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# Intermanual Apparent Tactile Motion and its Extension to 3D Interactions

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**Abstract**— Information provided by sensory systems is inherently ambiguous as to its source in the physical world. To arrive at a coherent representation, perception deploys heuristic rules and multimodal input, which potentially produce errors such as *illusions*. The current work uses these effects to create apparent tactile motion and illusory depth motion using sparse vibrotactile stimulation across the hands. Experiment 1 showed the effects of vibrotactile duration and temporal separation between the hands on the quality of perceived illusory linear motion. Experiment 2 indicated a compressed linear relation between the visual and tactile speeds, and established a linear function relating visual size to perceived tactile intensity at three durations. Experiment 3 introduced an "M-filter" algorithm that varies tactile stimulus amplitude by a parabolic function based on visual looming and receding. It demonstrated that the M-filters, accompanied by visual depth cues, can induce tactile motion in depth. Experiment 4 showed the M-filter algorithm is necessary to create tactile perception in depth, as opposed to apparent tactile motion. The current research has value for a basic understanding of haptic perception, as well as haptic applications that digitally generate perceptual representations of the distal world on small-sized devices in the space between the hands.

**Index Terms**— Human-Computer Interaction, Multimodal Systems, Perception and Psychophysics, Tactile Devices

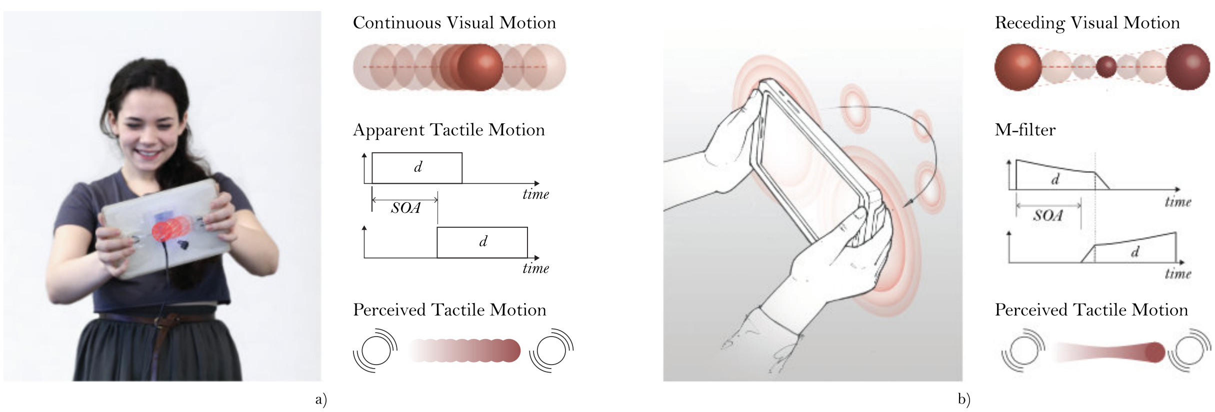


Fig. 1. a) *left:* A user holding a handheld device (tablet) embedded with two tactors pressing the hands. *right:* graphical illustration and parametric composition of apparent tactile motion and its corresponding visual and perceived tactile cues. b) *left:* An illustration of the illusory out-of-body tactile experience generated by the M-filters, resembling the trajectory of a boomerang. *right:* graphical illustration and parametric composition of M-filters and its visual and perceived tactile cues.

## 1 Introduction

The sense of touch is sometimes called a "proximal" modality to contrast it with vision and audition, which receive sensory stimulation from sources far outside the body. Touch shares with other modalities, however, the property of non-determinism: the same pattern of sensory stimulation can result from many different events. For example, the sensation registered by the fingers when touching a piece of soft rubber may resemble that of touching the skin; or pressure sensations triggered by the hand contacting a surface can also result from the impact of a light falling object.

Despite the ambiguous information from the senses, our perceptual systems arrive at a coherent representation of surfaces, objects, and events in space [1], [2]. One mechanism that perceptual systems employ to resolve the ambiguity is applying deeply embedded knowledge, or heuristic rules. For example, our life-long experience of perceiving and interacting with objects that are holistic and complete (embedded knowledge) has well adapted the visual perception system to arrive at a representation of an object's contours even when it is partly hidden. This embedded knowledge supports the assumption that edges complete along straight lines or simple curves, which

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give rise to Kanizsa's Triangle [3]. A parallel example in the touch modality is apparent motion, which arises from an underlying assumption that similar objects that are coupled in space and time are likely to be a single object undergoing motion. Such heuristic rules, while critical to formulating coherent and effective perception of the world, give rise to compelling illusory perceptions [4].

Although illusions arising from heuristic rules might be considered as perceptual errors, they can play an essential role in enriching the external world in the mind of the perceiver. A number of touch illusions triggered by discrete points on the skin with calculated timing and location can give rise to movement perception [5]. For instance, *apparent tactile motion* (Fig. 1a), generated by two separate but closely placed stimuli on the skin with different onset times, is perceived as a single vibration moving from one point of stimulation to the other [6], [7], [8], [9]. Similarly, the *saltation* illusion gives the percept of an illusory point jumping between the locations of physical stimulations even though it is created with two stationary vibrating stimuli [10], [11], [12]. Though originated from perceptual error, these illusions convert simple sensory stimulation to more dynamic percepts.

A further means of compensating for sensory ambiguity and arriving at a coherent perceptual representation is through integration with other modalities. Visual-touch interactions have been extensively studied in this regard. Ernst and Banks [1] proposed maximum-likelihood estimation as the method used by human perception to integrate visual and haptic information about a common spatial source. Under their model, the estimate of a physical property from multiple sensory modalities weights each input channel by its reliability, resulting in minimized variance in the bimodal percept. They found that in estimating the height of a step-edge, vision dominated over touch in the absence of noise, but haptic input was weighted more as visual noise increased. The higher weighting for vision in the context of visual-haptic stimulation also occurs when perceiving other features such as size, shape, stiffness, and depth [13], [14], [15]. A classic study by Rock and Victor demonstrated complete dominance of vision over touch, or visual capture, when participants were asked to report the width of an object that they simultaneously viewed and grasped [13]. Singer and Day reported similar results of visual capture for depth judgments of objects simultaneously seen and held in the hand [16].

Similar to the way in which embedded rules can lead to illusions, multi-sensory integration can also create misperception, particularly in the domain of motion. For example, an auditory click timed with the cross-over of two apparent motion paths can lead to the impression of collision for linear motion [17]. Another example is cross-modal motion after-effects: watching a drifting visual grating for 10 seconds alters the perceived direction of subsequent tactile sweeps across the finger pad [18]. Similarly, magnified scaling of visual motion in response to hand movement leads to false overestimation in subsequently haptically guided movement [19], [20].

