Augmenting Perceived Softness of Haptic Proxy Objects through Transient Vibration and Visuo-Haptic Illusion in Virtual Reality

Inrak Choi, Yiwei Zhao, Eric J. Gonzalez, and Sean Follmer

Abstract—In this work, we investigate the effects of active transient vibration and visuo-haptic illusion to augment the perceived softness of haptic proxy objects. We introduce a system combining active transient vibration at the fingertip with visuo-haptic illusions. In our hand-held device, a voice coil actuator transmits active transient vibrations to the index fingertip, while a force sensor measures the force applied on passive proxy objects to create visuo-haptic illusions in virtual reality. We conducted three user studies to understand both the vibrotactile effect and its combined effect with visuo-haptic illusions. A preliminary study confirmed that active transient vibrations can intuitively alter the perceived softness of a proxy object. Our first study demonstrated that those same active transient vibrations can generate different perceptions of softness depending on the material of the proxy object used. In our second study, we evaluated the combination of active transient vibration and visuo-haptic illusion, and found that both significantly influence perceived softness, with with the visuo-haptic effect being dominant. Our third study further investigated the vibrotactile effect while controlling for the visuo-haptic illusion. The combination of these two methods allows users to effectively perceive various levels of softness when interacting with haptic proxy objects.

Index Terms—Transient Vibration, Visuo-Haptic Illusion, Virtual Reality, Haptics, Softness, Softness Rendering, Softness Perception.

1 Introduction

Softness is one of the main haptic properties we perceive when interacting with objects [1], [2]. However, softness is a subjective and multisensory impression that integrates many different sensory cues [1]. The haptic rendering of softness can increase users' sense of immersion in virtual reality (VR) as well as aid in object discrimination and manipulation tasks [3]. Traditional kinesthetic haptic devices can provide many aspects of realistic haptic feedback for virtual objects [4]; however, these devices require complex and expensive hardware, and often have a limited workspace due to externally-grounded mechanical linkages.

To address the issues of cost, complexity, and workspace restriction of haptic devices, researchers have explored the use of passive haptic props [5], [6], [7], [8] and brake-based wearable haptic devices [9]. However, these systems only provide the user with a haptic representation of an object's global geometry, and cannot render different material properties such as softness for different virtual objects. These low-cost systems are limited to the fixed haptic properties of the passive proxies and brakes used.

In this paper, we augment the perceived softness of such low-cost haptic systems using multimodal visuo-haptic feedback. First, we investigate active transient vibration as means of augmenting the perceived softness of passive materials. After Okamura et al. [10] proposed a model of transient vibration for realistic tapping feedback, Kuchenbecker et al. [11] showed that active transient vibration could allow soft objects to be perceived as harder when using traditional kinesthetic haptic devices. Extending this concept, we investigate if active transient vibration can also allow users to perceive rigid passive haptic props as softer.

Active transient vibration has generally been used for making interactions with traditional kinesthetic haptic devices, which often feel inherently soft due to their limited bandwidth, seem stiffer; the opposite case – making stiff objects appear softer – has been less explored. Low-cost haptic systems such as proxy objects [12] and brakes [9] generally provide a fixed high stiffness, so users perceive virtual objects as hard and rigid. For these systems, we need techniques to make such rigid sensations feel softer, ideally in a dynamic and programmable way.

Following our investigation of the effect of active transient vibration on the perceived softness of passive haptic props, we combine these vibrotactile cues with visuo-haptic illusion. Visuo-haptic illusions are another effective technique for changing the perceived softness of an object. Srinivasan et al. [13] and Lecuyer et al. [14] showed that by changing the visual deformation of a virtual object, users could experience various stiffnesses through a single passive spring.

While active transient vibration and visuo-haptic illusion have been thoroughly investigated independently, their combined effect remains to be fully explored. Investigating this multimodal haptic effect is especially important for low-cost haptic devices, because the two techniques can be easily applied with such devices, potentially enhancing user experience without significant overhead. Both techniques are effective and practical for changing perceived softness without complex mechatronic components. We investigate if the combined multimodal feedback provides a wider range of rendered softnesses than the individual techniques alone.

In this paper, we have two main research questions:

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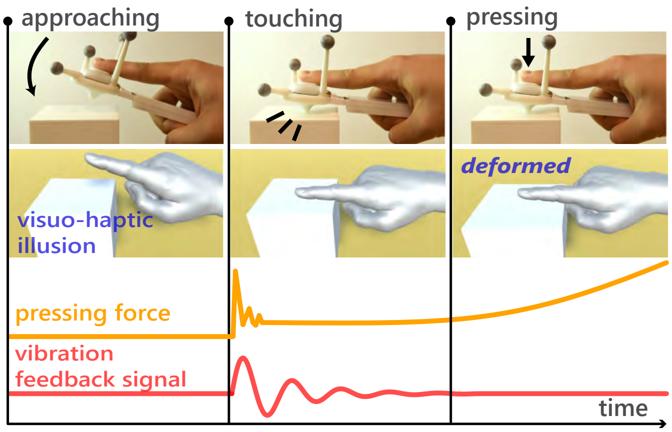

Fig. 1. Using a simple handheld haptic device, the user feels a soft sensation while tapping on a hard surface (a plastic box). When the user first contacts the object, the device generates an *active transient vibration*. When the user presses down further on the box, the virtual box is deformed creating a *visuo-haptic illusion*.

- Can active transient vibration dynamically alter the perceived softness of haptic proxy objects, including rigid objects?
- Does active transient vibration work in conjunction with visuo-haptic illusions to increase the range of perceived softness renderable in VR?

To answer these research questions, we designed a simple hand-held haptic device composed of a voice coil actuator and a force sensor. Fig. 1 illustrates the concept of combining of the two methods, and Fig. 2 shows an example scenario in VR with rigid haptic proxy objects. We conducted three user studies. In a preliminary study, users self-reported open-ended descriptions of how they perceived haptic proxy objects when active transient vibration was applied on contact. In the first study, users rated the perceived softness of both compliant and rigid materials when active transient vibration was applied during exploratory tapping. In the second study, users rated the perceived softness of a rigid proxy object when various levels of active transient vibration and visuo-haptic illusion were combined. In the third study, users conducted pairwise comparisons between two objects that had identical visuo-haptic illusion but different vibrotactile stimuli.

Results show that active transient vibration can generate various levels of perceived softnesses of haptic proxy objects. Users felt "softer" or "harder" sensations with the same applied vibration signal depending on the haptic proxy material. The combination of vibration with visuo-haptic illusion increases the range of softness users perceive in VR. Active transient vibration led to clear distinctions between the perceived softness of haptic proxies in addition to the effects of visuo-haptic illusion.

2 Related Work

There are three main haptic cues used in softness discrimination: stiffness (i.e., the ratio between displacement and force), local deformation of the surface in contact with the fingertip (i.e., contact area spread rate), and vibrotaction [1]. Although softness is primarily experienced through touch, visual and auditory signals also affect softness perception [1]. In this section, we review relevant work on the augmentation of haptic perception.

2.1 Stiffness Rendering with Kinesthetic Force Feedback

Conventional kinesthetic haptic devices control either position or force to render stiffness [4], [15]. Since the stability and transparency of their closed loop is highly reliant on accurate sensing, these devices require high-quality position or force sensors. Due to the high cost of such hardware components, these devices are typically expensive. However, human stiffness perception relies on both tactile and kinesthetic channels, and kinesthetic feedback alone does not allow for precise discrimination of stiffness; previous research has shown that with kinesthetic feedback alone, the just-noticeable difference (JND) for stiffness ranges from 8% to 22% [16]. To generate better softness perception, tactile feedback is necessary.

2.2 Softness Rendering with Tactile Feedback

Tactile cues improve softness discrimination [17]. Researchers have explored various ways to change perceived softness by applying different tactile stimuli. Bicchi et al. investigated the effect of contact area spread rate on perceived softness [18]. The researchers showed that changing the contact area spread rate is 30% more effective than kinesthetic feedback for softness discrimination. Similarly, Tan et al. showed that the JND of pressure (found to be 0.06-0.09 N/cm) is related to the perimeter of the fingertip contact area [19]. Kuchenbecker et al. [11] and Ikeda et al. [20] integrated high frequency vibration with a kinesthetic haptic device to increase perceived hardness. Quek et al. used skin stretch feedback on the fingertip as a form of force substitution in teleoperation [21], and Schorr et al. developed a fingertip-mounted 3DOF skin stretch device and showed how it was an intuitive modality for object manipulaiton [22]; De Tinquy et al. showed similar results using a 2DOF belt mechanism for the same purpose [23]. Others have developed entirely novel actuators to display stiffness [24], [25], [26]. Although not investigated on the fingertip, Visell et al. found that plantar vibrotactile stimulus during walking could alter subjects' perception of ground compliance [27]. Other researchers have used vibration to improve walking sensations in VR [28].

While many devices have been proposed with different types of tactile feedback for softness (or hardness) augmentation, with the exception of simple vibrotactile displays, most are bulky and complex, significantly limiting users' ability to interact with the physical world (e.g., haptic proxies).

