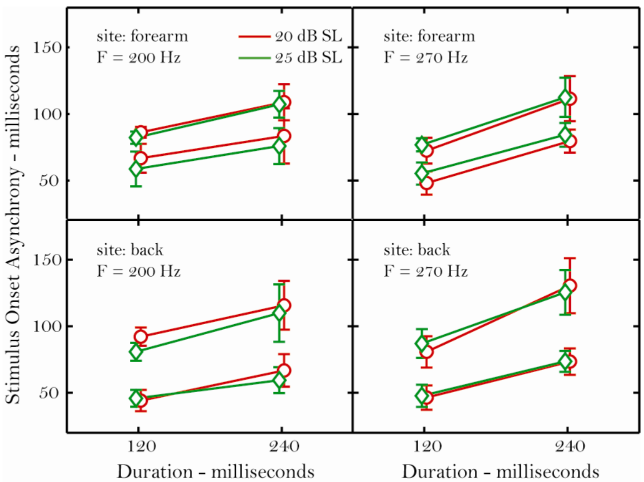



Figure 3. SOA thresholds and control space measured in Exp. 1

frequencies, intensities, durations and body sites in four panels. Top two panels are for the forearm and bottom panels are for the back. Left panels present measurements at 200 Hz and the right panels are for 270 Hz. Each data point shows the SOA threshold (either lower- or upper-) averaged across participants and the error bar represent the standard error of the mean threshold. The average SOA thresholds are plotted against the duration of stimulation and a straight line is passed through them in order to observe the effects of duration. In each panel, solid red lines show thresholds at 20 dB SL and green lines show those at 25 dB SL. Note that the lower- and upper-SOA thresholds are distinct in each test condition, as also shown by the ANOVA analysis [$F(1,6)=9.2$, $p<0.05$], indicating a clear range of SOA where participants neither felt simultaneous or successive stimulations.

*Effect of duration:* A thorough ANOVA analysis suggested that duration of stimulation was a significant factor [$F(1,6)=33$, $p<0.01$]. As the duration increased, both the lower- and upper-thresholds were also increased. In some cases, the SOA space between the lower- and upper-thresholds was greater at higher durations, indicating broader design space for creating slow continuous moving sensations on the skin.

*Effect of frequency and intensity:* In the present experiments, the SOA was not significantly affected by changing the frequency [$F(1,6)=0.12$, $p=0.74$] or intensity [$F(1,6)=0.26$, $p=0.63$] of stimulation. Interaction terms were also not significant. This suggested that a single model could be sufficient to incorporate control of variety of sensations resulted from varying the frequency and intensity of stimulations.

*Effect of body site:* The effect of body site was a significant factor on the SOA space ($p<0.01$). On the whole, the SOA space on the forearm was smaller than that on the back. This was not surprising, as the spatial resolution on the back is lower than that on the back, thus resulting in a higher control range for creating illusory motion on the back.

### 3.4 Experiment 2

In Exp. 1, we measured the SOA space of apparent motion for a variety of stimulation frequencies, intensities, durations and body sites. This provides us the data to elicit moving sensations on the skin. In Exp. 2, we measured the SOA space when the physical configurations of actuation points were varied. Specifically, we tested and compared following two conditions: (1) direction of stimulating motion, and (2) spacing of actuation points. Compared to the measurements of Experiment 1, we determined if spacing

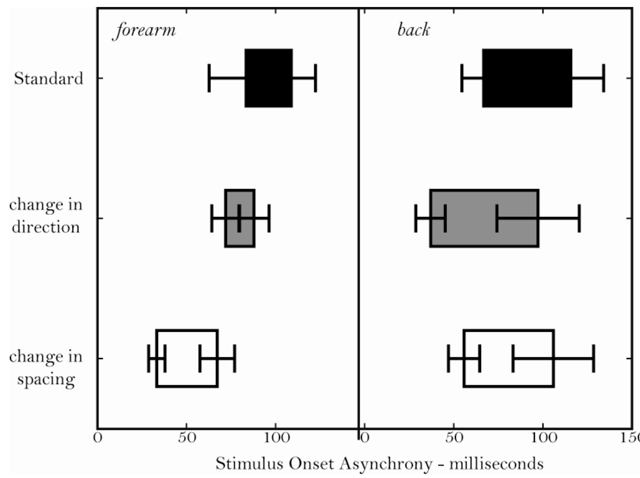



Figure 4. SOA thresholds and control space measured in Exp. 2

and direction of illusion would affect the control space on the forearm and on the back.

#### 3.4.1 Participants and Stimuli

Same seven participants of Experiment 1 took part in the Experiment 2. We utilized pure 200 Hz vibration stimulated at 20 dB SL with 240-msec duration, and tested both the back and the forearm in two test conditions. In condition 1, the direction of stimulated motion was perpendicular to the motion tested in Exp. 1. In the case of the back, the extreme right tactors of the top and center rows were stimulated such that the sensed motion was upward. On the forearm, the vibrations were presented on the two proximal points and the pattern moved from the dorsal to the lateral left forearm (Fig. 2b). In condition 2, the direction of motion was same as in Exp. 1 except that the spacing between the two vibration points was doubled (Fig. 2b).

