Intermanual Apparent Tactile Motion on handheld tablets*

Siyan Zhao, Ali Israr and Roberta Klatzky

Abstract—**Handheld and wearable devices frequently engage users with simple haptic feedback, such as alerting, shaking, and pulsating. Here we explored intermanual apparent tactile motion—illusory movement between two hands—as a means to enrich such feedback. A series of psychophysical experiments determined the control space for generating smooth and consistent motion across the hands while users held the device. Experiment 1 calibrated the system and showed that vibrotactile detection thresholds decreased with increasing frequency, with similar trends for both hands. Experiment 2 measured effects of vibrotactile parameters on perceived motion. Both duration and temporal separation of stimuli, but not frequency and amplitude, affected subjective motion ratings. In Experiment 3, subjective ratings showed that stimuli with gradual onsets produced a stronger percept of motion than those with abrupt onsets. Finally, Experiment 4 determined a multimodal factor to match moving visual cues across the screen to moving tactile motion across hands. Our results showed compression of visual duration by the tactile system by a factor of approximately 1/3 at two test frequencies. The results of this research are useful for media designers and developers to generate reliable motion across the hands and integrate haptic motion with visual media.**

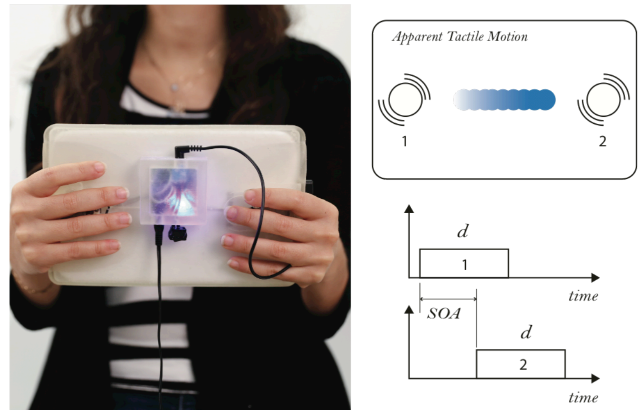

Figure 1. (*left*) A user holding a handheld device (tablet) embedded with two vibrators pressing the hands. (*right*) A pictorial illustration of apparent tactile motion and its parametric space.

I. Introduction

Handheld, wearable, and mobile devices are common and becoming an integral part of our daily interactions. Game controllers, tablets, cell phones, VR gloves, shoes, wrist bands, and watches are common artifacts with embedded electronics that respond to a user's activities, incoming messages and other media types. In order to further engage users with these devices, the media and activities are frequently accompanied by coherent and synchronized haptic feedback, thereby delivering an overall multisensory experience that is enjoyable and expressive to the user [1, 2]. Many cell phones and game controllers are embedded with a single eccentric-mass low-bandwidth DC-motor. However, the user experience with these devices is restricted to alerting, shaking, pulsating and/or poking-like sensations, mainly due to the homogenous and low-bandwidth nature of vibrotactile stimulations.

Recent research has extensively explored the use of multi-actuator arrays for stimulating the skin at several proximal locations and creating moving tactile cues on a hand (see for example, [3, 4]). These effects appear to produce expressive and dynamic interactions with handheld mobile devices. Sensory illusions, such as apparent tactile motion, are often utilized to generate percepts of illusory sensations in between only two actuators mounted on these devices [5, 6]; such sparse actuation reduces the cost, size, weight and design complexity.

More recently, Yannier and colleagues incorporated two voice-coil type actuators on extreme ends of a tablet sleeve (see Fig. 1) and showed that semantically enhanced *feel effects*, played along with children's stories, improved reading comprehension scores for 1st to 3rd graders [7]. The two actuators increased the bandwidth of the tablet sleeve by creating tactile content that was moving, expressive and coherent with the events in the stories. The authors relied on three known vibrotactile illusions for adjoining body sites [8] —apparent motion, funneling, and saltation—along with previously identified rough parameter ranges to generate moving tactile cues across and between the two actuators contacted by the hands holding the sleeve.

In this paper, we systematically investigate the psychophysics of apparent tactile motion and estimate control parameters to consistently generate continuous tactile motion across the two hands. Specifically, we explore the answers to three questions. First, do people feel the apparent tactile motion across hands separated by space, and how can we reliably generate such motion? Second, what are the parameters that influence the quality of this illusory motion; in particular, onset functions on the quality of motion? And finally, what are the multimodal effects of matching visual motion on the screen with the coherent illusory motion across the two hands? Answers to these questions will result in a procedure that will reliably create illusory motions and accompany them with the media content displayed on the screen of the device. Before conducting these experiments,

*This Research is supported by Disney Research, The Walt Disney Company.

S. Zhao is Research Associate with Disney Research, 4720 Forbes Ave. Pittsburgh, PA 15213 USA. (phone: 412-623-1801; fax: 412-578-9727; e-mail: {siyan.zhao}@disneyresearch.com).