2.3 Pseudo-Haptic Feedback and Delayed Stimulus

Previous research has found that using a passive isometric input device with coupled visual distortion can provide pseudo-haptic feedback [13], [14]. By deforming the visual representation of virtual objects proportional to the applied force, users can perceive different stiffnesses. This is an example of a visuo-haptic illusion where there are conflicts

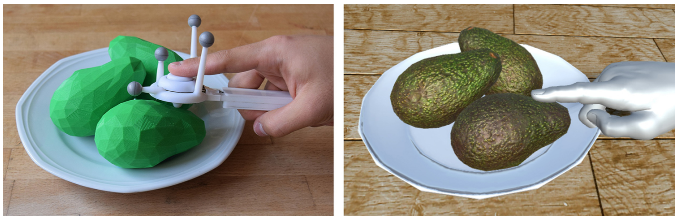

Fig. 2. Haptic proxies are useful to provide global shape information at low cost, but cannot actively change material properties. The combined effects of active transient vibration and visuo-haptic illusion however can enable users to, for example, feel both the shape and ripeness of different virtual avocados.

between visual, proprioceptive and haptic stimuli; vision often dominates human perception in such events [14], [29]. This illusion can be utilized for richer haptic sensation [30], [31], [32] and only requires a passive isometric input device in combination with visual feedback rather than an active force feedback device. Researchers have also used finger mounted devices as for passive haptic feedback and applied pseudo-haptics to render different virtual stiffnesses [33]. Other researchers have investigated the effect of auditory cues on stiffness perception [34], [35], [36]. Results show that users perceive objects as more stiff with shorter auditory feedback.

Visual and haptic delays have significant effects on perceived softness [37], [38], [39]. Previous work has shown visual delays can result in a decrease of perceived softness, while haptic delays can result in an increase of perceived softness [37], [38]. However, visual and haptic delays are typically unintended consequences of data acquisition and display latency. These types of delays are difficult to adjust as they arise from inherent hardware limitations.

3 Design and Approach

The prior work described above reveals the many perceptual modalities involved in softness perception, including tactile, kinesthetic, visual, and auditory stimuli. Similarly, there are multiple haptic exploratory procedures [40] for determining softness, including gripping an object, pressing it against another surface, and tapping it with a finger. To best isolate the effects of different cues on a single point of contact, we focus on tapping and pressing.

The cues involved in probing the softness of an object with a finger are as follows: When first contacting the object, a transient vibration (1) is generated, resonating through the object and to the fingertip. This signal depends on the speed at impact, the material of the object, and the tension of the finger muscle. As the user presses further, the contact area of the finger pad (2) changes according to the softness of the material. Finally, as the user continues to press, lower stiffness materials will elastically or plastically deform, and the user's finger will experience some displacement (3). As the material deforms elastically, the user will then increasingly feel a restoring force (4). Of these cues, our approach is intended to provide the user with both transient vibration (1) as well as visual displacement of the finger (3).

In contrast to much of the aforementioned work in rendering the stiffness of entirely virtual objects, our goal is to augment the softness perception of physical proxy objects. Haptic proxies can provide rich haptic cues without complex electromechanical systems [5], [6], [7], [8]. Traditionally, these physical objects must match the virtual model, and thus cannot be used to render different objects. However, recent work has explored how to utilize visuo-haptic illusions to warp user perception of proxy shape [41], position [12], and as previously mentioned, stiffness. We believe there is an opportunity to enhance our interactions with these passive props by using simple active haptic devices to augment their characteristics, without sacrificing much in the way of cost or mobility.

Researchers have investigated how to augment perceived softness of passive materials. Jeon et al. used existing kinesthetic haptic devices to augment the stiffness of various passive materials [42], and Hachisu et al. used a handheld stick providing active transient vibration to augment perceived softness [43]. While these two methods enable users to interact with passive objects through tool-mediated gestures, a precision grip and a power grip respectively, we introduce a handheld device allowing users to interact with proxy objects through their index fingertip, as this is one of the natural gestures humans use to explore objects with bare hands [44]. The device should be compact and lightweight to preserve the user's capacity to interact with physical proxy objects. At a minimum, we require a small actuator for the rendering of active transient vibration, and a force sensor to inform the visuo-haptic illusion.

4 Implementation

To provide active transient vibrations to the user, we designed a hand-held, controller-like device that allows users to tap and explore any physical proxy with their index finger. The user holds the device using a pointed grasp, with their index finger resting on an actuator, as shown in Fig. 1. A rigid contact point directly below the fingertip/actuator is used to physically contact proxy objects.

Users can use the device to interact with proxy objects in several ways. First, they can tap or press the physical object to explore its softness locally. The device generates an active transient vibration at the fingertip on contact and senses the user's pressing force to render a visuo-haptic illusion in VR. Second, users can also pass their fingertip (or device contact tip, in this case) over the physical object to parse the global shape and contour of the object. We can use visual retargeting techniques introduced by Azmandian et al. [30] and Zhao et al. [41] to visually render different virtual shapes over static physical objects. Third, the user can rub the surface to experience various textures generated from the device by vibrotactile feedback. However, we focus in this paper on the first interaction method.

4.1 Handheld Haptic Device Design

Fig.3 (Left) shows the haptic device structure. There are two main components in the device: a voice coil actuator and a force sensor. Fig.3 (Right) shows the contact locations of the index fingertip and physical object. The Young's modulus of the fingertip contact surface (red) and device contact tip (blue) parts is 2.8GPa.

A voice coil actuator (Tectonic Elements TEAX19C01-9) is used to provide active transient vibration to the index fingertip for virtual softness rendering. Detailed performance of this actuator will be described in the following section. The voice coil actuator is held with a support structure at the top of the device handle. On the top of the voice coil, there is a button-shaped structure (shown in red in Fig.3) which acts as the contact surface between the voice coil and the user's fingertip.

A capacitive force sensor (SingleTact S8-10N) is used to measure (1) the moment of contact, for initiating transient vibration and (2) the user's pressing force on a proxy surface for rendering a visuo-haptic illusion. We sample the force with a 1kHz sampling rate. The sensor's range of 10N and resolution of 0.02N are accurate enough for the measurement of tapping and pressing forces. Although the sensor resolution was 0.02N, we set a threshold of 0.2N for detecting the contact moment to account for sensor noise, which we found to have a standard deviation of approximately 0.05N. This sensor is placed between the device handle and a rigid contact tip (shown in blue in Fig.3).

A TB6612FNG motor driver is used to drive the voice coil actuator, and a Teensy 3.2 microcontroller (set to 72MHz clock speed) is used for controlling the device. The motor driver and microcontroller are located outside the device and are powered by a single 5V USB. The microcontroller communicates with a PC over USB serial at 12Mbit/sec.

4.2 Active Transient Vibration

As described by Kuchenbecker et al. [11], the realism of a tapping interaction can be dramatically improved by superimposing event-based, high-frequency transient vibrations. In previous work, the active vibration feedback was rendered on top of active kinesthetic force to render virtual objects; such work showed that the event-based vibration improved the realism of tapping virtual wood. This means that by providing high-frequency tactile feedback, we can improve the rendering of hard surfaces. We investigate a similar mechanism, but instead look at how providing a lower-frequency vibrotactile feedback component can make users perceive a hard physical object as softer.

We use a decaying sinusoidal wave model similar to [10], [11], [45]: $V(t) = A\exp(-Bt)\sin(2\pi ft)$, where A is the attack magnitude, a function of tapping speed, B is the decaying rate of the sinusoidal vibration, and f is the frequency of the sinusoidal vibration. While previous researchers define A as a function of tapping speed, we define A as a constant. In previous research with kinesthetic haptic devices, tapping speed could be calculated more reliably as the devices used optical encoders or hall effect sensors for position sensing. These sensors have relatively low noise with high sampling rates. However, since our hand-held device is not mechanically linked to ground, we use a camera-based tracking system (OptiTrack Prime 13). The tracking system limited our ability to reliably calculate the tapping speed in real-time, due to the noise and reduced sampling rate of position data. Although this is not physics-based, through empirical testing we found a constant magnitude is sufficient for general tapping speeds, given some constraints. While tapping speeds varied by trial and user, we experimentally found that the average tapping speed before contact is 0.19m/s (SD: 0.08m/s).

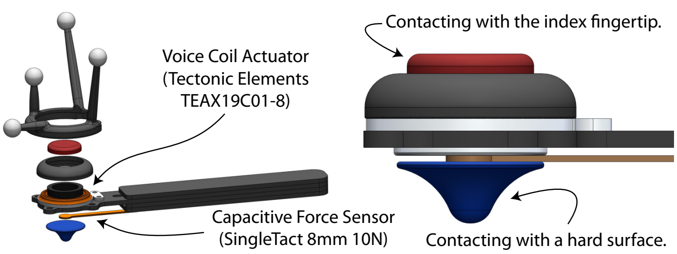

Fig. 3. (Left) The device is comprised of two main components: a voice coil actuator and a capacitive force sensor. Four retroreflective markers are attached around the index finger mount for an OptiTrack system. (Right) The end-effector of the voice coil actuator (Red) is in contact with the index finger. The rigid tip at the bottom (Blue) transmits the contact force from the proxy object to the user's finger.

We chose to render three different "classes" of active transient vibration, with the goal of rendering a range of perceived softnesses. Precisely determining the model parameters (i.e., A, B, and f) would have posed a significant challenge. Previous research [10], [14], [46] has directly and indirectly indicated that physics-based parameters do not necessarily provide more realistic and varied sensations. Accordingly, the researchers instead used "reality-based" parameters providing more exaggerated and distinct sensations than the haptic and visual sensations from real objects. To investigate our hypotheses, we also used reality-based parameters. Through iterative design and our own experimentation, we empirically found the three constant values (A, B, and f) of each transient vibration signal. First, we chose the frequencies of 30Hz, 90Hz, and 210Hz. We then selected values for B; we aimed to choose values that were not too low because we found that the vibration begins to feel unrealistic at low decay rates. The chosen B values were 11, 40, and 65 respectively. Finally, we selected values for A such that peak voltages reached 5V for each decaying sinusoidal wave, in order to utilize the full range of the 5V voltage supply. The chosen A values were 5.47, 5.57, and 5.37 respectively. Ultimately, the frequency and damping parameters (B and f) we selected have comparable magnitudes to those in previous work [10], [43]. For each tapping event, we play each vibration for 200ms. From here onwards, we will refer to these vibrations classes as "Soft" (A:5.47, B:11, f:30), "Mid" (A:5.57, B:40, f:90), and "Hard" (A:5.37, B:65, f:210) vibrations.