### 1.1 Haptic Technologies that Exploit Haptic Illusions and Inter-modal Interactions

Much research in haptic technology harvests the tendency for illusory and mis-perceived content in the haptic system to expand on the impact of haptic technologies. Illusions are especially useful in enhancing devices for which the basic effects are local and sparse.

Generating illusions on a device can be exploited to improve the experience and functionality of current haptic feedback technology, such as devices that use multiple vibrotactile actuators to stimulate several locations of the skin (e.g. grid and array configurations) [21], [22], [23]. For example, Yatani and Troung induced apparent motion between stimulation points on a mobile phone to deliver directional and attention information [22]. Israr and Poupyrev [24] created dynamic moving patterns with apparent motion on the back of a user using a grid of voice-coil actuators embedded in the chair. The haptic saltation illusion has been employed to replace visual progress bars [21], to give a percept of an object in between the fingertips [25], and to enhance children's reading on a tablet screen by simulating an animal running on the hands [26].

Illusions have further been used to create 3-dimensional percepts with a 2-dimentional surface. For example, Kim and Lee induced a haptic illusion of compliance of hard surfaces and used it to design virtual buttons for realistic and responsive user experience [27]. Saga and Raskar designed a system that allowed users to feel geometric shapes on flat touchscreens [28]. By sliding their fingers on the screen, users could detect 3D features, like large bumps. Kim and colleagues also modified lateral friction force with electro-vibration touchscreens to create the illusory perception of bumps and edges [29].

Beyond illusions, combining visual and haptic inputs is another method applied in haptic technology to recreate multisensory input and enhance virtual experience. ReFlex was designed to combine visual, tactile, and kinesthetic cues to augment the experience of a flexible smartphone [30]. Another example is a multisensory workbench that combined visual, audio, and haptic information to provide a fully immersive virtual working environment where users completed various tasks [31]. Such visual-haptic interactions can also be exploited creatively to scale interactive experience with multiple virtual objects using a single physical object. Azmandian and colleagues manipulated visual representation of the virtual human and world to re-adjust the haptic coordinate in a simulated environment, such that a single physical prop can provide haptics for multiple virtual objects [32].

### 1.2 Present Approach

The previous examples showcase how illusions and inter-model interactions have been utilized in haptic technology. The present studies combine the 2 mechanisms and introduce methods for inducing motion by means of tactile cues with supporting visual cues on a conventional tablet computer equipped with inexpensive vibrotactile actuators. First, we demonstrated that people could experience apparent tactile motion across the two hands holding a tablet with embedded actuators. Critical parameters that control the quality of the illusory motion were also investigated, resulting in a general equation for optimal values. A second set of studies augmented the platform with a simple visual display and a moving visual cue, and determined optimal visual parameters for pairing with the apparent tactile motion effect.

These initial results formed the basis of a custom algorithm for an *M-shaped filter on tactile intensity* (an M-filter) that varies vibrotactile amplitude by a pre-designed function. The "M" refers to the shape of the amplitude profile over time and across the two hands. The algorithm produces apparent tactile motion in depth with a spatio-temporal vibrotactile stimulation pattern. When strategically integrated with contraction and expansion of the visual display, the M-filter induces the illusion of an object traveling away from and back towards the device plane, similar to the traveling path of a *boomerang* (Fig. 1b). This technique augments haptic feedback to create complex moving trajectories beyond the 2D plane of small portable devices, e.g., tablets and hand controllers. A relevant approach was studied in [33] using multiple tactile pulses to convey tactile depth. However, it examined tactile depth perception on a continuous skin area, e.g., forehead, with a focus on one tactile depth pattern.

The current approach differs from existing force-feedback haptic devices that create depth information, such as TouchMover [34], SensAble's Phantom [35] and SPIDAR [36], in several ways. First, it requires no additional, often cumbersome, hardware to generate haptics. In addition, because the haptic feedback is delivered through the actuators placed on the back of the tablet, where the user's hands are placed, the users can perceive the feedback while maintaining their natural interactions with the device. This distinguishes our approach from another common method of creating depth information, which is to apply a lateral force on a sliding finger [28], [37], [38]. As this approach relies on users' actively exploring a surface over time in order to perceive the depth information, it potentially disrupts the use of the fingers for other purposes, such as control and motion. Another distinguishing feature of our method is that it creates illusory depth; users feel changing distance to a distal location rather than a depth profile at the point of contact. In contrast, the existing 3D haptic feedback devices provide haptic feedback for proximal stimuli, i.e., users only feel haptic input for events occurring at the point of contact.

## 2 Intermanual Apparent Tactile Motion

### *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 was embedded with two voice-coil actuators (Tectonic Elements Ltd., model: TEAX19C01-8, Cambridgeshire, UK) at the two ends. They were spaced 176 mm apart (determined by multiple users' hand positions when holding the tablet) and pressed against a vibrating flap on its back that directly stimulated the skin of the user's hands (Fig. 1). The detailed design of the sleeve is presented in [26].

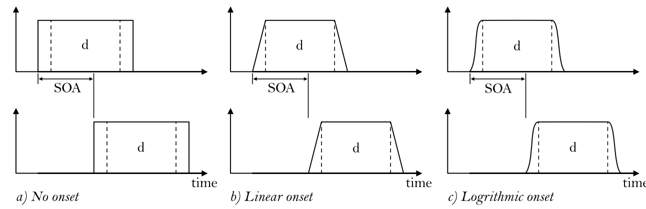


Fig. 2. Three types of onset function used in apparent tactile motion.

The sleeve was calibrated by 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 near detection threshold levels to 30 dB above threshold. While a user held the apparatus, vibrations were measured by a pair of MEMS accelerometers (ADXL335, Analog Devices, Inc, USA), mounted on the top of the vibrating elements. Each accelerometer measurement was analyzed by computing its FFT (Fast Fourier Transform) and plotting the FFT in the frequency-amplitude plane. The two actuators behaved identically in the FFT space and operated linearly with low noise and distortion across the test range. The response times for the two actuators were measured to be less than 1 msec. A frequency-dependent function was determined, which relates the waveform amplitude in the tablet software to the measured acceleration. This function was used to determine the detection threshold levels in acceleration units.

### 2.1 Experiment 1: Intermanual Apparent Tactile Motion[1]

As apparent tactile motion is the foundation for our evoked motion in depth, it was necessary to establish that apparent motion can be perceived between the two hands holding a tablet. The first two studies tested for linear motion between the hands and examined the parameters that determine the quality of the perceived motion in terms of continuity.