A. Israr is a Senior Researcher with Disney Research, Pittsburgh, PA 15213 USA. (israr@disneyresearch.com).

R. Klatzky is a Profession in the Department of Psychology, Carnegie Mellon University, Pittsburgh, PA 15213 USA. (e-mail: klatzky@cmu.edu).

we also determined the absolute detection threshold curves for sinusoidal stimulation at the two hands in order to calibrate the mobile handheld device for tactile stimulations in the later experiments.

The paper is organized as follows: After presenting related background, we describe the detection thresholds measured for the two hands and how they are used to calibrated the device. We follow this with a pair of psychophysical experiments investigating the control space of apparent tactile motion across the two hands. We then present a study to examine multimodal effects in matching the illusory motion with the moving visual cues on the screen. Finally, the paper concludes with a discussion and implications of the results.

II. BACKGROUND

A. Haptic Technologies for Multimodal Interactions

Haptic feedback has been viewed as an active ingredient of immersive and engaging experiences in the entertainment and media industry. An early cinematic multisensory experience called *Percepto* was used for the 1959 classic "The Tingler" [9], in which theater seats were equipped with vibrating devices that buzzed the audience during events in the movie. Recent research has shown that meaningful and synchronized tactile content on tablets and vests can enhance comprehension scores for young children during story reading and listening [7, 10].

Current consumer gadgets not only track users' gestures, motions, and interactions, but also allow users to send and receive electronic media. Many such devices incorporate and maintain a two-hand-hold posture for enhanced user interactions with the media. For example, handheld game controllers [11] augment video games with shaking and rumbling sensations at the two hands, and a wearable haptic glove system is used with movies to induce the impression that users have superpowers in their hands [12]. Other research has created tactile illusions across two hands to elicit rich dynamic sensations on and along mobile devices [6, 7, 13, 14].

B. Vibrotactile Perception and Illusions

Many mobile and handheld devices have utilized sensory illusions arising from vibrotactile stimulation in order to create dynamic tactile patterns and to reduce the cost and weight requirements for comfortable interactions [5]. Device design has not, however, always capitalized on the fact that these illusions have been modeled by rigorous psychophysical methods and basic research on the neural underpinnings of vibrotactile perception. Perhaps the most important psychophysical measure is the human detection threshold, which is defined as the minimum stimulus intensity that is perceivable. In general, the vibrotactile thresholds vary as a U-shaped curve with stimulus frequency, with the bottom of the curve corresponding to the greatest sensitivity and the slope indicating the sharpness of the tuning function [15, 16]. It is known that detection thresholds vary with body location, direction of vibrations, contact area and many stimulus parameters (see review in [17]). Therefore, it is recommended to determine these thresholds for reliable control of haptic stimulation given a specific device and context.

Three sensory illusions in touch have been frequently incorporated in mobile and wearable arrays, as was previously noted. They are apparent motion [18], funneling [19] and saltation [20, 21]. These robust illusions allow simple control schemes to generate a wide variety of tactile patterns that modulate in both space and time [5, 13, 22]. Another robust illusion is stimulated on a handheld to generate the motion of a rolling stone based on user gestures by using only a vibrator [23].

C. Apparent Tactile Motion

Apparent tactile motion is one of the most common and earliest known illusions. It is generated by two separate but closely placed stimuli on the skin having different onset times. Instead of being perceived as two separate vibrations, the two stimuli would feel as though a single vibration is moving from one stimulus to the other [24]. Much research has been done to understand the control space for this illusory motion in order to reliably and consistently generate it. It has been shown that duration and temporal separation (i.e., stimulus onset asynchrony, or SOA) between the stimuli play a significant role in generating the apparent motion[18, 24]. Sherrick and Rogers [18] measured the relation between stimulus duration and SOA by asking participants to identify when they felt "the longest uninterrupted feeling of movement" between two vibratory points on the thigh. The optimal SOA for producing movement varied linearly with duration for durations of 25-400 msec. Israr and Poupyrev [25] measured the control space of apparent tactile motion between two vibrations on the forearm and on the back by estimating SOA thresholds between no motion and motion (lower thresholds) and between discrete and continuous motion (upper thresholds). The midpoint between the upper and lower thresholds was determined to be the optimal SOA for generating continuous apparent motion at the test duration. Their results also showed a linear relation between the optimal SOA and stimulus duration at both test sites.

Other studies have used similar relations to devise a rendering model for their interfaces. For example, Israr and Poupyrev [22] used apparent motion to create dynamic moving patterns on the back using a grid of voice-coil actuators embedded in the chair. Yatani and Truong [5] mounted an array of vibrators on the back of a mobile device and created line patterns to indicate directional and attentional cues. Seo and Choi [6] demonstrated perceived motion on a hand grasping a mobile device with two vibrators located at the extreme ends of the device. In all these studies, the apparent tactile motion was investigated across contiguous body regions (such as within the back, forearm, palm of a hand). However, controlling the apparent motion across two separated hands (intermanual apparent motion) has rarely been explored and used in past efforts.