Compared to previous work on transient vibration, the voice coil actuator we use can not only provide normal force to the index fingertip, but also move the finger with fairly large displacements. This is because here the user is directly touching the voice coil end-effector, while previous researchers used an encapsulated voice coil actuator or a vibration motor for transient vibration feedback.

To investigate the actual movement and force at the user's index fingertip, we characterized the voice coil actuator. The first row of plots in Fig. 4 shows the voltage inputs for "Soft", "Mid", and "Hard" vibrations. The second row of plots in Fig. 4 shows the displacement of the end-effector (shown in red in Fig. 3) when there is no load, i.e., no index finger. To measure the displacements, we first took

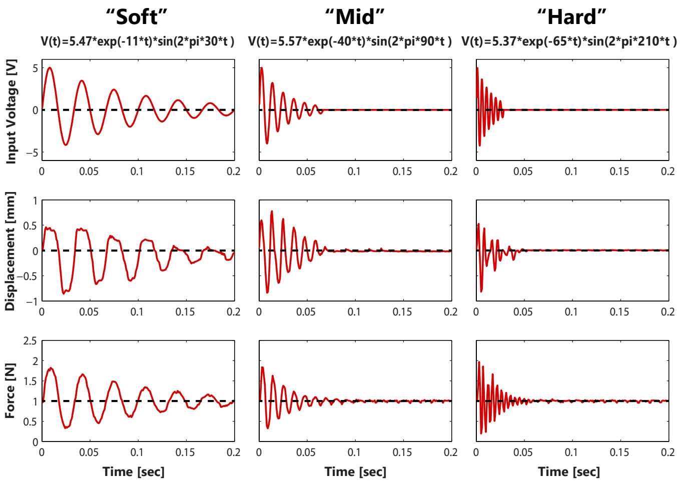

Fig. 4. (Top) Three voltage inputs for “Soft”, “Mid”, and “Hard” vibrations. (Middle) Displacement of the end-effector when there is no load. (Bottom) Force outputs of the end-effector when there pre-loaded with 1N. This data shows the range of the finger displacement and force output.

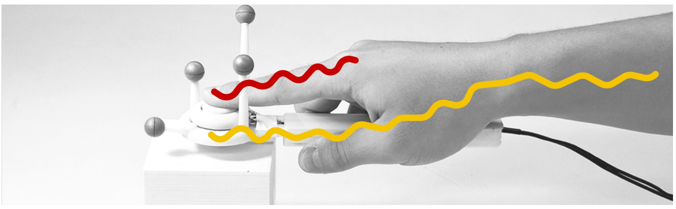

Fig. 5. During the tapping motion, the index finger and the rest of the arm get different vibrations (forces). While the index finger mainly senses the active transient vibration forces from the voice coil actuator (red line), the rest of the arm feels the kinesthetic force and tapping vibration created by the proxy object (yellow line).

videos at 1000fps with a Nikon 1 V1, then used Tracker 5.0, an open-sourced video analysis software. Results show that all three voltage inputs move the end-effector between -1mm and 0.5mm. The third-row of plots in Fig. 4 shows the force outputs of the end-effector. From our own empirical exploration, we found users apply roughly a 1N force through their index finger when holding the device. Therefore, to evaluate the force output of the voice coil actuator on a fingertip, we rigidly coupled the end-effector to a separate force sensor (TE Connectivity FC2231-0000-0010-L) and pre-loaded the end-effector with a 1N load. Measuring at a 1000HZ sampling rate, we then applied the above-mentioned voltage inputs and found that the voice coil actuator generates forces between 0.2 N and 2.0N (Fig. 4).

The displacement and force outputs in Fig. 4 show two extreme cases: 1) the case when there is no load and 2) the case when there is a very rigid object applying a 1N load. In real usage, the index finger will move between -1mm and 0.5mm, and the user will perceive forces ranging from 0.2N to 2.0N; the actual displacement and perceived force will vary depending on the impedance of the user’s index finger. Therefore, the displacement and force will change depending on the length, weight, and passive stiffness of the index finger, and how rigidly the user holds the device.

Fig. 5 shows a conceptual image of the actual device

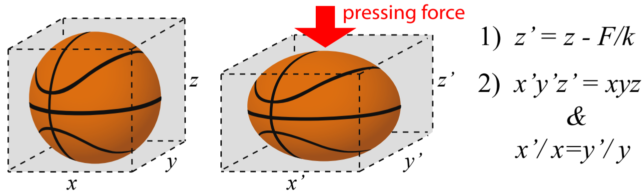

Fig. 6. A virtual deformation model for the visuo-haptic illusion.

behavior when the user taps on a proxy object. The device transmits kinesthetic force and passive transient vibrations created by the contact between the device and proxy object (yellow line). At the same time, the active transient vibration provides force and displacement to the fingertip (red line).

4.3 Visuo-Haptic Illusion

Similar to the work by Lecuyer et al. [14], we use a linear model to deform a virtual object for the visuo-haptic illusion. For a 3D virtual object, we first define its bounding box as a cube. We assume this cube has sides x, y and z and a virtual stiffness of K (Fig.6). Here, z is the length along the axis normal to the ground surface. When a pressing force, F, is applied to the top surface, a uniform scale change along this axis, Δz, is calculated based on the pressing force: $\Delta z = \frac{F}{K}$ and $z' = z - \Delta z$, where z' is the new cube height.

The virtual object in the Lecuyer’s work is a one-dimensional spring; therefore, only one dimension of deformation is applied to the virtual object. In our case, our virtual objects have three dimensions. Therefore, changing the scale of only one dimension of the 3D object would provide a less realistic visual feedback. As shown in Fig.6, we maintain a constant volume for the bounding box, which is $x'y'z' = xyz$. We also keep the deformation ratios for the other two axes of the cube same, i.e. $\frac{x'}{x} = \frac{y'}{y}$. In our implementation, this visual illusion is rendered only with respect to the axis normal to the ground surface. Virtual objects are not deformed when they are pressed from sides.

4.4 Virtual Environment Design

We implement a simple virtual environment which mimics the actual environment of our test setup. The VR scene has a virtual table and virtual cubes with identical dimensions to a physical table and haptic proxy cubes in the real world. The virtual objects are designed to be deformable. Based on the measured force (sampled at 1kHz) and programmed virtual stiffness, they are deformed to create the visuo-haptic illusion. The haptic proxy objects are fixed at a known location in the real world/virtual scene. The user cannot see the physical proxy objects – only the virtual objects are shown in the VR headset (Oculus Rift). The Unity game engine is used for VR rendering and programming, and an OptiTrack system is used to track the hand position. We use this tracking system to minimize the position errors and latency of the system for our psychophysical studies. However, recent commercial VR systems would also provide sufficient tracking performances at lower cost [47].

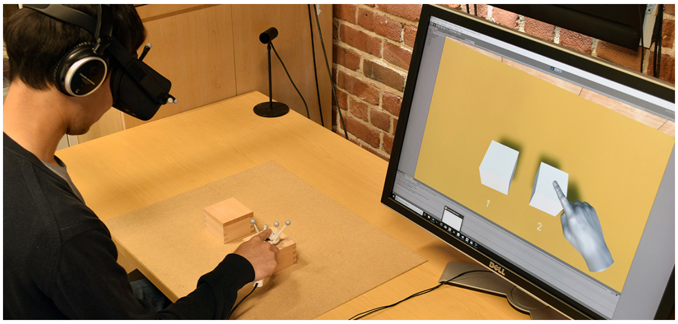

Fig. 7. The preliminary study setup. The VR scene shows a virtual table and objects with the same dimensions as real objects. Participants wear an Oculus VR headset and active noise-canceling headphones. Retroreflective markers are attached on the VR headset for an OptiTrack system. Wooden blocks were used for the passive objects.

5 Preliminary Study: Open-Ended Response to VR Interactions with Haptic Proxies Augmented by Transient Vibrations

In previous studies on active transient vibration, participants were asked to rate perceived softness [27], rate realism [11], and match material properties with reference [20], [43], [48]. Such instructions might already have suggested to participants that active vibration is intended to provide influence their perception of softness. In this preliminary study, we wish to confirm if active transient vibration *intuitively* changes the *perceived softness* of rigid haptic proxies. To answer this question, we asked participants to freely explore two boxes in a VR environment and freely respond about if and how the two boxes differ. We used different active transient vibration stimuli for each box, while all other conditions were kept the same.

The overall setup for the preliminary study is shown in Fig.7. Participants wore a head-mounted display while using the handheld device to touch the proxy objects (hard wooden boxes). The position and size of each physical box matched precisely with the virtual box in the virtual scene. Throughout the study, participants wore ear plugs and noise canceling headphones playing white noise.

In VR, participants were asked to interact with the two boxes with their right index finger while holding the haptic device. The two boxes in VR were visually identical, and the two haptic proxy objects were also identical. The only difference between the two boxes was the class of active transient vibration rendered on contact.

5.1 Task and Procedure

To prevent participants from knowing the purpose of the vibration, we provided minimal information and constraints. Before the participants wore a VR headset, an examiner instructed how to hold the handheld device. Participants then explored the two haptic proxy objects in VR for 75 seconds. During the entire study, participants only looked at the virtual boxes, and they did not know the shape and properties of the haptic proxy objects.