#### *2.1.1 Experiment 1a: Control Parameters for Intermanual Apparent Tactile Motion*

The purpose of this experiment was to demonstrate the perception of tactile apparent motion across the hands and to determine how it is moderated by 4 parameters: frequency $f$, amplitude $A$, duration $d$ and *SOA*.

#### *Participants*

Eleven naive participants (6 males; 19-38 years old, average=25.4 years) were recruited. All participants gave signed consent.

#### *Stimuli*

Haptic stimuli that create apparent tactile motion are typically defined by duration ($d$), frequency ($f$), and amplitude ($A$). Other parameters that characterize the stimulus are temporal onset interval (SOA, short for stimulus onset asynchrony) and attack and decay fading functions (Fig.

[1] Experiment 1a, 1b, and 2a were previously published at World Haptics Symposium 2015 [40]

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2). Much research on the control space for apparent tactile motion has shown that duration and SOA between the stimuli play a significant role in generating the apparent motion [6], [7], [24].

In this experiment, 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. The SOA variable had 7 levels, specific values of which depended on the duration. A pilot study 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 SOA ranges were: for 100 msec duration, 15-160 msec; for 400 msec duration, 15-350 msec; and for 700 msec duration, 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 over an interval equal to 20% of the stimulus duration, as shown in Fig. 2b.

### Procedure

Participants held the tablet sleeve with the experiment interface displayed on the screen. They experienced 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 a total of ~45 minutes. Breaks between blocks and pink noise masks were used.

Participants were initially told that the vibratory-induced motion was an illusion and there was no physical object traveling across their hands. In each trial, they felt the illusory motion cue 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.

### Results

User ratings (0 through 5) were averaged for each parameter across participants. For catch trials (SOA = 0), where low scores would be expected, average 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-participant factors). The analysis showed no effect of frequency [$F(1,10)=0.06$; $p=0.81$ $\eta_p^2=0.006$] or amplitude [$F(1,10)=3.16$, $p=0.11$, $\eta_p^2=0.24$]; nor was the frequency-amplitude interaction significant [$F(1,10)=0.56$, $p=0.47$, $\eta_p^2=0.05$]. There was a significant interaction between amplitude and SOA [$F(6,60)=3.32$, $p=0.007$, $\eta_p^2=0.25$], 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.

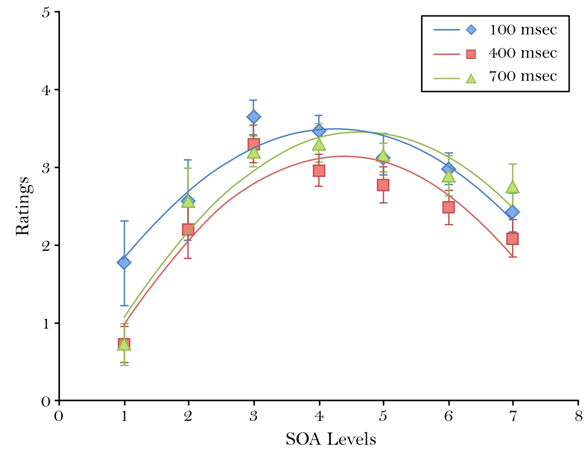



Fig. 3. Average ratings of continuous motion as a function of SOA. Error bars show standard error.

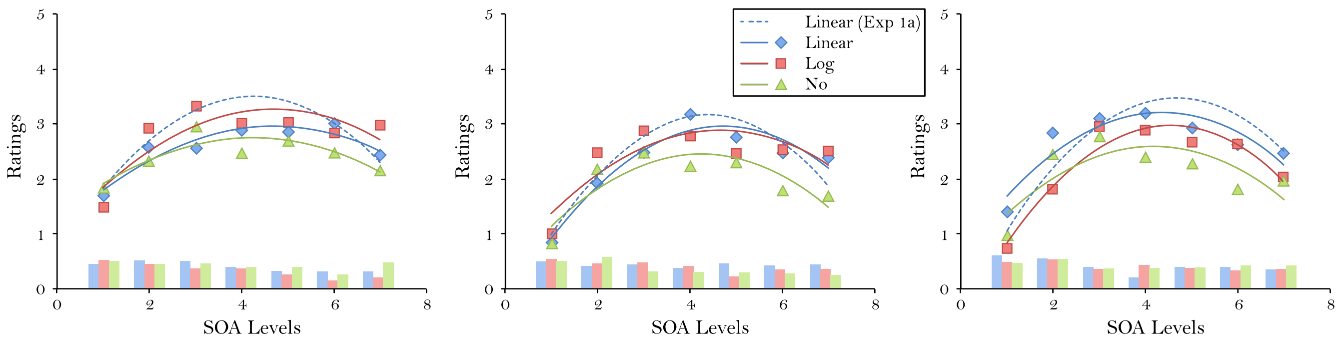
The principal findings were that stimulus duration and SOA produced significant effects: duration [$F(2,20)=6.0$, $p=0.009$, $\eta_p^2=0.38$] and SOA [$F(6,60)=11.92$, $p<0.001$, $\eta_p^2=0.54$]. The duration-SOA interaction was also significant [$F(12,120)=2.30$, $p=0.01$, $\eta_p^2=0.19$]. Fig. 3 presents the interaction by plotting average ratings as a function of SOA for the three test durations, along with best-fit quadratic trends. The peak location, which indicated the optimal SOA, tended to be near the midpoint of the SOA range, i.e. between level 3 and level 5.

### 2.1.2 Experiment 1b: Effect of Onset Functions on Apparent Tactile Motion

Experiment 1a excluded two critical parameters of apparent tactile motion, the onset and decay of the waveform. Experiment 1b examined the effects of these parameters on the quality of illusory motion. This was motivated by pilot tests indicating that gradual change in amplitude resulted in smoother apparent motion than when the amplitude changed abruptly. As Alles [39] showed that location of illusory sensations between two vibrating points are better represented by modulating their amplitudes with a logarithmic function than a linear one, we compared log and linear progressive onsets to abrupt onset.

### 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 1a, except that three onset functions were compared: no (abrupt) onset, linear onset and logarithmic (log) onset, as shown in Fig. 2. In the linear onset condition, the amplitude changes linearly from 0 (actuator off) to the maximum level, $A$. In the log onset, the amplitude changes linearly from 0 dB (relative to the threshold measure in [40]) 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 stimulation.




*a) Duration = 100 msec* *b) Duration = 400 msec* *c) Duration = 700 msec*

Fig. 4. Average ratings of continuous motion as a function of SOA levels for three stimulus durations and onset functions. Bars at the bottom show the standard errors by condition.

Each participant was tested in 261 trials (2*f* × 2*A* × 3*d* × 7*SOA* × 3 onset functions + 9 catch trials with SOA=0). 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 as in Experiment 1a.

