Perception of Soft Objects In Virtual Environments Under Conflicting Visual and Haptic Cues

Cagatay Basdogan, Berke Ataseven, Mandayam A. Srinivasan

Abstract—In virtual/augmented/mixed reality (VR/AR/MR) applications, rendering soft virtual objects using a hand-held haptic device is challenging due to the anatomical restrictions of the hand and the ungrounded nature of the design, which affect the selection of actuators and sensors and hence limit the resolution and range of forces displayed by the device. We developed a cable-driven haptic device for rendering the net forces involved in grasping and squeezing 3D virtual compliant (soft) objects being held between the index finger and thumb only. Using the proposed device, we investigate the perception of soft objects in virtual environments. We show that the range of object stiffness that can be effectively conveyed to a user in virtual environments (VEs) can be significantly expanded by controlling the relationship between the visual and haptic cues. We propose that a single variable, named *Apparent Stiffness Difference*, can predict the pattern of human stiffness perception under manipulated conflict, which can be used for rendering a range of soft objects in VEs larger than what is achievable by a haptic device alone due to its physical limits.

Index Terms—hand-held haptic devices, haptic rendering of soft objects, visual-haptic interactions, stiffness perception, multi-modal illusions, sensory integration, virtual environments.

1 Introduction

One of the goals of virtual reality (VR) research is to augment the effectiveness of virtual environments (VEs) by displaying sensory modalities in an ordered or altered manner to a human operator. To achieve this goal, we need a better understanding of human perceptual, cognitive, and motor control skills in multimodal VEs. In this study, we investigate the human perception of compliant (soft) objects in virtual environments under conflicting visual and haptic cues. For this purpose, we designed and built a new hand-held haptic device and then conducted psychophysical experiments with human participants. In this regard, the following sub-sections review the related literature on a) wearable and hand-held haptic devices and b) multi-modal interactions between vision and touch with an emphasis on the perception of compliant objects.

1.1 Wearable and Hand-held Haptic Devices

Displaying force feedback to a user in VEs through ungrounded actuated gloves and exoskeletons, or grounded force-reflecting robotic arms has been extensively investigated (see the review of haptic devices for VR in Dangxiao et al. [1] and Culbertson et al. [2]). These systems aim to provide high-fidelity haptic feedback but limit users' comfort and convenience by requiring them to attach bulky hardware to their arms as in ungrounded devices or by restricting the user to a small working space as in grounded devices. As an alternative, wearable and handheld devices have emerged for VR and gaming applications during the last decade.

Wearable haptic devices have been utilized to stimulate tactile (equivalently, cutaneous) receptors within the human skin or display object shape and material properties via net (resultant) force feedback. Gleeson et al. [3] developed a fingertip-mounted tactile device capable of stretching the fingerpad skin (i.e. applying shear force) to display directional cues to a user. Using the idea of skin stretch, Salazar et al. [4] altered the perceived stiffness and shape of physical objects via a wearable device attached to the index finger. Chinello et al. [5] developed a wearable fingertip device for rendering stiffness. In this system, three servo motors move an end-effector to simulate contacts of a finger with arbitrarily oriented surfaces. Tao et al. [6] developed a finger-worn wearable device that constrains the lateral deformation of the user's fingerpad via a hollow frame. As a result, when the user interacts with the surface of a rigid object, they perceive the object as softer than it is. Bianchi et al. [7] developed a wearable device that can stretch a fabric sliding against the user's fingerpad to render different levels of stiffness for virtual objects. Gu et al. [8] designed a lightweight and wearable exoskeleton for displaying force feedback in VEs to multiple fingers of the hand. Wolverine [9] is a low-cost wearable device, which displays forces between the user's thumb and the three other fingers to simulate virtual objects being held in hand. In addition to displaying force feedback for grasping virtual objects with fingers, gravitational effects were also rendered by using

- *C. Basdogan and B. Ataseven are with the Robotics and Mechatronics Laboratory, Koc University, Istanbul 34450, Turkey. E-mail: {cbasdogan, bataseven15}@ku.edu.tr.*
- *M.A. Srinivasan is with the Department of Computer Science, University College London, London, WC1E 6BT, United Kingdom, and the Department of Applied Mechanics, IIT Madras, Chennai-36, India. E-mail: srini@mit.edu.*

#*Corresponding author:* cbasdogan@ku.edu.tr
Manuscript received XX XX, 2023; revised XX XX, 2023.

two voice coil actuators embedded in Grabity, another wearable device by Choi et al. [10]. Hinchet et al. [11] developed a wearable glove (DextrES) that utilizes electrostatic braking mechanisms to restrict users' finger motion, giving a sense of grasping virtual objects with the index finger and thumb. The readers may refer to a taxonomy of wearable haptic devices for finger and hand in Pacchierotti et al. [12], and a more focused review of wearable gloves for VR in Perret and Poorten [13].