There were six combinations for pairing two different vibrations out of four vibration types (“Soft”, “Mid”, “Hard”, and “No”) so each participant compared two boxes six times. The order was randomized (balanced latin square).

Table 1
The preliminary study results. We categorized each response from participants into one of four groups. Numbers in parentheses indicate totals only for the last three out of six responses.

	No difference	Texture	Softness	Just vibration
Participant 1	3 (0)	0 (0)	3 (3)	0 (0)
Participant 2	1 (0)	0 (0)	3 (2)	2 (1)
Participant 3	0 (0)	1 (1)	5 (2)	0 (0)
Participant 4	1 (0)	0 (0)	3 (3)	2 (0)
Participant 5	1 (0)	1 (0)	4 (3)	0 (0)
Participant 6	1 (0)	0 (0)	2 (1)	3 (2)
Sum (*total 36*)	7 (0)	2 (1)	20 (14)	7 (3)

Table 2
Example statements from participants related to softness.

Participant 1 *“The left box [“mid” vibration] felt like it was a big block of rubber, like a, if I had a big eraser and I was tapping it ... the box on the right [“hard” vibration] felt like a harder rubber, like a more like, a car tire rubber than an eraser rubber.”*
Participant 2 *“The box on the right [“soft” vibration], it had, when I tapped on it, it had some feedback on it, like reverberation, like guitar strings almost? Maybe like tapping something hollow.”*
Participant 3 *“The right one [“no” vibration] felt pretty hard, and the left one [“soft” vibration] felt pretty bouncy.”*
Participant 4 *“It [“soft” vibration] almost felt like I was touching something very elastic rubbery, like gel.”*
Participant 5 *“The left one [“hard” vibration] was like plastic, and the right one [“soft” vibration] is still sort of rubbery but more like medium rubbery.”*
Participant 6 *“The one on the right [“soft” vibration] was softer so when you push it, it kind of a it feels like you can squish down into the cube ... the one on the left [“hard” vibration], I would say it’s still a little elasticky, like if you push into it, it pushes back, but like stiffer kind of rubber.”*

In this study there was no visuo-haptic illusion for all conditions, and participants touched the proxy objects in any direction with any speed. We did not provide any restriction for their motions.

After exploring the two boxes, an examiner asked the following questions. “Did you notice any difference between the two boxes?”. “If you did, how were the two boxes different?”. Participants verbally answered and compared the two boxes for 60 seconds. The entire process took approximately 30 minutes.

5.2 Participants

We recruited 6 participants (3 female, all right-handed) for the subjective softness rating evaluation. The average age was 24.2 (2.6 std.dev). All participants received $10 for their participation. The study was approved by our institution’s IRB, and all participants provided informed consent.

5.3 Results and Discussion

Table 1 summarizes the preliminary study results. We categorized each response from participants into one of four groups. Six participants answered six times each so there were total 36 responses. All participants mentioned at least one statement related to softness during the task. In most responses (20 out of 36), participants compared the two objects with respect to softness. Table 2 shows some example statements from participants.

Participants explored the objects very mildly in early trials. They tried to explore the objects with rubbing motions with small pressing force to recognize the shapes and sizes. All "No difference" responses were answered during the first three trials. After few trials, participants noticed the active vibration feedback makes difference only when they press or tap. In the last three trials of each participant, participants mostly used tapping motions. 14 out of 18 responses in last three trials were related to softness.

These qualitative results indicate the active transient vibration intuitively affects perceived softness, and confirm past studies on the effect of transient vibration. Even though the examiner did not regulate the motions of the participants and did not provide any information on the device, participants connected the vibration feedback with tapping motions and compared the two objects with respect to softness in a majority of trials.

However, three participants (P1, P4, and P6) verbally reported that the active vibration feedback did not feel natural when they touched the objects softly. The tactile feedback created by the active vibration was larger than expected given momentum of the user's hand, because the vibration intensities were constant regardless of the pressing velocity. This shows our system setup would work only if the users tap or press fast. For the following studies, we asked users to use fast tapping motions to prevent the unnatural effects of touching gently. We also asked users to tap only on the top surface of the virtual boxes, as we only render the visuo-haptic illusion in the vertical dimension.

6 Study 1: Perceived Softness of Materials Augmented by Transient Vibration

In this first study we further explore how active transient vibration affects the perceived softness of different haptic proxy objects. Here we investigate if the active vibrations are effective in spite of the natural, passive transient vibrations generated by tapping the handheld device on a proxy object.

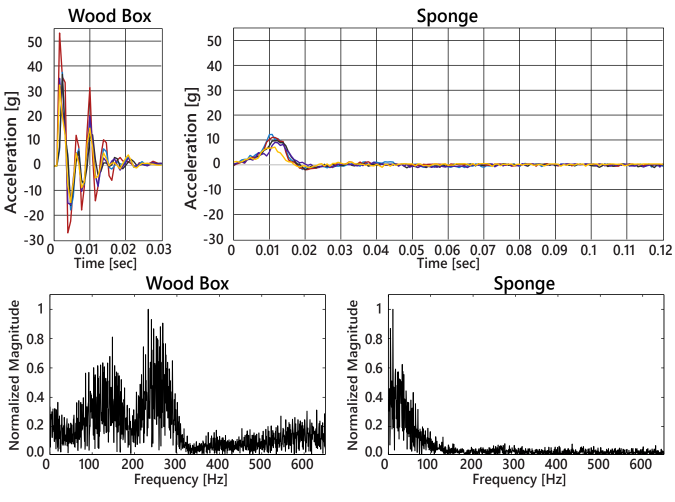

Fig. 8. (Top) Vibration measurement of the device when tapped on a wood box and a sponge (measured 5 times). (Bottom) DFTs of the vibration on each material. Peak accelerations are observed at 250Hz and 10Hz, respectively.

This study also investigates if the effect of active transient vibrations is dependant on the material of a proxy object.

A soft object (a stack of sponges) and a hard object (a wooden box) were selected for the proxy objects, as they were likely to have significantly different stiffnesses and corresponding natural frequencies. To measure their natural frequencies, we measured the device's acceleration in the direction normal to the ground during tapping of the two objects. Fig. 8 (Top) shows five sample acceleration magnitudes of the handheld device when a user taps on the two reference objects, measured with an ADXL377 accelerometer at a 1300Hz sampling rate. The accelerometer was attached to the main handle body (the black structure between the red and blue parts in Fig. 3). These are the transient vibrations naturally created by tapping the handheld device on the proxy objects (the yellow line in Fig. 5). Fig. 8 (Bottom) shows the discrete Fourier transforms (DFTs) of the vibrations. While the wooden box has a wide vibration frequency range, the peak magnitude was observed at around 250Hz. The stack of sponges has a narrower frequency range of vibration, and the peak magnitude was observed at 10Hz.

Participants subjectively rated their perceived softness of the two different proxy objects after tapping and pressing on them while the device displayed one of four active transient vibrations. Fig. 9 shows the study setup. To investigate the haptic effects alone, participants were not allowed to see the objects and wore ear plugs and noise-cancelling headphones playing white noise. There were four vibration modes ("Soft", "Mid", "Hard", and "No") and 2 proxy object materials (sponge and wood), for a total of 8 different stimuli.

6.1 Participants

We recruited 10 participants (5F, 9 right-handed) for this study. The participants did not overlap with the participants in the preliminary study. The average age was 25.9 (4.2 std. dev). All participants received a nominal compensation, $15, for their participation. The study was approved by our institution's IRB, and all participants provided informed consent.

6.2 Task and Procedure

Before running the study, an experimenter showed participants how to grasp the device with their dominant hand. The experimenter also instructed participants to not press the end-effector too hard in order to feel a reasonable amplitude of vibration feedback. To encourage thorough exploration of the presented perceived softness, participants were required to tap the objects at least three times for each trial. As participants could not see the location of the objects, they first found a comfortable location and then the experimenter placed one of the objects beneath their hand for each trial. The purpose of the study was not revealed and participants were not restricted strongly on how they should interact with the objects; participants tapped and pressed the objects with various forces and speeds. After experiencing each stimuli, participants rated the perceived softness with a score from 1 to 7 (1: softest, 7: hardest). The sequence of the 8 stimuli were randomized in a block and there were 12 blocks (total 96 trials). The study took approximately 30 minutes.

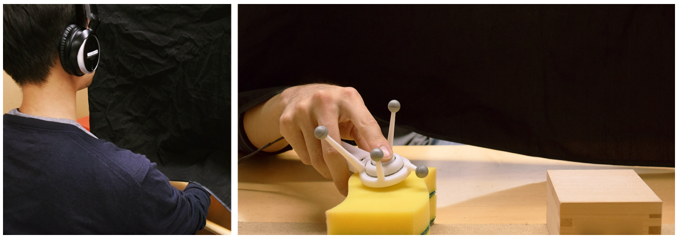

Fig. 9. Study 1 setup. Participants rated perceived softnesses. A stack of sponges and a wooden box were used for the proxy objects.

6.3 Hypotheses

While researchers have investigated the effect of active transient vibration on softness perception [11], [20], [43], [48], the effects of active vibration on tool-mediated tapping (i.e., when a tool mediates interaction between the user's fingertip and a physical object) are not well understood. Previous research [43] has demonstrated the use of active transient vibration on a passive material, but interaction effects between the type of vibration and type of material were not studied, as the researchers used only a single material. Here we investigate the effects of active transient vibration during tool-mediated tapping on passive materials more rigorously. We have the following hypotheses:

- Active transient vibrations affect the perceived softness of passive objects, even though passive transient vibrations are naturally generated between the object and device.
- The same active transient vibrations can create both softer and harder sensations depending on proxy material.