### *Results*

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 the catch trials was 1.52, indicating that the scale was properly used by the remaining participants.

A repeated measures ANOVA (duration, SOA and onset function are within-participant factors) performed on the movement ratings showed a main effect of duration [F(2, 16)=7.0; p=0.007, $\eta_p^2$=0.47]; SOA[F(6, 48)=5.06, p<0.001, $\eta_p^2$=0.39]; and function [F(2, 16) = 7.0, p=0.007, $\eta_p^2$=0.47]. The function–SOA interaction was also significant [F(12,96)=2.0, p=0.03, $\eta_p^2$=0.20]. The absence of a 3-way interaction indicates that the rating/SOA function varied with onset function similarly at each duration. The common pattern is shown in Fig. 4. 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.

### *Discussion*

Experiment 1a and 1b show 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 SOA. Onset functions that generate a smooth transition of amplitude, either linearly or logarithmically, at the beginning and the end of the stimulus, are critical to crafting a continuous motion. Frequency and amplitude of stimulation have little influence on the apparent motion. These results are consistent with previous studies by [7], [8].

The results indicate that the peak location on the rating versus SOA function, corresponding to 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:

$$SOA_o = 0.28 \times d + 60.70 \tag{1}$$

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

## 2.2 Experiment 2: Visual-Haptic Multimodality Effect on Intermanual Apparent Tactile Motion

Experiment 1 determined control parameters for generating smooth apparent tactile motion. Experiment 2 assessed the potential contribution of vision to the phenomenon by testing whether the tactile effect could be enhanced by pairing the vibratory cues with a moving visual stimulus. The speed (Experiment 2a) and size (Experiment 2b) of the visual display were varied to seek optimal values.

### *2.2.1 Experiment 2a: Tactile-Visual Speed Matching*

In this study, participants adjusted the vibrotactile cues in order to match the apparent speed of tactile illusory movement with the speed of a visual stimulus that crossed the tablet.

### *Methods*

The same physical setup was used as in Experiment 1. In each trial, participants were presented with a black ball (diameter 16 mm) moving continuously from the extreme left to the right on the white background screen (screen width: 172 mm). This visual cue was accompanied by a tactile illusory motion cue, which was triggered simultaneously with the onset of the visual path. 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 varied both the duration of tactile vibration (20 msec to 1000 msec) and the SOA, where the two parameters were cross-mapped according to Equation 1 in order to to optimize the tactile illusory motion. Participants had an unlimited period to respond, during which paired visual/tactile events re-occurred. After matching the two cues,

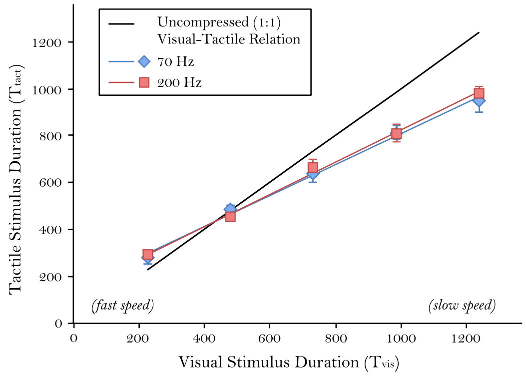



Fig. 5. Duration of tactile event for 5 visual durations. Error bars show standard error.

participants rated their confidence in the judgment on a 5-point scale (1: low confidence and 5: high confidence).

Ten naïve participants (5 males; 18-27 years old, average = 22.6 years) performed the matching task with signed consent. Each participant matched the tactile motion to visual stimuli of five travel durations ($V_{dur}$ = 229, 481, 733, 985 and 1237 msec), initially judged by the experimenters to span a range from "fast and lively" to "slow and sluggish". Two vibrotactile frequencies (70 and 200 Hz) were tested, and a participant completed 20 trials (2 *f* × 5 *d* × 2 repetitions) within 20 minutes.

#### *Results*

From the participants' responses, the total time of the tactile event ($T_{tact}$) that was matched on average to each visual stimulus was determined for each visual stimulus duration $T_{vis}$. $T_{tact}$ was measured from the time of ramp-up of the first stimulus to the complete decay of the second stimulus as shown in Fig. 2b. Therefore, $T_{tact} = SOA_o + 1.4d$ where $SOA_o$ is computed by Equation 1 and $d$ is the duration of the vibratory period on a single hand.

The data suggest that participants matched total event time between the modalities, as can be seen by the linearity of the relation between $T_{tact}$ and $T_{vis}$ shown in Fig. 5. Linear fits show essentially equivalent compression of tactile event time relative to visual stimulus time, regardless of frequency, by a factor of approximately 1/3, according to the equation below:

$$T_{tact} = 0.67 \times T_{vis} + 143.05 \qquad (2)$$

A repeated-measures ANOVA with vibrotactile frequency and visual stimulus time as factors showed a significant effect of visual stimulus time [$F(4, 36)=30.70$; $p<0.001$; $\eta_p^2=0.77$]; no effect was observed for vibrotactile frequency [$F(1, 9)=0.38$; $p=0.55$; $\eta_p^2=0.04$] or the two-way interaction [$F(4, 36)=1.23$; $p=0.31$; $\eta_p^2=0.12$].

### *2.2.2 Experiment 2b: Tactile Intensity-Visual Size Matching*

In this study, the size of the visual ball was adjusted to match the tactile event. The ball speed was set to the value found to be optimal for the given tactile event in Experiment 2a.

#### *Methods*

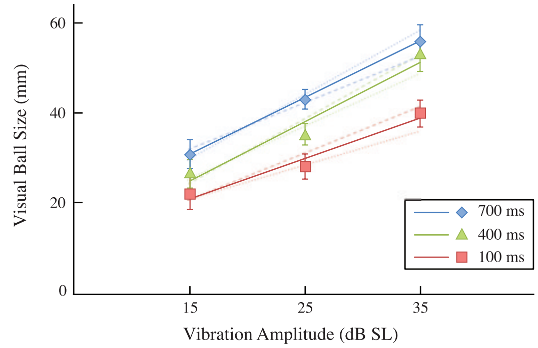



Fig. 6. Average visual ball size response (solid lines) of 70 and 200 Hz as a function of vibration amplitude for three durations (separate plots for 70 Hz: dashed lines and 200 Hz: dotted lines). Error bars show standard errors.