Another phantom sensation is caused by so-called funneling of the skin [19]. Alles [26] showed that a virtual vibration site occurred between two simultaneously modulated real vibrators and the quality of the illusion was better with logarithmic scaling of vibration intensities than with linear scaling.

III. EXPERIMENT 1: HUMAN DETECTION THRESHOLDS

Human detection thresholds are important psychophysical measures for determining the baseline of the dynamic range of a user's perception. The threshold also provides a reference for vibrations presented on a device. In this section, we report estimated detection thresholds for pure sinusoidal stimulus at two hands holding a tablet device and calibrate the device to deliver precise vibrotactile stimulations.

A. *Apparatus*

A Samsung Galaxy Note 8.0 tablet (screen width 172 × 110 mm) enclosed in a 3D printed semi-flexible sleeve was used as the apparatus for all experiments. The sleeve is embedded with two voice-coil actuators at the two ends, spaced 176 mm apart, that press against the vibrating flap on the back of the sleeve. When a user holds the sleeve, it directly stimulates the skin of the hands as shown in Figure 1. Both actuators are driven by a custom electronic driver to amplify the stereo audio output of the tablet. The detailed design of the sleeve is presented in [7].

The sleeve is calibrated to reliably generate vibratory stimuli on the hands. The calibration procedure includes exciting the actuators with pure sinusoidal waveforms at five test frequencies (40, 70, 120, 200 and 320 Hz) and at seven equally spaced amplitude levels ranging from around detection threshold levels to 30 dB above them. A user holds the apparatus, and vibrations are measured by a pair of MEMS accelerometers (ADXL335, Analog Devices, Inc, USA) mounted on the top of the vibrating elements. The accelerometer measurements are analyzed by computing the FFT (Fast Fourier Transform) of each measurement and then plotting them in the frequency-amplitude plane. The calibration routine shows that both actuators behave identically and operate linearly in the test range. Moreover, noise and distortion was low in this range. Finally, a frequency dependent function is determined that relates the waveform amplitude in the tablet software to measured acceleration. This function is later used to determine the detection threshold levels in acceleration units.

B. *Methods, Results and Discussion*

Ten participants (five males; 19-38 years old, average=25.4 years) took part in the experiment. Seven participants were right handed and none of the participants reported any sensory impairment influencing this study. All participants signed a consent form approved by Carnegie Mellon University's Institutional Review Board.

A two-interval forced-choice one-up two-down adaptive staircase procedure [27] was used to determine the absolute detection thresholds for both hands at five test frequencies (40, 70, 120, 200 and 320 Hz). Thresholds obtained in this way correspond to 70.7% on the psychometric function. Participants sat comfortably on a chair holding the tablet sleeve such that they could feel the stimulations on the fingertips of the index, middle and ring fingers, as shown in Figure 1. Each frequency and hand condition was tested in a random order and the experiment lasted ~45 minutes per participant. Participants were asked to take rest in between test conditions. They also wore headphones playing pink noise to mask hardware and environmental sound.

In each test run (one frequency and hand condition), participants were presented with a series of trials. Each trial consisted of two 500 msec intervals separated by a 300 msec pause. Visual and auditory cues were played to mark the beginning and end of each interval. A vibratory stimulus (500 msec sinusoidal waveform with 50 msec rise and fall Hanning window) would play in either the first interval or the second interval, selected randomly in each trial, and the participant's task was to indicate the interval with vibrations by pressing a button marked as '1' or '2' with their thumbs. The amplitude of vibration was initially set roughly at 20 dB above the estimated threshold (determined in the pilot) and was changed during the run. Two consecutive correct responses decreased the stimulus amplitude by a step size for subsequent trials, and one incorrect response increase the amplitude. The step size was initially set to 4 dB and then 1 dB after the first three reversals. A reversal occurred when a decreasing amplitude trend was changed to an increasing trend, or vice versa. The run terminated after 8 reversals at 1 dB step size. The estimated threshold was determined by taking the average of the amplitude at last 8 reversals. These thresholds were converted to acceleration units by using the calibrated function determined earlier, and then to displacement units by integrating twice, i.e., scaling twice by $2\pi f$, where f was the test frequency.

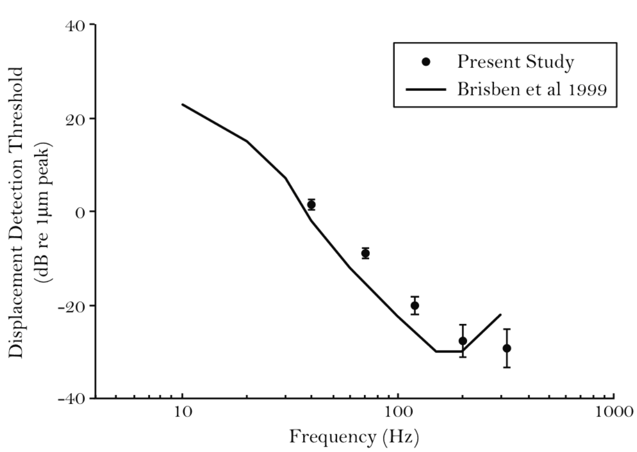

Figure 2. A detection threshold curve as a function of test frequency. Error bars show standard errors. For comparison the detection threshold levels from [15] are shown.