6.4 Results

6.4.1 Vibration Changes the Perceived Softness of Passive Proxy Objects.

Fig.10 shows the Study 1 results. We fit a linear mixed effects model to the data, with vibration level and material as fixed effects, participant as a random effect, and perceived softness as the response variable. An analysis of deviance (ANODE) via Type II Wald tests revealed significant main effects of both vibration level (χ^2(3, N=960) = 397.55, $p < 0.001$) and material (χ^2(1, N=960) = 3354.07, $p < 0.001$). A significant interaction effect was also found (χ^2(3, N=960) = 434.32, $p < 0.001$). The significant main effect of vibration indicates our first hypothesis is validated.

6.4.2 Vibration Creates Both Softer and Harder Sensations Depending on Proxy Material.

A post-hoc Tukey test identified significant differences between all pairwise combinations of stimuli ($p < 0.001$), except between the "Hard" and "No" vibrations on the wooden box ($p = 0.085$). The significant interaction between the two factors and these post-hoc test results support our second hypothesis.

6.5 Discussion

The linear mixed effects model and ANODE results show that both vibration and material independently affect softness perception. The more interesting outcome is that there is a significant interaction effect between the two factors. The three vibration signals provided different effects on the two materials; while the vibrations created harder sensations on the sponge material, they created softer sensations on the wood material.

How can we explain this? Our results show that the active transient vibrations significantly change the softness perception on top of the transient vibrations naturally generated by the collisions between the handheld device and proxy objects. Prior work has shown there is a tendency that vibrations of lower frequency and lower damping ratio are associated with softer objects [49]. In our study, the soft sponge object generated vibration with a 10Hz main frequency, which was lower than our active transient vibration frequencies (30, 90, and 210Hz). The hard wooden object generated vibration with a 250Hz main frequency, which was higher than the active vibration frequencies.

Then why was generating softer sensations rare in prior work? Most previous work used the active transient vibration with kinesthetic haptic devices (e.g.., PHANToM) or a bare fingertip and a proxy object. Such haptic devices have narrow impedance bandwidth, and the bare fingertip is soft. Both cases generate lower frequency tapping vibrations than our system setup; unless the active transient vibration has a lower frequency than the damped natural frequencies of the systems while tapping, it would produce a "harder" sensation. Our device has a hard plastic tip and it naturally generates high frequency vibration when it is tapped on a hard surface. Hence, the active vibrations provided "softer" sensations with the hard passive prop.

Latency is another factor we would like to discuss. Researchers have found vibration with latency generates softer sensations [37], [38]. In our implementation we used a force threshold (0.2N) to detect contact. While there is no uniform haptic latency because we did not regulate users' tapping speed, this may provide a noticeable latency effect. If participants tap on the two materials with the same speed, the sponge requires a longer time to reach the force threshold than the wood due to its lower stiffness. Thus, the time difference between the actual contact moment and the moment vibration is actuated (i.e., latency) should be larger for the sponge than the wood. In accordance with the

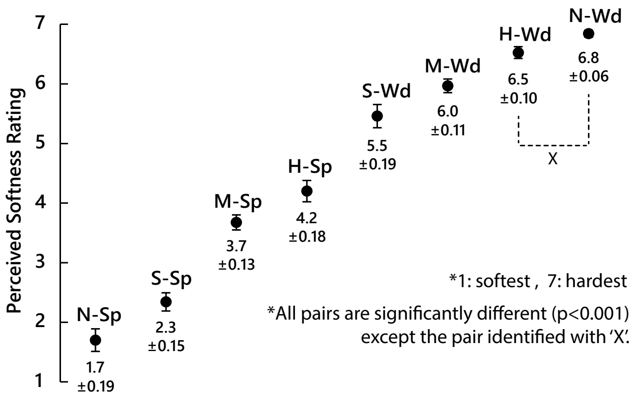

Fig. 10. Study 1 results. The rating for all combinations (4 vibrations × 2 materials). For each label, the letter before the hyphen indicates the vibration type (S:"Soft", M:"Mid", H:"Hard", and N:"No"), and the letters after the hyphen indicates the material type (Sp:Sponge and Wd:Wood). Error bars show standard error of the mean (SEM).

known latency effect, the vibration feedback should provide softer sensations on the sponge than on the wood. However, our results show all active vibrations created harder sensations on the sponge, while the same vibrations with shorter latency on the wood created softer sensations. These results are contrary to the latency effect and would imply that the interaction effect between vibration and material type is more dominant in our implementation.

Another interesting finding is the apparent increase in confusion caused by vibration-material conflicts. Vibrations that vary significantly from the proxy material's natural frequency create larger changes in perceived softness, but also increased the variance of reported values. For example, when tapping on wood, participants responded that the "Soft" vibration generated softer sensations than the "Mid" vibration (S-Wd vs. M-Wd), but the "Soft" vibration has a noticeably larger error bar. Thus, users were likely more confused by multimodal stimuli which were significantly mismatched.

In summary, active transient vibration made the material feel softer if the naturally generated vibration frequency was higher than the active frequency, and harder if the natural frequency was lower.

7 Study 2: Combined Effects of Transient Vibration and Visuo-Haptic Illusion

We ran a second study to evaluate how effectively our system can render different levels of softness by using the combination of the active transient vibration and visuo-haptic illusion methods in VR. Previous research has raised the effectiveness of multisensory enhancement [50], and researchers have shown that multimodal stimuli provide faster response times than unimodal stimuli [51]. Softness is not just the inverse of stiffness; it is a subjective and multisensory impression [1]. The effects of multimodal stimuli on perceived softness have accordingly been investigated [11], [14], [52]. This study explores the individual and combined effects of active transient vibrations and visuo-haptic illusion; we investigate if the combined stimuli provide a superadditive, additive, or subadditive effect on perceived softness.

We presented the participants with different active transient vibrations and visual illusions when interacting with the same proxy object. We then asked them to rate their perceived softness. Four vibration modes were used (the same as those in the first study) and three virtual stiffnesses: k=200 N/m, k=600N/m, and k=infinite (no illusion). In total there were 12 different combinations. For the haptic proxy object, we chose a wooden box because haptic proxy objects have typically been rigid [5], [6], [41] for a variety of reasons, including ease of tracking, ease of fabrication, and robustness to haptic exploration for shape perception.

7.1 Task and Procedure

The setup for Study 2 was the same used in Study 1. At the beginning of the study, all participants were asked to grasp the handheld device using their dominant hand and use it to tap and press the haptic proxy object while looking at its virtual counterpart through the VR headset.

Each trial included a combination of an active transient vibration mode and a virtual stiffness mode. Participants were required to tap the haptic proxy object at least three times, then press or tap again with various forces and speeds. After each trial, participants rated their perceived softness of the object with a score from 1 to 7 (1: softest, 7: hardest). There were 8 blocks of 12 stimuli (4 vibrations $\times$ 3 illusions), resulting in 96 trials for each user. The sequence of combinations was randomly permuted within each group. Each participant took approximately 30 minutes to complete the study.

7.2 Participants

We recruited 10 right-handed participants (3F) for the subjective softness rating task. The average age was 25.5 (2.6 std. dev). The participants did not overlap with the participants in previous studies. Each participant received a nominal compensation of $15. The study's intent was not provided. The study was approved by our institution's IRB, and all participants provided informed consent.

7.3 Hypotheses

While researchers have investigated the combined effect of visual and haptic cues for softness perception [13], [53], the haptic cues used in their studies were kinesthetic forces rendered simultaneously with the visual cues. In our study setup, active transient vibration is generated at the start of contact, while the visuo-haptic illusion occurs in response to the user pressing on the proxy object. For this study we have the following hypotheses:

- Both active transient vibration and visuo-haptic illusion independently contribute to making rigid proxy objects feel softer.
- There is an interaction effect between the two modalities, increasing perceived softness further.

7.4 Results

The results are shown in Fig. 11. Fig. 11(a) represents all the rating results under the different stimuli combinations. Fig. 11(b) and Fig. 11(c) represent the individual effects of the vibration and illusion averaged across the raw results.

We fit a linear mixed-effects model to the data, with vibration level and virtual stiffness as fixed effects, participant as a random effect, and perceived softness as the response variable. An analysis of deviance (ANODE) via Type II Wald tests revealed significant main effects of both vibration level (χ^2(3, N=960) = 107.1, $p < 0.001$) and virtual stiffness (χ^2(2, N=960) = 1329.3, $p < 0.001$). No significant interaction effect was found (χ^2(6, N=960) = 0.95, p = 0.99).

Because there was no significant interaction effect, we can pairwise compare the effects of vibration level and virtual stiffness separately/independently. A post-hoc Tukey test identified significant differences between all vibration levels averaged over virtual stiffness ($p < 0.01$), except between the "Mid" and "Hard" vibrations (p = 0.09). A post-hoc Tukey test identified significant differences between all virtual stiffness levels averaged over vibration level ($p < 0.001$). A post-hoc Tukey test identified significant differences between all individual pairwise combinations of the 12 stimuli ($p < 0.05$), except those identified in Fig. 11.