Twenty-two naïve participants (13 males; 19 – 49 years old, average = 23.28) completed the experiment with signed consent. In each trial, participants were presented with a black ball moving continuously from the left to the right of the screen. The ball had a random diameter between 10 - 600 pixels, translating to 1.34 – 80.63 mm on the experiment tablet. As the perceived size of a pixel depends on the screen resolution and other factors, the remainder of the paper refers to all visual sizes on screen in terms of mm. A stimulus producing apparent tactile illusory motion from the left to the right hand was presented simultaneously with the moving ball. Three independent variables characterizing the vibrotactile stimulus on each hand were varied factorially: frequency (*f* = 70 Hz, 200 Hz), amplitude (*A* = 15 dB, 25 dB, 35 dB), and duration (*d* = 100, 400, and 700 ms). These durations correspond to three levels of total tactile event time ($T_{tact}$, which includes vibrations on both hands, ramp periods, and SOA): 229, 733 and 1237 msec. Applying Equation 2, the visual event duration corresponding to the tactile event duration were set at $T_{vis}$ = 276, 638, and 944 msec. The participants' task was to "change the size of the moving ball until it best matches with the haptic vibration". A slider changed the diameter of the moving ball on the screen. Participants were allowed to play the haptic/visual event pair up to five times before setting the ball size. They then rated how confident they were with the match on a 1 (low) – 5 (high) scale. Each participant completed a total of 54 trials (2*f* × 3*A* × 3*d* × 3 repetitions) in less than 25 minutes. Trials were randomly ordered.

#### *Results*

Data for two participants were removed due to a logging error. A repeated-measures 2 × 3 × 3 ANOVA with vibrotactile frequency, amplitude and duration as the factors showed a significant effect of amplitude [$F(2, 38) = 24.07$, $p<0.001$, $\eta_p^2 = 0.56$] and duration [$F(2, 38) = 17.43$, $p<0.001$, $\eta_p^2 = 0.48$], but no significant main effect of frequency on the matched visual size [$F(1, 19) = 0.20$, $p = 0.66$]. Neither a significant 2-way nor 3-way interaction was observed between factors, indicating that the effects of amplitude and duration on visual size are independent. Fig. 6, plotting the two frequencies combined and separately, shows a positive linear relation between both vibrotactile amplitude and duration and matched visual

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size. A multivariate regression using the amplitude and duration of vibration as predictors of visual size accounted for 96.1% of the variance and produced the equation:

$$\text{Size in mm} = 1.16 \times A + .02 \times d - 0.611 \quad (3)$$

### *Discussion*

Experiment 2 provides a foundation for coupling vision with touch in creating illusory movement. It determined parameters that would best match a visual motion cue to apparent tactile motion. When speed was matched (Experiment 2a), two findings emerged: First, the data indicated that participants matched the duration of the two modalities, with systematic compression of the tactile relative to the visual. 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). Although some error might reflect temporal summation in peripheral receptors, particularly Pacinian corpuscles [41], the magnitude of the effect -- a reduction in apparent duration on the order of 300 msec for a 1200 msec stimulus -- suggests an origin deeper in the perceptual stream. Second, the size of the visual object matched to tactile stimulation (Experiment 2b) increased with overall vibrotactile intensity, as jointly determined by amplitude and duration.

Experiments 1 and 2 collectively establish illusory tactile motion in the plane of the hands with matching visual cues on the table. Next, we turn to the possibility that the illusory motion can be extended into depth with the aid of vision.

## 2.3 Experiment 3: M-Filters - Conveying Tactile Illusory Depth with Visual Context

To generate tactile depth with multi-modal interactions, we implemented an algorithm to manipulate the spatio-temporal distribution of vibrotactile stimulation across the two hands. The intention is, by modeling the tactile effect after corresponding effects in vision, to elicit the illusion of an object moving and changing in depth relative to the device plane.

The algorithm is based on an important visual depth cue for distance in the sagittal direction: optical expansion and compression [42]. As an object moves in depth, its visual angle projected on the retina changes, so that the ratio of perceived object size to perceived distance is preserved (Fig. 1b). This association leads to the perception that a 2D object that changes in size over time in the picture plane is changing in depth.

The present haptic algorithm, called an M-filter, provides an analogous cue: similarly to the function relating visual motion in depth to retinal size, the temporal function for apparent tactile motion is varied by intensity, such that the perceived vibration impression is reduced and then strengthened as it travels from one vibrating actuator to the other, as shown in Fig. 7a. Specifically, the amplitude of the leading hand is decreased by a quadratic function while the amplitude of the receiving hand increases linearly. Consistent with apparent tactile motion stimuli, the vibrotactile stimuli on the two actuators are

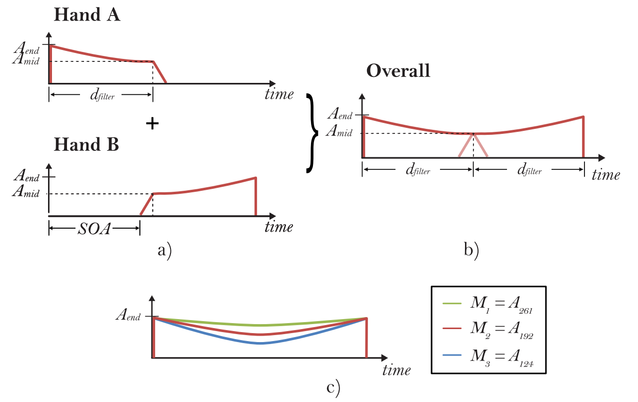


Fig. 7. a) Amplitude/time profile for M-filters separated by hand. b) The profile of amplitude over time of an M-filter across the two hands. c) M-filters with different midpoint amplitudes.

offset by a time period defined by the SOA. When the amplitudes are equal, the shapes of the functions on the two hands are exchanged, with the receiving hand now increasing quadratically and the leading hand decreasing linearly. The quadratic term is used because the relation between the area subtended on the retina by a visual stimulus and its depth is approximated by a quadratic. The linear component on the alternate hand smooths the inter-manual transition, as shown in Experiment 1b.

The total duration of the M-filter is determined by the duration of the apparent tactile motion and the duration of the stimulus on each hand, $d_{filter}$, is exactly half of the total duration. The duration of the linear component is a function of $d_{filter}$ and $SOA$, i.e., $d_{linear} = d_{filter} - SOA$ (Fig. 7a). Two additional parameters that control the M-filter are the amplitude at the end-points ($A_{end}$) and the midpoint amplitude ($A_{mid}$), which is intended to control the maximal depth of the illusory haptic percept. Fig. 7b shows the combined amplitude on the hands and Fig. 7c illustrates M-filters at 3 depths.

Experiments 3a, 3b and 4 tested whether tactile motion in depth could be induced using M filters. Experiment 3a presented vision and touch simultaneously, with baseline measures for each modality alone; 3b used vision to provide a context for subsequent tactile sensations. Experiment 4 compared the depth cue provided by the M-filter to the comparable condition where apparent motion was induced across the hands.