#### 3.4.2 Results

The measured SOA space is shown in Fig. 4. Left hand side of the figure shows measurements on the forearm and the right hand shows that on the back. The black rectangular bars on the top represent the standard SOA space for similar stimulus parameters in Experiment 1.

*Effect of direction:* The ANOVA analysis for comparison between the SOA thresholds of standard and condition 1 suggested significant effect of direction on both the forearm and on the back [$F(1,6)=7.1$, $p<0.05$]. Other factors and interaction effects were not significant on the measured SOA. On the forearm, the illusion along the lateral direction had a smaller control range of SOA. However, on the back, the illusion direction did not substantially change the absolute range but shifted the entire range to lower SOA values. In both body sites, participants were more sensitive to the direction change–i.e., the SOA thresholds between simultaneity and movement, and the SOA thresholds between the merged stimulations and total discreteness were small, compared to the standard condition of Experiment 1.

*Effect of spacing:* The ANOVA analysis for comparison between the standard and condition 2 suggested significant effect of spacing [$F(1,6)=8.2$, $p<0.05$]. However, interaction between the body site and tactor spacing was also significant [$F(1,6)=7.4$, $p<0.05$] indicating mixed trends in the SOA thresholds. Further analysis showed that that spacing was a factor on the forearm [$F(1,6)=11.5$, $p<0.05$] and not on the back [$F(1,6)=1.1$, $p=0.33$]. This could be due to the poor resolution (two point limen) of the skin of the back than that of the forearm, enabling participants to localize the tactors on the forearm more easily.

### 3.5 Experiment 3

In Experiment 3, we extended our investigations and measured the control space for SOA between two stimulation points. In this case, we measure the SOA thresholds for a single axis apparent motion between four actuation points and for a two-dimensional apparent motion. Our goal was to determine the control space for apparent motion that extends beyond the use of mere start and end points, but include intermediate points as well. For this experiment, we kept the spacing between the tactors same as in previous experiments and only tested the skin of the back.

#### 3.5.1 Participants and Stimuli

Two sets of new participants were recruited for the two test patterns in Experiment 3. The first test pattern consisted of four vibrating points on the center row that created a moving sensation from right to left (Fig. 2c). Ten participants (five males and five females; avg. age 25 years old) took part in this study. The second test pattern consisted of a two dimensional 'S' shaped test pattern as shown in Fig. 2c using all nine tactors of the back display. Eight participants (four males and four females; avg. age 29 years old) took part in this study. Stimulation parameters in the two sub-studies were same as that in the Exp. 2, i.e. 200 Hz at 20 dB SL and 240-msec.

#### 3.5.2 Results

The range of control space for the two patterns that created a moving line sensation across the back and a 'S' shaped pattern on the back are shown in Fig. 5. For comparison, the control space of the illusion created by two point stimulations is also shown. The SOA threshold space for the line illusion across the back was larger than that for the 'S' shaped pattern illusion. In fact, the thresholds of 'S' shaped patterns are within the control space of the line illusion. This suggest that there is a small space for the high dimensional apparent motion.

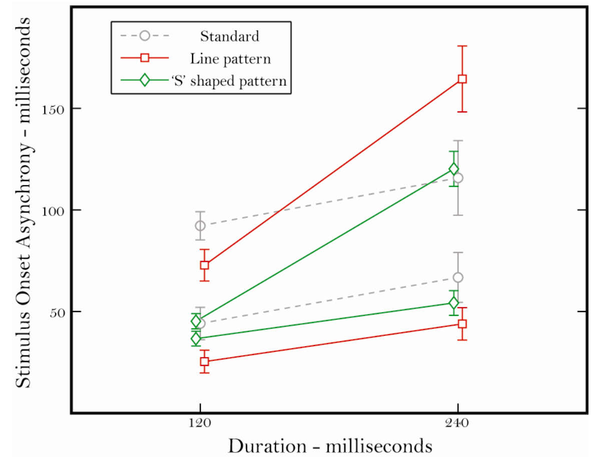



Figure 5. SOA thresholds and control space measured in Exp. 3

## 4 Usability Evaluation Study

One of the motivations for this study was to determine the control space of apparent motion and use control parameters within this space to recreate continuous moving sensations on the skin. This space should be applied to almost any vibrotactile actuators, from inexpensive vibrating motors to military-grade tactors. In this section, we show that the SOA space determined in the last section could be applied to inexpensive, eccentric mass motors for producing a variety of continuous motion sensations.