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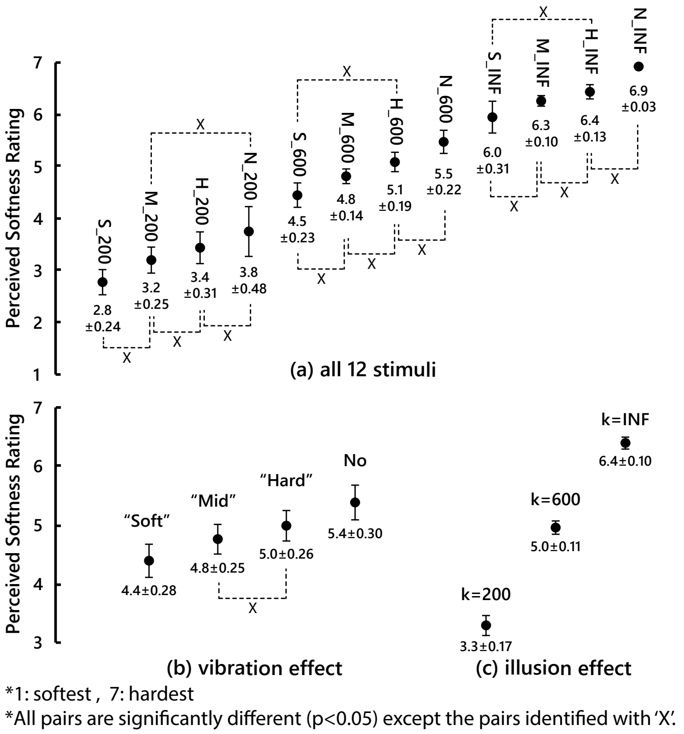

Fig. 11. Study 2 results. (a) The rating for all vibration and illusion combinations (4 vibrations $\times$ 3 illusions). For each label, the letter before the underscore indicates the vibration type (S:"Soft", M:"Mid", H="Hard", N="No"), and the letters after the underscore indicate the illusion type (200: k=200N/m, 600: k=600N/m, INF: k=infinite). (b) Average rating for the individual vibration effect. (c) Average rating for the individual illusion effect. Error bars show ± 1 SEM.

7.5 Discussion

Our results show that both factors had significant effects, each individually contributing to augmenting perceived softness. However, there was no significant interaction effect between vibration and illusion levels. Thus, the multimodal feedback did not provide a superadditive effect increasing perceived softness; the visual and haptic cues were integrated in a more linearly additive fashion.

The general trend in Fig. 11(a) shows that our system successfully renders a large range of perceived softnesses by combining active transient vibrations and visuo-haptic illusions. However, in Fig. 11, many pairs of vibrations within the same visual illusion level did not yield significant differences. In the pooled post-hoc results, all visual illusion levels yielded significantly different perceived softness ratings, while one one pair of the vibration levels did not show a significant difference. Previous results in [54], [55] also showed this visual dominance in compliance estimation tasks. Based on the results in [54], we can infer that users' perceptual variance of the visual illusion is lower than that of the active transient vibration in the present scenario. In other words, the visual illusion is likely more reliable to users as a softness cue, and therefore has a more dominant effect on perceived softness.

The effect sizes and general trends in Fig. 11(b) and (c) also demonstrate that the visual illusion was more dominant than the vibration feedback. This can also be seen from the differences between the most multimodally mismatched conditions (k=infinite with "Soft" vibration and k=200N/m with "No" vibration); however, such significantly mismatched conditions had larger standard errors.

Visuo-haptic illusion alone is effective at changing perceived softness. It is also simple to implement and has a continuous range of values. However, visuo-haptic illusion alone might feel unrealistic to some users if we set the virtual stiffness too low. In real life, objects deform more locally, and it is harder to visually perceive the deformations between different objects. Most objects in our life also have higher stiffnesses than the conditions we chose. In this context, adding active transient vibration to visuo-haptic illusion can perhaps simulate softer feeling while keeping realism.

8 Study 3: Forced Choice Task Among Different Vibrations While Controlling For Visuo-Haptic Illusion

The results of Study 2 did not clearly show that active transient vibration can influence perceived softness within each level of visuo-haptic illusion (i.e., virtual stiffness). Specifically, the condition pairs labeled 'X' in Fig.11(a) and the "Mid" and "Hard" vibration groups in Fig.11(b) did not show statistically significant differences. Furthermore, these results suggested a dominance of the visual illusion in combined (active vibration + visual illusion) interactions, likely due to the higher reliability of vision in the perceptual integration process [54]. To more clearly identify the effects of vibration on perceived softness while controlling for the effect of the visual illusion itself, we designed Study 3.

While Study 1 demonstrated the effectiveness of active transient vibrations for augmenting the perceived softness of different proxy object materials, here we investigate if the three vibration signals still yield distinct perceived softnesses when when presented with the same visuo-haptic illusion stimulus. In this study we asked participants to perform a series of two-alternative forced choice (2AFC) tasks to see the difference between the transient vibration patterns more objectively and directly. During each 2AFC task, the visual illusion was regulated to the same level but the active transient vibration was varied.

8.1 Hypothesis

This study investigates the effect of active transient vibration more rigorously. By regulating the visual illusion to same levels in the 2AFC tasks, we compare the effects of each active vibration more clearly.

- "Soft" vibrations will be perceived as softer than "Mid" vibrations, and "Hard" vibrations will be perceived as harder than "Mid" vibrations, regardless of the level of visuo-haptic illusion.
- All vibration patterns will result in increased perceived softness compared to no vibration regardless of the level of visuo-haptic illusion.

8.2 Task and Procedure

The setup for Study 3 was identical to that in Studies 1 and 2. However, for this study we used a 2AFC experiment design

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to test our hypotheses. There were two identical boxes in the VR scene. Two identical rigid physical boxes matching the size and position of the virtual boxes were fixed to the table in front of the user. The task was told to choose the box that felt softer after tapping, pressing, and observing both visually and haptically. Participants verbally reported their choice to the experimenter.

Again, there were two parameters - the active transient vibration mode and the level of virtual stiffness (visuo-haptic illusion). In this study, however, the virtual stiffness was kept constant for each pair to observe the vibration effect more clearly; therefore, for each trial the two boxes had the same virtual stiffness. One of the two boxes was used as a reference which had the reference vibration pattern, and the other box had the target stimulus vibration pattern. For trials evaluating Hypothesis 1, we set the "Mid" vibration as the reference. The "Mid" vibration was compared with "Soft", "Mid", and "Hard" vibrations for each virtual stiffness condition. To evaluate Hypothesis 2, "No" vibration was set as the reference in some trials. For these trials, only the "Mid" and "Hard" vibrations were compared with the reference for each virtual stiffness.

15 conditions ("Soft" vs. "Mid", "Mid" vs. "Mid", "Hard" vs. "Mid", "Mid" vs. "No" and "Hard" vs. "No" for three virtual stiffness conditions) were tested for each block. Each participant experienced 8 blocks, for a total of 120 total trials per participant. The sequence of 15 conditions in each block was randomized; the location of the reference and target stimuli were also randomized. The study took approximately 40 minutes.

8.3 Participants

To avoid learning effects from previous studies, we recruited 10 new participants for the 2AFC experiment (7M, 3F, avg. age 26.5±2.8 SD, all right-handed). The purpose of the study was not known to the participants. The study was approved by our institution's IRB and all participants provided informed consent. All participants received $15 for their participation.

8.4 Results

The results of Study 3 are shown in Fig. 12. Fig. 12(a) shows the results for trials with "Mid" vibration as the reference, and Fig. 12(b) shows the results for trials with "No" vibration as the reference. For each tested condition, we calculated the sensitivity index, d' (also shown in Fig. 12), which is useful in the analysis of 2AFC task results [56]. In haptics research, d'=1 is a criterion to measure JND [57]. To calculate d', we assumed there was no response bias from the participants, as condition order and reference position were both randomized within each block.

8.4.1 Vibration Varies Perceived Softness when Controlling for Visuo-Haptic Illusion

Fig. 12(a) shows the d' for each condition, averaged across participants when using "Mid" vibration as the reference. Results indicate that participants found the "Soft" vibration significantly softer than "Mid" vibration for virtual stiffness illusions of k=200N/m and k=600N/m. Participants also found the 'Mid" vibration reference significantly softer than

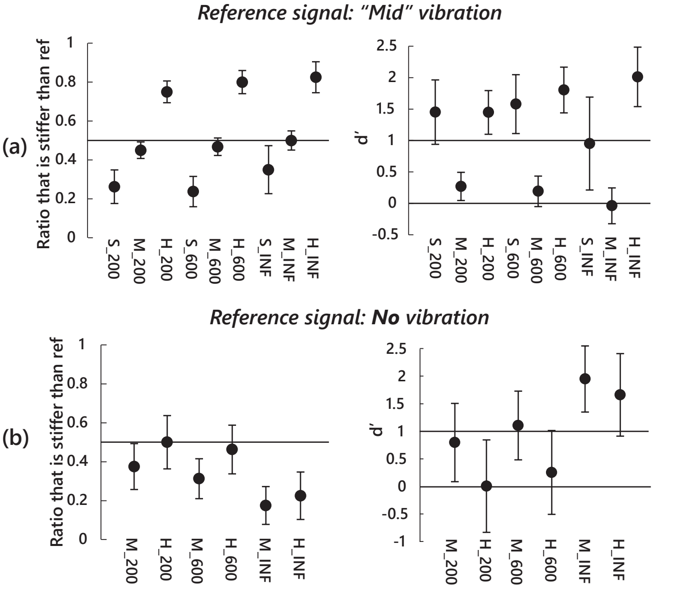

Fig. 12. The ratios in which each condition in Study 3 were reported "stiffer" than the reference, and their corresponding sensitivity indices (right), averaged across participants and separated by reference signal: (a) "Mid" vibration and (b) "No" vibration. For each condition label, the first portion indicates the vibration type (S:"Soft", M:"Mid", H="Hard", and N="No"), and the second portion indicates the virtual stiffness of the illusion (200: k=200N/m, 600: k=600N/m, INF: k=infinite). Error bars indicate ±SEM.

the "Hard" vibration for all virtual stiffness illusion levels. This supports our first study hypothesis.