Fig. 2 shows the estimated displacement detection thresholds as a function of test frequencies. Each data point is the mean threshold of ten participants and two hands. The error bars indicate one standard error of the mean. A detection threshold curve from the past literature [15] is also plotted for comparison. The threshold levels determined with our apparatus are similar to those in the literature, except that the most sensitive frequency was shifted higher. A repeated measures ANOVA (Analysis of Variance) with frequency and hand as within factors showed a significant effect of frequency on the detection thresholds [$F(4,36)=10.8$, $p<0.001$ and no significant effect of the two hands [$F(1,9)=1.3$, $p=0.29$]. No significant interaction indicated that the thresholds decreased with the increase in frequency, and the thresholds for two hands were not significantly different.

IV. Experiment 2: Apparent Tactile Motion

The objective of this experiment is two-fold. First, we wish to confirm that two actuators can evoke tactile apparent motion across the hands. Second, we intend to characterize effects of critical stimulus parameters. Figure 1 (*right*) shows that illusory tactile motion is evoked as a result of two temporally separated vibratory stimulations. Therefore, we investigate frequency f, amplitude A, duration d and SOA.

A. Methods

Participants

Eleven naive participants (six males; 19-38 years old, average=25.4 years) were recruited for this experiment. All participants gave signed consent.

Stimuli

Four independent variables were varied: frequency (70 and 200 Hz), amplitude (25 and 35 dB above the detection thresholds), duration (100, 400 and 700 msec) and SOA (7 levels corresponding to each duration). To set SOA values, in a pilot study we determined the range of SOA for each duration such that the minimum was a non-zero value that resulted in no perception of motion, and the maximum resulted in movement but with a clear gap between the hands. The resulting values were: for 100 msec duration, SOA range = 15-160 msec; for 400 msec duration, SOA range=15-350 msec and for 700 msec duration, SOA range = 25-400 msec. Note that the effective maximum SOA, where motion was disrupted by a gap, emerged as varying log linearly with total stimulus duration. The specific SOA values used at a given duration were obtained by dividing the range into seven equally spaced levels.

To avoid sudden onset and offset, the amplitude of each vibrotactile stimulus was ramped up and down at a constant rate. The ramp durations for both onset and offset were set at 20% of the stimulus duration as shown in Fig. 4(b).

Procedure

Participants held the tablet sleeve displaying the experiment interface on the screen. They were told that the vibratory motion was an illusion and there was no physical object traveling across their hands. They ran two training trials before starting the main experiment. Each participant was tested for 336 trials ($2f \times 2A \times 3d \times 7SOA \times 4$ repetitions). In addition, 6 catch trials with $SOA = 0$ msec were added to confirm that the scale was used properly. These trials were divided into three blocks that lasted ~45 minutes. Participants were asked to rest between blocks and wore headphones to mask environmental and device sounds.

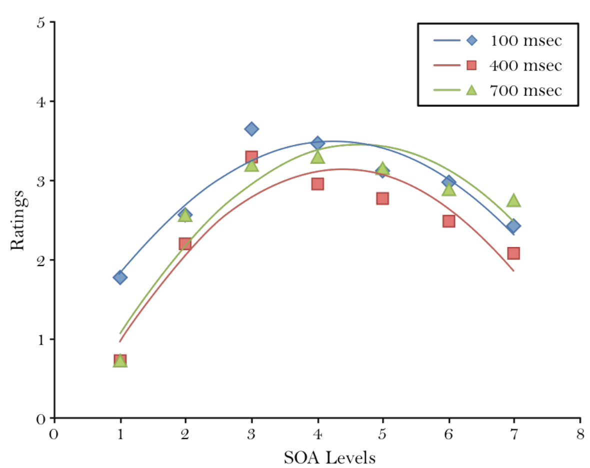

Figure 3. Average ratings of continuous motion as a function of SOA levels at three test durations.

In each trial, participants felt an illusory motion and were asked if they experienced motion across their hands. If they responded ‘no’ then the rating was scored as ‘0’ and a new trial started. If they responded ‘yes’ then they were asked to rate the overall continuity of the motion on a 5-point scale, where 1 indicated that motion was felt with a gap and 5 indicated a continuous motion with no gap. All responses were entered using buttons on the experiment interface.