### *2.3.1 Experiment 3a: M-Filters with Simultaneous Presentation of Visual and Haptic Depth Cues*

#### Methods

Twelve naive participants (5 males; 18 – 39 years old, average = 24.5) completed the study with signed consent. Optical expansion and compression were used to create a sense of visual depth on the flat screen of the handheld tablet. As a ball moved from the left to the right side of the screen, its size changed by a quadratic function simulating smoothly receding to a maximal distance, then looming back to the starting depth (similar to Fig. 1b right). The size of the visual ball as it entered from the left side of the screen was 52.68 mm. Its size initially decreased along a quadratic function to a minimum of 16.67, 25.8, or 35.07 mm at the midpoint of the screen, and then

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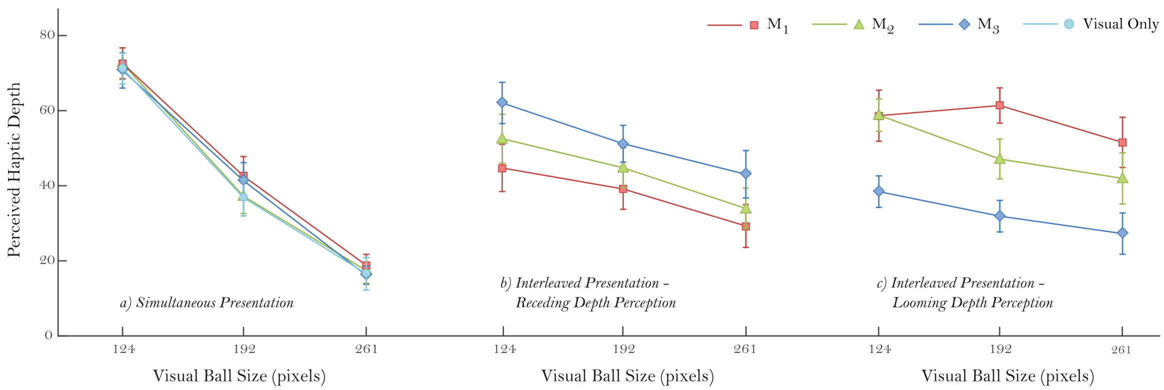


Fig. 8. Average of haptic depth responses across three visual depths for participants who perceived a) simultaneous visual-haptic cues (Exp. 3a) and b) interleaved visual-haptic cues but with the haptic event as receding away from them (Exp. 3b) and c) with the haptic event as looming towards them (Exp. 3b). Error bars show standard errors.

increased at the same rate back to 52.68 mm when it exited from the right side of the screen. The total duration of the ball's movement was 638 msec (i.e., $d$ = 400 msec).

Haptic stimulation coincident with the visual event was generated by the two actuators vibrating at 70 Hz with an amplitude defined by the M-filters. The beginning and ending amplitudes ($A_{end}$) of the M-filters were 36 dB above the absolute detection threshold. This matched with the size of the visual object as it entered and left the screen, according to Experiment 2b. At mid points, the amplitude values ($A_{mid}$) were 22.7 (M1), 15.7 (M2), 8.7 (M3) dB above absolute detection threshold (Fig. 7c), corresponding to the sizes of the visual ball at the mid point (35.07, 25.8, 16.67 mm). We hypothesized that the less the midpoint amplitude, corresponding to a smaller visual circle, the deeper people would perceive the haptic event to be. The total duration of the haptic event across both hands was 733 msec, as was used in Experiment 2.

Trials with visual and haptic only stimulation were included for comparison. In total, each participant completed 45 trials: 3 repetitions of [4 visual sizes (no visual, 16.67, 25.8, 35.07 mm) × 4 M-filter depths (no haptics, 22.7, 15.7, 8.7 dB mid amplitude)]. Trials were randomly ordered.

For each trial, participants were presented with a stimulus generated by a combination of the visual and/or haptic protocols. The stimulus was repeated three times before a vertical slider appeared on the right side of the screen. Participants moved the slider to indicate how far the object seemed to move away from them at its furthest point based on the visual and haptic cues provided to them. A higher slider position indicated greater maximum depth. In the logged data, the position of the slider was translated to a numeric value between 0 and 100, where 100 corresponded to the highest slider position. However, in the experiment, the slider was not marked with measuring units nor values at the two ends. Hence, to get a sense of how to map depth to the slider, participants completed five training trials where they experienced the full range of the depth variations before starting the recorded experiment.

### *Results and Discussion*

A 3 × 3 repeated-measures ANOVA with visual object size and M-filter depth as factors analyzed the sub-design in which both modalities were present. It showed no significant effect of the M-filter depth on depth ratings of the objects [$F(2, 22) = 1.98$, $p = 0.16$], but the visual ball size significantly affected the responses [$F(2, 22) = 159.56$, $p < 0.001$, $\eta_p^2 = 0.94$]. The different M-filter levels, when presented simultaneously with visual stimuli, did not influence people's depth perception of the object. In fact, people's responses to visual cues alone were the same as their responses for visual and haptic cues together (as shown in Fig. 8a). Instead the visual information completely controlled the response, demonstrating visual capture and visual dominance.

The ANOVA was followed with two separate analyses examining the effect of multimodal over uni-modal stimulation. To assess the effect of a haptic cue on the visual depth, a 2-way repeated measures ANOVA was done with factors: visual depth (3) and presence/absence of haptic stimulation. The haptics-present condition used data from trials with visual stimuli accompanied by the deepest M-filter haptic stimuli (M3). The result showed no effect of presence/absence of haptic stimulation in addition to the visual depth stimuli [$F(1, 11) = 0.21$, $p = 0.66$]. A corresponding analysis was done to assess the effect of the presence of visual input, on the influence of haptic depth, now using data for the deepest visual depth for the vision-present condition. It showed a significant effect of the presence of visual stimuli on participants' sense of depth [$F(1, 11) = 32.10$, $p<0.001$, $\eta_p^2 = 0.75$]. In fact, the haptic-only data showed that the depth illusion could not be induced without the presence of vision: the means for the three M-filter depths were 39.0, 42.7, and 39.4, where 0 meant no perceived depth and 100 represented maximum perceived depth.

Taken together, the analyses illustrate the dominating effect of vision on the haptic stimuli and the lack of effect of the haptic M-filters when vision is present. In Experiment 3b, we attempted to reduce visual dominance while retaining visual influence by separating the two modalities in time. We hypothesized that the strong illusion of depth induced by vision might create a spatial mental representation that modified depth perception of the subsequent illusory haptic depth cue, similar to a motion

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aftereffect [43].