8.4.2 Vibration Increases Perceived Softness When No Visuo-Haptic Illusion is Present

Fig. 12(b) shows the d' for each condition, averaged across participants when using "No" vibration as the reference. There was no significant effect of vibration on perceived softness when the virtual stiffness illusion was k=200N/m. When k=600N/m, the "Mid" vibration was perceived significantly softer than "No" vibration. When there was no illusion (k=INF N/m), both "Mid" and "Hard" vibrations gave significantly softer sensations than "No" vibration. However, because all vibration stimuli did not increase perceived softness in every visuo-haptic illusion case, our second hypothesis is not supported by these results.

8.5 Discussion

This study required participants to directly compare the softness of two virtual objects with different active vibrations. The results show that active vibration can significantly affect a user's perception of softness under a variety of tested virtual stiffness illusions (Fig.12(a)).

One interesting and non-obvious finding here is that when a visuo-haptic illusion was present (i.e., k=200 N/m, k=600 N/m), users did not significantly discriminate between "Hard" vs "No" vibrations or "Mid" vs "No" vibrations (except when k=600 N/m). We hypothesize that this is because the significant sensory difference between experiencing "No" vibration and any active transient vibration makes them difficult to compare (as opposed to say, comparing two active vibrations of different frequencies).

Using the perceptual integration model proposed by Ernst & Banks [54], this reduced reliability of the haptic perceptual channel in turn increases users' reliance on visual feedback to make perceptual judgements as in the 2AFC task. Thus, in 2AFC trials with "No" vibration as a reference but strong visual illusion cues (i.e., k=200 N/M, k=600 N/m), the visual illusion tends to dominate perception and users perceive less of a difference in softness (Fig. 12(b)). In contrast, in 2AFC trials where users compared two active vibrations (Fig. 12(a)), different vibration levels were effective in altering perceived softness regardless of the visual illusion level.

When visuo-haptic illusion was not present (i.e., k=INF), both "Mid" and "Hard" vibrations were perceived as softer than "No" vibration (Fig. 12(b)). Given our findings in Study 1 suggesting that the presence of vibration tends to make rigid objects – such as the box used here – feel softer (see Fig. 10), we expected this result. As stated in our original hypothesis, however, we expected the presence of active vibration to reduce perceived softness in *all* illusion cases; in contrast, these results suggest this to be the case only in interactions lacking a significant visual cues about softness.

One important takeaway of this study is that our results suggest under identical visual illusions, the inclusion of "No" vibration is not helpful to users in judgements of the relative softness of proxies. Our results indicate that it may instead add perceptual confusion and cause users to ignore haptic information and rely more heavily on visual cues.

9 Limitations and Future Work

We augment indirect contact between the index fingertip and passive haptic proxies object with a device that senses a user's pressing force and generates active transient vibrations on contact. Although the current device is handheld and comfortable to use, the design needs to be improved in the future. First, the device does not measure velocity for rendering active transient vibrations. Previously, researchers have placed external sensors to measure the velocity of a handheld device [38], and we would like to integrate a velocity sensor into our device. Second, because of the large gap between the index finger and proxy object (due to the haptic device), the global shape of proxy objects is also distorted. The main challenge to minimize its size comes from the actuator selection for the vibrotactile feedback. There are not many commercially available vibrotactile actuators providing such displacement and force. Novel thinner actuators, such as bimorph actuators and soft actuators, need to be developed to make the overall design compact. It could then be possible to make the entire system lie on a single finger, and perhaps create a multi-finger version.

The setup could also be improved to increase realism. Currently users are not in direct contact with the proxy objects, thus they cannot feel the texture and local curvature. A better design could be investigated in the future where the proxy object directly renders vibration and senses force of the user. One simple solution would be to install the proxy object on an apparatus that has a force sensor and a voice coil actuator. In this case, the transient vibration would only generate harder sensations because the fingertip generates low frequency vibrations while tapping, as we explained in the discussion section of the second study.

While our exaggerated virtual stiffness values amplified the visual dominance in Studies 3 and 4, the results clearly show the two methods are independently effective without an interaction when combined. This suggests that we can utilize the active transient vibration feedback to enlarge perceived softness when the visuo-haptic illusion should not be exaggerated too much in some circumstances. Future work should find realistic gains for each cue and investigate their effect on realism [58]. An interesting contradiction of the interaction with haptic proxy objects in VR is that we have to provide unrealistic stimuli to simulate various sensations. Both visual deformation and active transient vibration are unrealistic in the sense that the properties of the actual proxy do not change. An important question then is how we can create the "least unrealistic" stimuli while providing these various sensations. Optimizing such gains for realism should be investigated.

Although we investigated the effect of combining these two techniques only for augmenting the perceived softness of rigid passive haptic props, these outcomes may still be applicable for other existing haptic devices. For example, a binary brake-based haptic systems [9] or open-loop systems for rendering shapes [59], [60] are currently limited to rendering one stiffness. The vibration and visual illusion could enlarge the scope of perceived softness for these types of devices. We would also like to further explore combining our results with other illusion techniques to improve softness rendering. For example, adding visual delays and auditory effects may allow us to more effectively modify perceived softness. Beyond illusions for augmenting softness, we wish to better investigate how these techniques can be used with other illusions in VR to combine changes in shape, position, and orientation of passive props [12], [30], [41].

10 Conclusion

We investigated the combined effects of active transient vibration and visuo-haptic illusion to augment the perceived softness of haptic proxy objects, as both methods can be applied easily without complex mechatronic/control systems. We designed a simple handheld haptic device which can generate transient vibration actively and measure the force applied on a proxy object. The preliminary and first studies showed that the active transient vibration changes the perceived softness of proxy objects. We found that the active transient vibration can generate softer sensations even while tapping on a hard surface. The other two studies showed that the two techniques can be combined in an additive manner. While visual illusion was more dominant than active transient vibration for modifying perceived softness, the active vibration also had a significant effect which can increase the range of renderable softness on top of the visual effect. The inclusion of "No" vibration have added perceptual confusion, and made users rely more on the visual effect.