B. Results and Discussion

User ratings (0 through 5) were averaged for each parameter across participants. At $SOA = 0$ (catch trials), these overall ratings were 1.36, 1.0 and 0.27 for durations of 100, 400 and 700 msec, respectively, indicating that the scale was used appropriately. The remaining data were analyzed using a repeated measures ANOVA (all four parameters were within factors). The analysis showed no effect of frequency [$F(1,10)=0.06$; $p=0.8$] or amplitude [$F(1,10)=3.2$; $p=0.1$]; nor was the frequency-amplitude interaction significant [$F(1,10)=0.6$; $p=0.5$]. There was a significant interaction between amplitude and SOA [$F(6,60)=3.3$; $p<0.001$], resulting from movement ratings tending to be slightly higher at the longest SOAs for the low amplitude (25 dB SL). As this effect was neither systematic nor large in magnitude, it was not considered further.

The principal results pertained to stimulus duration and SOA, both of which showed significant effects: duration [$F(2,20)=6.0$; $p<0.001$] and SOA [$F(6,60)=11.9$; $p<0.001$]. The duration-SOA interaction was also significant [$F(12,120)=2.3$; $p=0.01$]. The interaction can be seen in Figure 3, which plots average ratings as a function of SOA for the three test durations, along with best-fit quadratic trends. Table 1 shows the goodness of fit along with the peak location of the quadratic in msec for each duration. The peak location, which indicated the optimal SOA, tended to be near the midpoint of the SOA range, i.e. between levels 3 and level 5.

TABLE I. Peak locations of quadratic curves (optimal SOA for apparent motion) and the corresponding R-values.

Test Duration (msec)	Peak Location (msec)	Quadratic Fit (r value)
100	78.7	0.97
400	190	0.95
700	244	0.97

Experiment 2 confirms that an optimal temporal separation (SOA) evokes illusory motion across the two hands. The data suggest that the critical factors to control the generation of this apparent tactile motion are stimulus duration and onset asynchrony. Frequency and amplitude of stimulation have little influence on the apparent motion. These results are consistent with previous studies by [18, 28].

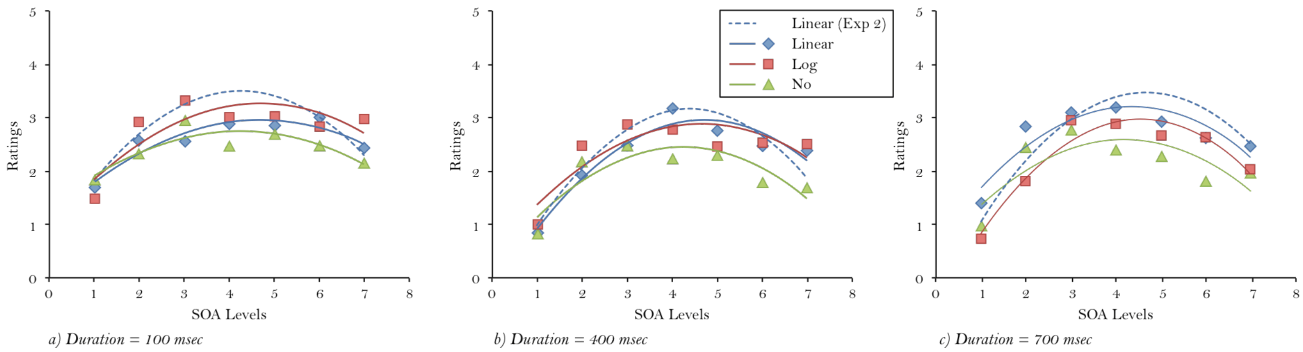

Figure 5. Average ratings of continuous motion as a function of SOA levels for three stimulus durations and onset functions.

Our results indicate that the peak location on the rating versus SOA function, indicating the optimal SOA to produce illusory movement (SOA_O), is linearly related to stimulus duration (d). This arises from two underlying phenomena: (i) illusory motion tends to be produced across a wider range of SOAs at longer durations (essentially by a log-linear relation of maximum effective SOA to duration), and (ii) the peak SOA is found near the midpoint of the effective range. For the present data, linear regression showed that the best-fit function relating optimal SOA to duration is:

$$SOA_O = 0.28 \times d + 60.7 \qquad (1)$$

This function was used to generate consistent apparent motion across the two hands in our subsequent studies.

V. EXPERIMENT 3: COMPARISON OF ONSET FUNCTIONS ON APPARENT TACTILE MOTION

In Experiment 2, we determined the parametric space for generating a smooth apparent tactile motion between the two hands. Our pilot testing indicated that gradual change in amplitude resulted in smoother apparent motion than when the amplitude was abruptly changed. In Experiment 3, we examine the effect of waveform parameters, such as onset

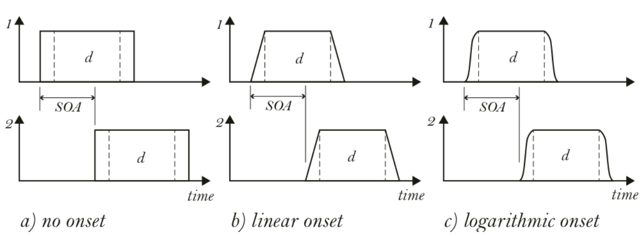

Figure 4. Three types of onset function used in apparent tactile motion.

and decay functions, on the quality of illusory motion. As Alles [26] showed that location of illusory sensations between two vibrating points are better represented by modulating their amplitudes with a logarithmic function than a linear function, we compare the three onset and decay functions shown in Fig. 4 .