#### 2.3.2 Experiment 3b: M-Filters with Interleaved Presentation of Visual and Haptic Depth Cues

*Methods*

Twenty-one participants (11 males; 20 – 50 years old, average = 24.90; none participated in previous experiments) completed the study with signed consent. The stimuli for Experiment 3b were the same as Experiment 3a, with three levels of M-filters and three midpoint ball sizes as the independent variables. However, instead of presenting the visual and haptic cues simultaneously, they were interleaved, i.e., the visual cue preceded the haptic cue. After each cue, participants were asked to use the slider to rate how far away the visual object or haptic object seemed to go, similar to Experiment 3a. In order to avoid perseverative spatial mapping for the visual and haptic responses, the sliders for visual and haptic ratings were on different sides of the screen. All possible visual and haptic combinations were presented as two-trial sequences, in random order. Participants were not informed about the alternation of modalities and treated each trial, visual or haptic, as an independent event to be rated for depth. After the participants had completed all the trials, they were asked which direction they perceived the haptic object to travel, i.e., towards them or away from them. Participants were also asked how they used the haptic cues in their reports. Each participant completed 27 visual-haptic paired cues (3 repetitions × 3 visual ball sizes × 3 M-filter depth) in approximately 20 minutes.

*Results*

One participant's data were excluded from the analysis because the participant reported poor vision in one eye and could not properly perceive the visual depth cue. Based on our post-study interview, of the remaining 20 participants, 15 participants perceived the haptic stimuli as receding away from them before returning to its starting depth. When asked what physical property of the haptic stimuli they associated with the distance the objects travelled, these participants responded that the less the intensity at the midpoint, the farther away they would perceive the haptic object to be, analogously to visual size and depth (similar to Fig. 1b top). The remaining five participants perceived haptic depth in the reversed direction, such that the haptic object loomed towards them and then away from them to the starting depth. Of these, two reported that they perceived lower midpoint intensity as near them; the others gave alternative explanations that led to the same use of the response scale.

Examination of the haptic depth responses for the two groups of participants showed reversed effects of the M-filter manipulation, consistent with participants' reports of the illusory direction of the haptic stimulus. The 15 participants who felt haptic objects as receding away from them rated the haptic stimulus as further for M3 [M = 53.00] than M1 [M = 38.61], while the remaining five participants felt the haptic objects was closest to them or looming the farthest out of the screen, for M3 [M = 32.62] compared to M1 [M = 57.28]. The distance responses for the visual conditions indicated no comparable reversal of the simulated direction.

Ratings of the haptic stimuli from both groups are shown in Fig. 8b and c. Although the haptic trials were independent from the visual trials, we hypothesized cross-talk between them would occur. Accordingly, we analyzed the ratings of the haptic stimuli by both the M-filter on the current trial and the visual display on the preceding trial.

A 3 × 3 repeated-measures ANOVA was initially performed on the haptic ratings from the 15 participants whose haptic depth direction matched the visual (i.e., the haptic event receded in depth) with visual ball size on the preceding trial and haptic M-filter depth on the current trial as within-subject factors (Fig. 8b). It showed a significant effect of M-filter [$F(2, 28) = 9.59$, $p<0.001$, $\eta_p^2 = 0.42$] and preceding visual depth [$F(2, 28) = 6.56$, $p = 0.015$, $\eta_p^2 = 0.32$]. The interaction between visual ball size and haptic M-filter was not significant [$F(4, 56) = 0.42$, $p = 0.80$].

It might be argued that the cross-talk from vision to touch on a subsequent event merely reflects perseveration from the previous response. To test for this, we reversed the direction of analysis, examining the effect of a prior haptic trial on the next visual rating. As we did not explicitly balance the sequence of haptic prior to visual trials, this excludes two participants who lacked data for a haptic-visual pairing. In an ANOVA on visual depth and prior haptic depth with the data for the remaining 13 participants, there was, as expected, a significant effect of current visual ball size [$F(2, 24) = 219.44$, $p<0.001$, $\eta_p^2 = 0.95$], but no effect of the haptic depth on the subsequent visual trial [$F(2, 24) = 1.52$, $p = 0.24$]. This argues against perserveration from previous response.

The data for the remaining five participants, whose impression of the haptic illusion caused the ball to come toward them, illustrated in Fig. 8c, showed that they perceived the M-filter effect as reversed from that predicted, consistent with their reports. However, the effect of preceding visual depth was still unambiguously further in the sagittal direction from the screen for this group as for the other 15 participants. Accordingly, greater illusory depth of the preceding visual stimulus led to a shallower haptic depth for these five participants. That is, when the preceding visual stimulus cued deeper visual depth, they had the percept that the haptic object came out of the screen less, and they responded accordingly with the rating response.

*Discussion*

The data from the two studies indicate that the M-filters, when presented separately from the visual cues, influenced participants' depth perception of haptic stimuli. However, the direction of the haptic M-filters varied between people, with a subset having the illusion that the haptic stimulus came toward them rather than receding in depth from the screen. In addition to the effect of M-filter depths, the size of the visual object at the midpoint, and hence the indicated visual depth, had an effect that carried over to people's depth perception of the next haptic cue. Our analysis also showed that this carryover effect of

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vision on haptics was not a result of response perseveration from one trial to the next as the carryover was unidirectional from vision to touch.

### 2.4 Experiment 4: Validation of M-Filters

Experiment 3 found that M-filters induced and modulated perceived tactile depth, in the context of prior vision. However, it is possible that the reported depth response was a response bias from the participants, as they were instructed to indicate perceived depth. To identify the contribution of M-filters to perceived depth, Experiment 4 compared their effects to apparent tactile motion as implemented in Experiment 1, which should deliver no or little depth information.

*Methods*

Seventeen naïve participants (9 male; 19 – 48 years old; average = 25.31) completed the study with signed consent. Experiment 4 followed the same procedure as Experiment 3b. The haptic depths were no induced depth (M0), which was generated by the apparent tactile motion algorithm used previously (Eq. 1), versus M1 and M3 from Experiment 3. The visual depths were the same as the last experiment. This design led to a total of 27 trials for each participant (3 haptic depth × 3 visual ball sizes × 3 repetitions). The trials were presented randomly, and each participant completed the testing within 20 minutes.

*Results and Discussion*

The post-study interview showed that all but 1 of the 17 participants perceived the haptic stimuli as receding away before returning to its starting depth. The data for the 16 participants were used for a repeated-measures ANOVA on the haptic depth response with haptic depth (3) and visual depth of the preceding trial (3) as the within-subject factors.