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REFERENCES

[1] M. Di Luca, "Multisensory softness," 2014.
[2] S. Okamoto, H. Nagano, and Y. Yamada, "Psychophysical dimensions of tactile perception of textures," *IEEE Transactions on Haptics*, vol. 6, no. 1, pp. 81–93, First 2013.
[3] E. P. Scilingo, N. Sgambelluri, D. De Rossi, and A. Bicchi, "Towards a haptic black box for free-hand softness and shape exploration," in *2003 IEEE International Conference on Robotics and Automation (Cat. No. 03CH37422)*, vol. 2. IEEE, 2003, pp. 2412–2417.
[4] T. H. Massie, J. K. Salisbury *et al.*, "The phantom haptic interface: A device for probing virtual objects," in *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, vol. 55, no. 1. Chicago, IL, 1994, pp. 295–300.
[5] A. Hettiarachchi and D. Wigdor, "Annexing reality: Enabling opportunistic use of everyday objects as tangible proxies in augmented reality," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 2016, pp. 1957–1967.
[6] Y. Zhao, L. Kim, Y. Wang, M. Le Goc, and S. Follmer, "Robotic assembly of haptic proxy objects for tangible interaction and virtual reality," in *International Conference on Interactive Surfaces and Spaces*. ACM, 2017.
[7] J. Sheng, R. Balakrishnan, and K. Singh, "An interface for virtual 3d sculpting via physical proxy." in *GRAPHITE*, vol. 6, 2006, pp. 213–220.
[8] A. Roudaut, R. Reed, T. Hao, and S. Subramanian, "Changibles: analyzing and designing shape changing constructive assembly," in *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 2014, pp. 2593–2596.
[9] I. Choi, E. W. Hawkes, D. L. Christensen, C. J. Ploch, and S. Follmer, "Wolverine: A wearable haptic interface for grasping in virtual reality," in *Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on*. IEEE, 2016, pp. 986–993.
[10] A. M. Okamura, M. R. Cutkosky, and J. T. Dennerlein, "Reality-based models for vibration feedback in virtual environments," *IEEE/ASME Transactions on Mechatronics*, vol. 6, no. 3, pp. 245–252, Sep 2001.
[11] K. J. Kuchenbecker, J. Fiene, and G. Niemeyer, "Improving contact realism through event-based haptic feedback," *IEEE Transactions on Visualization and Computer Graphics*, vol. 12, no. 2, pp. 219–230, March 2006.
[12] L.-P. Cheng, E. Ofek, C. Holz, H. Benko, and A. D. Wilson, "Sparse haptic proxy: Touch feedback in virtual environments using a general passive prop," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 2017, pp. 3718–3728.
[13] M. A. Srinivasan, G. L. Beauregard, and D. L. Brock, "The impact of visual information on the haptic perception of stiffness in virtual environments."
[14] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, "Pseudo-haptic feedback: can isometric input devices simulate force feedback?" in *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*, 2000, pp. 83–90.
[15] R. Q. van der Linde and P. Lammertse, "Hapticmaster - a generic force controlled robot for human interaction," *Industrial Robot: An International Journal*, vol. 30, no. 6, pp. 515–524, 2003.
[16] B. Wu, R. L. Klatzky, and R. L. Hollis, "Force, torque, and stiffness: Interactions in perceptual discrimination," *IEEE Transactions on Haptics*, vol. 4, no. 3, pp. 221–228, July 2011.
[17] M. A. Srinivasan and R. H. LaMotte, "Tactual discrimination of softness," *Journal of Neurophysiology*, vol. 73, no. 1, pp. 88–101, 1995.
[18] A. Bicchi, E. P. Scilingo, and D. D. Rossi, "Haptic discrimination of softness in teleoperation: the role of the contact area spread rate," *IEEE Transactions on Robotics and Automation*, vol. 16, no. 5, pp. 496–504, Oct 2000.
[19] H. Z. Tan, M. A. Srinivasan, B. Eberman, and B. Cheng, "Human factors for the design of force-reflecting haptic interfaces," *Dynamic Systems and Control*, vol. 55, no. 1, pp. 353–359, 1994.
[20] Y. Ikeda and S. Hasegawa, "Characteristics of perception of stiffness by varied tapping velocity and penetration in using event-based haptic," in *Proceedings of the 15th Joint virtual reality Eurographics conference on Virtual Environments*. Eurographics Association, 2009, pp. 113–116.
[21] Z. F. Quek, S. B. Schorr, I. Nisky, A. M. Okamura, and W. R. Provancher, "Sensory augmentation of stiffness using fingerpad skin stretch," in *2013 World Haptics Conference (WHC)*, April 2013, pp. 467–472.
[22] S. B. Schorr and A. M. Okamura, "Three-dimensional skin deformation as force substitution: Wearable device design and performance during haptic exploration of virtual environments," *IEEE Transactions on Haptics*, vol. 10, no. 3, pp. 418–430, July 2017.
[23] X. De Tinguy, C. Pacchierotti, M. Marchal, and A. Lecuyer, "Enhancing the stiffness perception of tangible objects in mixed reality using wearable haptics," in *IEEE Virtual Reality-2018 IEEE Conference on Virtual Reality and 3D User Interfaces*, 2018.
[24] F. Carpi, G. Frediani, and D. De Rossi, "Electroactive elastomeric haptic displays of organ motility and tissue compliance for medical training and surgical force feedback," *IEEE transactions on biomedical engineering*, vol. 56, no. 9, pp. 2327–2330, 2009.
[25] T. P. Chenal, J. C. Case, J. Paik, and R. K. Kramer, "Variable stiffness fabrics with embedded shape memory materials for wearable applications," in *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on*. IEEE, 2014, pp. 2827–2831.
[26] A. A. Stanley, J. C. Gwilliam, and A. M. Okamura, "Haptic jamming: A deformable geometry, variable stiffness tactile display using pneumatics and particle jamming," in *World Haptics Conference (WHC), 2013*. IEEE, 2013, pp. 25–30.
[27] Y. Visell, B. L. Giordano, G. Millet, and J. R. Cooperstock, "Vibration influences haptic perception of surface compliance during walking," *PLoS one*, vol. 6, no. 3, p. e17697, 2011.
[28] L. Terziman, M. Marchal, F. Multon, B. Arnaldi, and A. Lécuyer, "The king-kong effects: Improving sensation of walking in vr with visual and tactile vibrations at each step," in *2012 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 2012, pp. 19–26.
[29] J. J. Gibson, "Adaptation, after-effect and contrast in the perception of curved lines." *Journal of experimental psychology*, vol. 16, no. 1, p. 1, 1933.
[30] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson, "Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 2016, pp. 1968–1979.
[31] L. Kohli, "Redirected touching: Warping space to remap passive haptics," in *3D User Interfaces (3DUI), 2010 IEEE Symposium on*. IEEE, 2010, pp. 129–130.
[32] M. Achibet, A. Girard, A. Talvas, M. Marchal, and A. Lecuyer, "Elastic-arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments," in *Virtual Reality (VR), 2015 IEEE*. IEEE, 2015, pp. 63–68.
[33] M. Achibet, B. Le Gouis, M. Marchal, P.-A. Leziart, F. Argelaguet, A. Girard, A. Lécuyer, and H. Kajimoto, "Flexifingers: Multi-finger interaction in vr combining passive haptics and pseudo-haptics," in *3D User Interfaces (3DUI), 2017 IEEE Symposium on*. IEEE, 2017, pp. 103–106.
[34] F. Avanzini and P. Crosato, "Haptic-auditory rendering and perception of contact stiffness," in *Haptic and Audio Interaction Design*, D. McGookin and S. Brewster, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 24–35.
[35] F. J. Canadas-Quesada and A. Reyes-Lecuona, "Improvement of perceived stiffness using auditory stimuli in haptic virtual reality," in *MELECON 2006 - 2006 IEEE Mediterranean Electrotechnical Conference*, May 2006, pp. 462–465.
[36] B. L. Giordano, "Sound source perception in impact sounds," *Unpublished doctoral dissertation, University of Padova, Italy*, 2005.
[37] B. Knorlein, M. D. Luca, and M. Harders, "Influence of visual and haptic delays on stiffness perception in augmented reality," in *2009 8th IEEE International Symposium on Mixed and Augmented Reality*, Oct 2009, pp. 49–52.
[38] T. Hachisu and H. Kajimoto, "Vibration feedback latency affects material perception during rod tapping interactions," *IEEE Transactions on Haptics*, vol. 10, no. 2, pp. 288–295, April 2017.
[39] M. D. Luca, B. Knörlein, M. Ernst, and M. Harders, "Effects of visual–haptic asynchronies and loading–unloading movements on compliance perception," *Brain Research Bulletin*, vol. 85, no. 5, pp. 245 – 259, 2011, presence: Brian, Virtual Reality and Robots.
[40] S. J. Lederman and R. L. Klatzky, "Hand movements: A window into haptic object recognition," *Cognitive psychology*, vol. 19, no. 3, pp. 342–368, 1987.
[41] Y. Zhao and S. Follmer, "A functional optimization based approach for continuous 3d retargeted touch of arbitrary, complex boundaries in haptic virtual reality," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, ser. CHI '18. ACM, 2018.

[42] S. Jeon and S. Choi, "Haptic augmented reality: Taxonomy and an example of stiffness modulation," *Presence: Teleoperators and Virtual Environments*, vol. 18, no. 5, pp. 387–408, 2009.
[43] T. Hachisu, M. Sato, S. Fukushima, and H. Kajimoto, "Augmentation of material property by modulating vibration resulting from tapping," in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2012, pp. 173–180.
[44] L. A. Jones and S. J. Lederman, *Human hand function*. Oxford University Press, 2006.
[45] A. M. Okamura, J. T. Dennerlein, and R. D. Howe, "Vibration feedback models for virtual environments," in *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146)*, vol. 1, May 1998, pp. 674–679 vol.1.
[46] T. Hachisu, G. Cirio, M. Marchal, A. Lécuyer, and H. Kajimoto, "Virtual chromatic percussions simulated by pseudo-haptic and vibrotactile feedback," in *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology*. ACM, 2011, p. 20.
[47] L. C. Shum, B. A. Valdés, and H. M. Van der Loos, "Determining the accuracy of oculus touch controllers for motor rehabilitation applications using quantifiable upper limb kinematics: Validation study," *JMIR Biomedical Engineering*, vol. 4, no. 1, p. e12291, 2019.
[48] K. Higashi, S. Okamoto, H. Nagano, M. Konyo, and Y. Yamada, "Vibration-based rendering of virtual hardness: Frequency characteristics of perception," in *Consumer Electronics (GCCE), 2017 IEEE 6th Global Conference on*. IEEE, 2017, pp. 1–2.
[49] R. H. LaMotte, "Softness discrimination with a tool," *Journal of Neurophysiology*, vol. 83, no. 4, pp. 1777–1786, 2000.
[50] B. E. Stein and T. R. Stanford, "Multisensory integration: current issues from the perspective of the single neuron," *Nature Reviews Neuroscience*, vol. 9, no. 4, pp. 255–266, 2008.
[51] A. Diederich and H. Colonius, "Bimodal and trimodal multisensory enhancement: effects of stimulus onset and intensity on reaction time," *Perception & psychophysics*, vol. 66, no. 8, pp. 1388–1404, 2004.
[52] M. L. Dematte, D. Sanabria, R. Sugarman, and C. Spence, "Cross-modal interactions between olfaction and touch," *Chemical senses*, vol. 31, no. 4, pp. 291–300, 2006.
[53] M. Kuschel, M. Di Luca, M. Buss, and R. L. Klatzky, "Combination and integration in the perception of visual-haptic compliance information," *IEEE Transactions on Haptics*, vol. 3, no. 4, pp. 234–244, 2010.
[54] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature*, vol. 415, no. 6870, pp. 429–433, 2002.
[55] C. Cellini, L. Kaim, and K. Drewing, "Visual and haptic integration in the estimation of softness of deformable objects," *i-Perception*, vol. 4, no. 8, pp. 516–531, 2013.
[56] N. A. Macmillan and C. D. Creelman, *Detection theory: A user's guide*. Psychology press, 2004.
[57] L. A. Jones and H. Z. Tan, "Application of psychophysical techniques to haptic research," *IEEE transactions on haptics*, vol. 6, no. 3, pp. 268–284, 2013.
[58] C. C. Berger, M. Gonzalez-Franco, E. Ofek, and K. Hinckley, "The uncanny valley of haptics," *Science Robotics*, vol. 3, no. 17, pp. Art–No, 2018.
[59] A. F. Siu, E. J. Gonzalez, S. Yuan, J. Ginsberg, A. Zhao, and S. Follmer, "shapeshift: A mobile tabletop shape display for tangible and haptic interaction," in *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*, ser. UIST '17. New York, NY, USA: ACM, 2017, pp. 77–79.
[60] H. Benko, C. Holz, M. Sinclair, and E. Ofek, "Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers," in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 2016, pp. 717–728.

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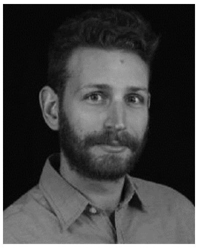

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