A. Method

Eleven naive participants (four males; 19-34 years old, average=24.7 years) took part in the study with signed consent. The stimuli and procedures were the same as in Experiment 2, except that three onset functions were compared: no (abrupt) onset, linear onset and logarithmic (log) onset, as shown in Fig. 4. In the linear onset condition, the amplitude is linearly changed from 0 (actuator off) to the maximum level, A. In the log onset, the amplitude is linearly changed from 0 dB (relative to the threshold measure in Experiment 1) to the A dB sensation level. With no onset, the amplitude abruptly changes from 0 to A. Corresponding decay functions were used at the end of a period of stimulation. Each participant was tested in 261 trials ($2f \times 2A \times 3d \times 7SOA \times 3$ onset functions + 9 catch trials). The test trials were divided into 9 blocks and tested in a single session of ~ 25 minutes. Participants rated the motion across hands on a 0-5 scale like that in Experiment 2.

B. Results and Discussion

The data for two participants were not included in the analysis because they used only the upper two points of the rating scale. The average rating for catch trials was 1.52, indicating that the scale was properly used by the participants.

A repeated measures ANOVA (duration, SOA and onset function are within factors) performed on the movement ratings showed a main effect of duration [$F(2, 16)=7.0$; $p<0.001$], SOA[$F(6, 48)=75.1$; $p<0.001$], and function [$F(2, 16) = 7.0$; $p=0.007$]. The function–duration interaction was also significant [$F(12,96)=2.0$; $p=0.03$]. The absence of a 3-way interaction reflected the finding that the rating/SOA function varied with onset function similarly at each duration. The common pattern is shown in Fig. 5. Also shown are quadratic fits. The trend is that the no-ramp onset elicits increasingly poorer ratings as the SOA increases, with little difference between linear and log onsets.

As linear onset conditions were used both in this study and Experiment 2, a comparison is useful to show the reliability of the findings (see Fig. 5). The two studies produced highly similar results both qualitatively (quadratic trends, peak location near midpoint of range) and quantitatively, except that the present data show a flattening of ratings across the mid-range SOAs for the 100-msec duration. This relative insensitivity to SOA near the optimal value could reflect uncertainty introduced by the presence of non-linear onset functions in the current study, particularly as the stimulus duration approaches the lower limit for consistently generating continuous apparent motion.

Our results show onset functions, as well as duration and SOA, affect the quality of illusory motion across two separated hands. Participants rated a movement more continuous when an onset function was introduced, especially for long SOAs. This suggests that to generate a continuous motion, it is important to have a smooth transition of amplitude, either linearly or logarithmically, at the beginning and the end of the stimulus.

VI. Experiment 4: Tactile-Visual Matching

In Experiments 2 and 3, we determined control parameters for generating smooth apparent tactile motion. In Experiment 4, we match the apparent motion across the two hands with coherent moving visual cues presented on the tablet screen, in order to examine visual-tactile modality effects. A function that optimizes the relation of visual motion to tactile motion, can potentially be used to create coherent visual-tactile multisensory content on the tablet screen, thereby enhancing tactile effects.

A. Methods

Ten participants (five males; 18-27 years old, average = 22.6 years) performed the matching task with signed consent.

Participants sat comfortably on a chair and held the tablet sleeve as instructed by the examiner. In each trial, participants were presented with a black ball (diameter 15.88 mm) moving continuously from the extreme left to the right on the white background screen (screen width: 172 mm). A tactile illusory motion cue was also played simultaneously with the moving visual cue. Participants were asked to "match the haptic vibration with the visual ball" by adjusting a slider whose ends were marked as "slow" and "fast", highlighting the temporal aspect of the events as the relevant dimension of comparison. The slider simultaneously varied the duration of tactile stimulation (20 msec to 1000 msec) and the SOA by the function presented as (1) in order to optimize the continuous motion. Participants could play the visual cue as many times as they wanted and had unlimited time to adjust the slider that resulted in best visual-tactile coherence. After matching the two cues, participants rated their confidence in the judgment on a 5-point scale (1: low confidence and 5: high confidence).