Figure 9 illustrates participants' depth responses for the three visual and haptic depth levels. As in Experiment 3, the analysis showed a significant effect of the levels of haptic depth [F(2, 30) = 8.37, p = 0.006, $\eta_p^2$ = 0.36] and the preceding visual depth [F(2, 30) = 3.55, p = 0.04, $\eta_p^2$ = 0.19]. Although the figure suggests that the visual depth effect is reduced in the absence of the M-filter shape ($M_0$), the interaction between visual and haptic depth was not significant [F(4, 60) = 1.04, p = 0.39]. Two subsequent tests indicated that the depth effect requires the M-filter. First, a one-factor repeated-measures ANOVA examining the effect of visual depth on haptic response for $M_0$ alone reported no significant difference in response between visual depths [F(2, 30) = 0.62, p = 0.55]. In contrast, a repeated-measures ANOVA on the haptic depth response with factors of visual depth (3) and the two M-filter levels (M1 and M3) analyzed the sub-design that replicated the study design of Experiment 3b, i.e., excluding the trials with apparent tactile motion (M0). The analysis showed a significant effect of M-filter depth [F(1, 15) = 4.75, p = 0.046, $\eta_p^2$ = 0.24], as well as a significant effect of visual depth, as expected [F(2, 30) = 4.29, p = 0.02, $\eta_p^2$ = 0.22]. No interaction between the two factors was observed [F(2, 30) = 0.39, p = 0.68].

To check for response perseveration, we reversed the direction of the analysis, as in Experiment 3b, and conducted a repeated-measures ANOVA on visual depth and prior haptic depth. The result showed no effect of previous haptic depth on the following visual depth response [F(2, 24) = 0.17, p = 085] but a significant effect of current ball size [F(2, 24) = 257.41, p<0.001, η = 0.96].

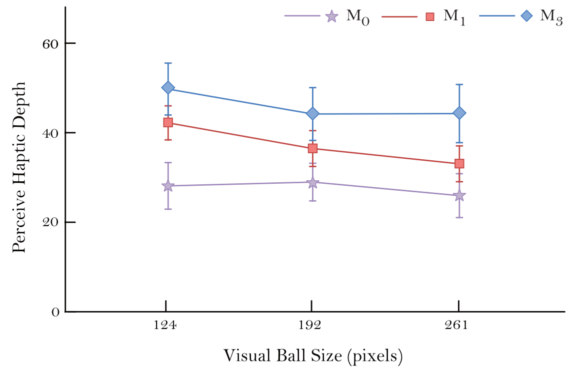


Fig. 9. Average of haptic depth responses across three visual depths for M0, M1, and M3. Error bars show standard errors.

The data for Experiment 4 confirm the results from Experiment 3b, namely, that a) visual depth cues had an effect on people's haptic depth perception, which carried over to the following haptic cue and b) people perceived different M-filters as distinctive haptic depths. Moreover, the study shows that depth reports are not simply the result of response bias, as the nature of the inducing tactile stimulation proved to be critical. As shown in Fig. 9, people's depth responses for the algorithm used to induce linear apparent motion were lower than the M filter algorithm. Furthermore, the lack of effect of visual cues on depth perception of apparent motion cues (M0), which conveys no depth information, indicates that M0 did not trigger depth perception in the participants as the M-filters did. This suggests that the M-filters are necessary to deliver depth information.

## 3 Conclusions and Future Work

To summarize our findings, the first part of the paper was dedicated to demonstrating apparent tactile motion, determining optimal parameters for the illusory motion (Experiment 1), and coupling that effect to visual parameters (Experiment 2). We presented equations relating apparent tactile motion between the hands to the SOA and duration of the vibrotactile stimulus, coupling visual and haptic speed, and pairing haptic amplitude and duration with visual size. In the second part of the paper, we demonstrated that the apparent motion could be extended to convey illusory haptic depth in the context of prior visual depth (Experiment 3). The haptic depth effect relied on, and was systematically modulated by, a vibrotactile gradient we termed an M-filter. In the final study (Experiment 4), we demonstrated the necessity for the M-filter pattern to elicit haptic depth.

These findings have values both for a basic understanding of haptic perception and applications. With respect to basic science, the illusions demonstrated here link the sense of touch to a broader literature that emphasizes how embedded rules, those that are essential to the

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achievement of a coherent representation of the physical world, can lead to mis-perception. While many tactile illusions have been previously demonstrated [5], [44], [9], the present paper focuses on extending these demonstrations to digitally generate perceptual representations of the distal world in the space between the hands.

An important mechanism capitalized on here is the interaction of touch with vision, especially the effect of prior context on the following cue. Many studies have shown that pre-existing contextual information prepares the brain to perceive and interpret sometimes ambiguous cues [45], [46], [47]. In the present study, it appears that visual context of depth prepares the perceiver for the possibility of a moving object in depth, which is then realized by subsequent tactile stimulation with matching pattern.

Our findings suggest new methods to enhance touch displays by eliciting illusory movement beyond the body. Although apparent tactile motion can be induced in the absence of vision, the present results pertain particularly to haptic/visual interactions. One methodology described here is to design specific vibratory stimuli that can be matched to simultaneous visual displays in speed and size. Another method presents vibrotactile filters, preceded by visual context, to induce depth from touch alone. These filters can extend beyond the M-filters presented in the current paper. For example, in our experience, an inversed M-filter with low onset amplitude that gradually increases and then decreases, elicits the illusion of an object approaching the user before receding into the distance. These types of filters can enhance interactive experience with devices using sparse tactile displays (such as gloves, hand controllers, wearables, etc) by supporting the representation of an object that is initiated by vision or touch, and sustained across movement when vision is occluded or contact is interrupted. Application domains that fit this description are broad, and include entertainment, education, and training using conventional and VR equipments.

To demonstrate the use of our approach, we designed and developed a game on a tablet computer that educates young children to develop healthy eating choices. A user ricochets healthy and non-healthy food items to a user's avatar. When the user releases the food item, he or she not only sees the trajectory of the objects but also feels them traveling across the two hands. If the avatar catches the food, a special haptic effect is triggered, based on factors such as the food item, release velocity, subjective preferences, etc. Our intention is to augment the visual cues with coherent haptic feedback to allow children to make quick informed decisions on food selection. The demonstration of the game is presented in [48]; however, a formal user study is left for future investigation.

Other directions for future work include: determine the psychophysical relationships of sensory illusions through wearable, handhelds and environmental haptic units in VR and AR, and extend the Mixed Reality experience, such as in [9], [48] with concurrent visual 2D and 3D interactions.

Our efforts in this work are to control moving haptic percepts in 3D environment to enhance the sense of immersion and cohesiveness. Effectively, the haptic effects introduced here may be thought of as tethering simulated objects to the perceiver despite active interaction such as exploration, gesturing, or purposive disturbance, in visually or haptically cluttered environments. Like a boomerang, an object rendered with optimally vibrotactile cues would return to the actor along expected and well-understood trajectories.

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