We utilized a readily available eccentric mass motor (model: Z6DL2H0125215, Jinlong Machinery, NY, New York), which had a fast response time (40-msec) and peak frequency of ~170 Hz. A total of twelve such motors were arranged in a 3×4 grid layout in a foam padding, similar to that stimulated the back in the last section. The passing was placed inside a vest that users wore during the testing. The motors were computer controlled via Processing and Arduino prototype board. The motors were actuated with their peak rating voltages and stimulation duration was set to 240-msec. We used three patterns with different directions, (horizontal, vertical and diagonal in Fig. 6) and used two test conditions: controlled (SOA of 90-msec) and uncontrolled (SOA of 200-msec). The 90-msec SOA value was the center point between the upper and lower thresholds of line motion of Fig. 5. The 200-msec SOA was well above the upper threshold and should feel discrete. Each of the six patterns was randomly presented three times in a test session that last no more than 5 minutes.

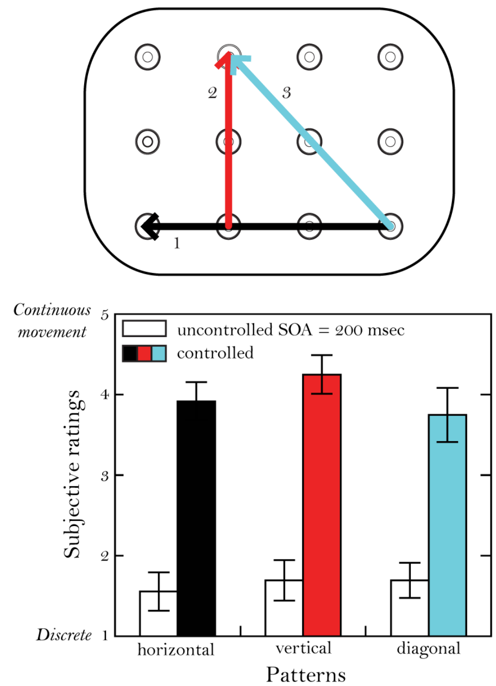



Figure 6. Usability evaluation

We asked twelve participants (nine males, ave. age 29 year old) to rate the eighteen test patterns in the 1-5 scale, where '1' corresponded to "Discrete" and '5' corresponded to "Continuous" feelings. '3' corresponded to "not sure". The subjective ratings per pattern were combined together and plotted in Fig. 6. The average ratings for the controlled (or continuous) patterns were 3.97 which was significantly greater than the ratings for non-controlled (or discrete) patterns [$F(1,11)=71$; $p<0.01$]. Thus the control parameter derived from the psychophysical measurements produced continuous motion in arbitrary directions.

## 5 Discussion and Concluding Remarks

The motivation of our ongoing research is to develop control schemes that render realistic and compelling haptic feedback for entertainment purposes. Our long term goals are to augment high quality haptic feed with stereoscopic visuals and surround sounds in order to enhance user experiences for deeper sense of immersion and believability. In our recent article, we proposed a control

Figure 7. Application scenarios of apparent haptic motion

architecture that utilized low-resolution actuator grid to produce high-resolution and multi-dimensional haptic sensations directly on the skin [8]. The key contribution of the paper was the design of a control algorithm that was based on psychophysical modeling of sensory illusions in touch, particularly apparent haptic motion. In one experiment, we measured the SOA space for straight line apparent motion on the skin for variation in frequency, duration and direction of stimulations. Based on the measurements, we developed a model that related the perceived illusory motions to the stimulation parameters such as SOA and duration. In the present study, we extended our investigations, and measured the SOA space for two point apparent motion, that varied in frequency, intensity, duration and body site. Moreover, we investigated the parameter control space when the direction and spacing between actuators were varied. The purpose of the present investigations are to explore which factors could affect our model and how to adjust the model in order to account for variations in the quality, speed and size of sensations, as well as utilizing variety of body sites and actuation grid topologies in the control scheme.

In addition to the two point apparent motion, we investigated the control space of motion sensations when the line motion was produced using more than two actuation points and in the two dimensional space. The significance of these measurements is that the derived models could be used by a range of actuation technologies, such as from high end military grade actuators to low cost eccentric pager motors, to produce continuous moving sensations. This would have three major advantages: one is the reduction of cost in the consumer products and toys, which usually have small margins of profits. Two, the size, weight and power consumption of actuators for the desired packaging and embodiments, and finally, the effects are robust.

While there are many potential uses for the presented data, developing compelling and seamless visio-tactile-audio experiences for games, movies, rides and music is our major application goal. We derived models from the measured data and demonstrated their use in video games and while watching movies (Figure 7), where we synchronized dynamic directional stroking sensations with graphic contents to create feelings of drops of water, the recoil of a gun, buzzing of insects, crawling of insects and air movement from passing cars. A detailed discussion of potential applications, however, is beyond the scope of the present paper. A concise description of these haptic contents are discussed in [8].

Finally, In order for the haptics technology to be widely deployed in the mainstream consumer product market, we must emphasize a need for development of authoring tools. The present paper provides a basis data for developing such authoring tools that would allow non-programmers to draw tactile sensations on a computer screen and then play them back on a haptic device, save them for later use, or share them with friends. The data would allow users to create haptic contents with a wide variety in sensations, which includes different speeds, thicknesses, length, locations, frequencies and intensities.

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