Each participant matched the visual stimulus, corresponding to five travel durations (V_t = 229, 481, 733, 985 and 1237 msec), with tactile motion. These travel durations corresponded to "fast and lively" to "slow and sluggish" motion of the ball (as judged by the experimenters) and were assigned to the full slider range. Two frequencies

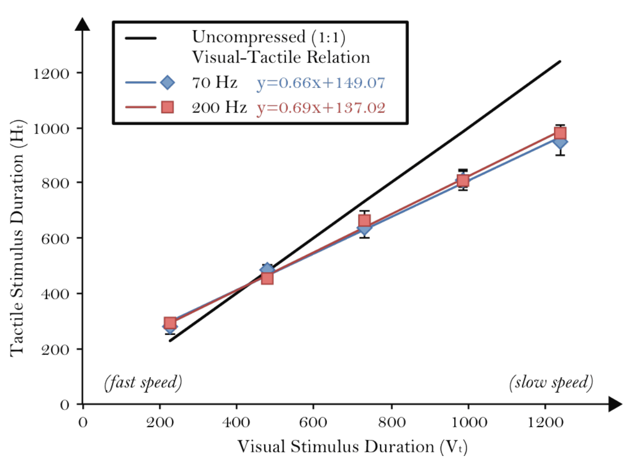

Figure 6. Duration of tactile event for 5 visual durations. Error bars are 1 standard error.

(70 and 200 Hz) were tested, and a participant completed 20 trials (2 frequencies × 5 durations × 2 repetitions) within 20 minutes.

B. Results and Discussion

From the matching data, the duration of tactile stimulation (H_t) corresponding to each duration of the visual stimulus V_t was determined. Tactile stimulation was measured from the time of ramp-up of the first stimulus to the complete decay of the second stimulus as shown in Fig. 4(b). Therefore, $H_t = SOA_O + 1.4d$.

The data suggest that participants matched duration between the modalities, as can be seen by the linearity of the relation between tactile and visual durations, as shown in Fig. 6. Linear fits show essentially equivalent compression of visual duration by the tactile system, regardless of frequency, by a factor of approximately 1/3. There was very little error at short durations, but increasing fall-off of the tactile duration judgment as visual duration increased. A repeated measures ANOVA with frequency and visual duration as within-subject factors showed significant effects of the duration of the visual stimulus [$F(4, 36)=30.703$; $p<0.001$]; no effect was observed for frequency [$F(1, 9)=0.377$; $p=0.554$] or the duration-frequency interaction [$F(4, 36)=1.231$; $p=0.314$].

The under-estimation of duration occurred despite the slightly greater tactile distance (4 mm more for the actuator distance between hands than the screen width). Such an error could be due to the temporal summation in Pacinian corpuscles (PCs), the sensitivity of which is reduced at stimulation durations less than 250 msec [17].

The results of Experiment 4 set a foundation for efforts to link apparent tactile motion to vision. Rendering algorithms must clearly adjust the tactile stimulus to compensate for tactile compression of duration. This study triggers many other interesting questions, such as whether the distortion is isotropic, how to match curved pathways when multiple actuation pairs are possible, whether the size of the ball should yoke to the intensity of vibrations, etc. These effects are left for future investigations.

VII. Concluding Remarks & Implication of Results

In this paper, we investigate inter-manual apparent tactile motion while holding a handheld tablet sleeve. The main motivation is to determine how the media displayed on the tablet screen can be augmented with coherent, dynamic and expressive tactile content. We present four experiments that systematically evaluate the illusory motion evoked by stimulating the hands with vibrotactile stimulations. We first calibrate the device and estimate the absolute detection thresholds at five test frequencies. The thresholds are similar and follow the same trend as in prior literature, and are the same at the two hands.

Experiments 2 and 3 determine the control parametric space for apparent motion across the hands. Frequency and amplitude of vibrations influence the illusory motion; however, duration of stimulation and SOA are key parameters to control the quality of continuous motion between two vibratory points. Moreover, gradual transitions of amplitude further smoothen the illusory motion. We present a psychophysical model that relates stimulus durations to optimal SOA values for creating smooth continuous motion, and then utilize this model to determine visual-tactile matching functions for generating coherent tactile experience for visual media. Such results will be useful for media designers, game developers, researchers to use them with gloves, tablets and cellphones, hand controllers, toys and many more.

Acknowledgment

We wish to thank Micah Fenner for programming the experiment interfaces.

References

[1] S. Zhao, O. Schneider, R. Klatzky, J. Lehman, and A. Israr, "FeelCraft: Crafting Tactile Experiences for Media Using a Feel Effect Library," in *Proceedings of the Adjunct Publication of the 27th Annual ACM Symposium on User Interface Software and Technology*, New York, NY, USA, 2014, pp. 51–52.

[2] S. Brewster, F. Chohan, and L. Brown, "Tactile feedback for mobile interactions," in *Proceedings of the SIGCHI conference on Human factors in computing systems*, 2007, pp. 159–162.

[3] E. Hoggan, S. Anwar, and S. A. Brewster, "Mobile multi-actuator tactile displays," in *Haptic and audio interaction design*, Springer, 2007, pp. 22–33.

[4] G.-H. Yang, M. Jin, Y. Jin, and S. Kang, "T-mobile: Vibrotactile display pad with spatial and directional information for hand-held device," in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, 2010, pp. 5245–5250.

[5] K. Yatani and K. N. Truong, "SemFeel: a user interface with semantic tactile feedback for mobile touch-screen devices," in *Proceedings of the 22nd annual ACM symposium on User interface software and technology*, 2009, pp. 111–120.

[6] J. Seo and S. Choi, "Initial study for creating linearly moving vibrotactile sensation on mobile device," in *Haptics Symposium, 2010 IEEE*, 2010, pp. 67–70.

[7] N. Yannier, A. Israr, R. Klatzky, and J. Lehman, "FeelSleeve: Haptic Feedback to Enhance Early Reading," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2015.

[8] S. J. Lederman and L. A. Jones, "Tactile and haptic illusions," *Haptics IEEE Trans. On*, vol. 4, no. 4, pp. 273–294, 2011.

[9] G. Riva, F. Davide, and W. A. IJsselsteijn, "Presence in the past: what can we learn from media history?," in *Being there: concepts, effects and measurements of user presence in synthetic environments*, Amsterdam ; Washington, D.C. : Tokyo: IOS Press ; Ohmsha, 2003, pp. 17–40.

[10] S. Zhao, "Feeling Stories: Enriching Story Listening Experience for Children with Haptic Feedback." Unpublished senior honors thesis, Carnegie Mellon University Dept. of Psychology, 2014.

[11] *"Sony DualShock®4 Controller,"* [online] 2014, http://www.playstation.com/en-us/explore/accessories/dualshock-4-wireless-controller/

[12] Y. Kim, J. Cha, I. Oakley, and J. Ryu, "Exploring Tactile Movies: An Initial Tactile Glove Design and Concept Evaluation," *Multimed. IEEE*, vol. PP, no. 99, pp. 1–1, 2009.

[13] J. Lee, S. Lee, and G. J. Kim, "Funneling and Saltation Effects for Tactile Interaction with 'Detached' Out of the Body Virtual Objects," in *Human-Computer Interaction–INTERACT 2013*, Springer, 2013, pp. 104–121.

[14] M. Miyazaki, M. Hirashima, and D. Nozaki, "The 'cutaneous rabbit' hopping out of the body," *J. Neurosci.*, vol. 30, no. 5, pp. 1856–1860, 2010.

[15] A. Brisben, S. Hsiao, and K. Johnson, "Detection of vibration transmitted through an object grasped in the hand," *J. Neurophysiol.*, vol. 81, pp. 1548–1558, 1999.

[16] A. Israr, S. Choi, and H. Z. Tan, "Detection threshold and mechanical impedance of the hand in a pen-hold posture," in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, 2006, pp. 472–477.

[17] R. T. Verrillo and G. A. Gescheider, "Perception via the sense of touch," *Tactile Aids Hear. Impair.*, pp. 1–36, 1992.

[18] C. E. Sherrick and R. Rogers, "Apparent haptic movement," *Percept. Psychophys.*, vol. 1, no. 3, pp. 175–180, 1966.

[19] G. Bekesy, "Funneling in the nervous system and its role in loudness and sensation intensity on the skin," *J. Acoust. Soc. Am.*, vol. 30, no. 5, pp. 399–412, 1958.

[20] R. Flach and P. Haggard, "The cutaneous rabbit revisited.," *J. Exp. Psychol. Hum. Percept. Perform.*, vol. 32, no. 3, p. 717, 2006.

[21] F. A. Geldard and C. E. Sherrick, "The cutaneous' rabbit': a perceptual illusion," *Science*, vol. 178, no. 4057, pp. 178–179, 1972.

[22] A. Israr and I. Poupyrev, "Tactile brush: drawing on skin with a tactile grid display," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2011, pp. 2019–2028.

[23] H.-Y. Yao and V. Hayward, "An experiment on length perception with a virtual rolling stone," in *Proceedings of Eurohaptics*, 2006, pp. 325–330.

[24] H. E. Burtt, "Tactual illusions of movement.," *J. Exp. Psychol.*, vol. 2, no. 5, p. 371, 1917.

[25] A. Israr and I. Poupyrev, "Control space of apparent haptic motion," in *World Haptics Conference (WHC), 2011 IEEE*, 2011, pp. 457–462.

[26] D. S. Alles, "Information transmission by phantom sensations," *Man-Mach. Syst. IEEE Trans. On*, vol. 11, no. 1, pp. 85–91, 1970.

[27] M. R. Leek, "Adaptive procedures in psychophysical research," *Percept. Psychophys.*, vol. 63, no. 8, pp. 1279–1292, 2001.

[28] C. E. Sherrick, "Bilateral apparent haptic movement," *Percept. Psychophys.*, vol. 4, no. 3, pp. 159–160, 1968.