Hand-held devices have been typically preferred over wearables by researchers in academia and commercial companies marketing VR devices such as Oculus Rift and HTC Vive since they do not require attaching and detaching a device to the finger, hand, or body of a user. The haptic feedback provided by most of these devices is vibrotactile (cutaneous). The vibrotactile actuators are low-cost and small, hence easy to integrate into the hand-held devices, but limited in their ability to convey a sense of 3D shape and material properties such as softness. Ki-Uk Kyung and Jun-Young Lee developed the Ubi-Pen [14], which utilized a single vibration motor to transmit vibration cues to the user and an embedded pin array to display virtual texture information to the user's fingertip. Arasan et al. [15] embedded two vibration motors into a haptic stylus to generate a perceptual sense of bidirectional flow (known as phantom sensation) along the long axis of the stylus. They demonstrated the potential applications of this stylus in digital games played on a tablet. Kildal [16] developed a hand-held user interface (a rigid box embedded with a vibration actuator) that can render varying levels of softness to the index finger and thumb of the user that grasps it by displaying vibrations and visual cues imitating the illusion of squeezing a virtual object. Similarly, Heo [17] developed PseudoBend, a hand-held haptic interface made of two hollow cylindrical handles, a 6-DOF force/torque sensor, and a voice coil actuator to create an illusion of bending and deforming an object. Based on the forces applied by the hands of the user to the handles, the actuator renders vibrations to generate an illusion of stretching, bending, and twisting a deformable virtual object.

In addition to vibrotactile, some other actuation methods for displaying haptic feedback have been also implemented with hand-held devices. Quek et al. [18] showed that stretching the fingerpad skin while simultaneously displaying kinesthetic force feedback augments the perceived stiffness during interactions with soft virtual objects, though adding visual feedback appears to weaken this perceptual effect [19]. Guzererler et al. [20] designed a hand-held haptic device that applies skin stretch to the palm which affords a larger area for deformation. They showed that not only the tactor displacement but also the velocity has a significant effect on the perceived intensity of shear force due to the viscoelastic nature of human skin. Whitmire et al. [21] developed a handheld controller which utilizes a rotating and interchangeable wheel at its tip to apply shear forces to the index finger of the user. Walker et al. [22] utilized two pantograph mechanisms attached to a handle to provide tangential displacements to the user's fingertips for motion guidance. Winfree et al. [23] developed iTorqU, an ungrounded hand-held device that utilizes a flywheel inside a two-axis actuated gimbal to generate directional

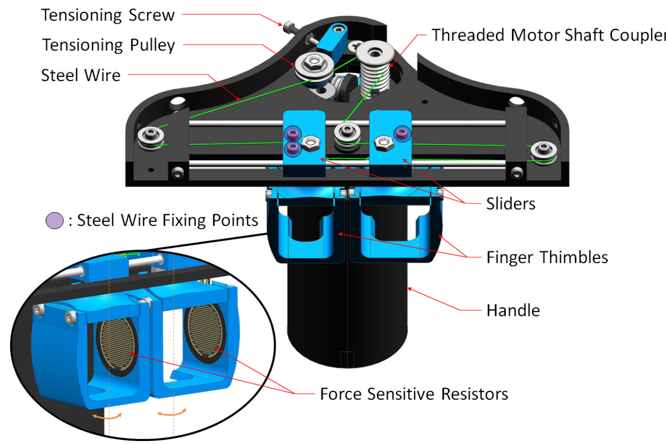

Fig. 1. Internal structure of our hand-held haptic device and the close-up view of the thimbles. The electric motor inside the handle translates the thimbles in accordance with the forces applied by the index finger and thumb, which are measured by the pressure sensors attached to the inner walls of the thimbles Hence, there are two FSRs used for each thimble to capture the forces when squeezing the fingers together and when pulling them apart. This allows a resistance-free movement of the fingers when there is no contact with the virtual object and renders its stiffness when there is. For easy fit to fingers and comfortable use of the device, the thimbles can passively rotate around the vertical axis shown in the close-up view.

torque feedback. Amemiya and Gomi [18] used a hand-held rotating flywheel to transmit directional torque feedback to a user. Nakayama and Liu [24] developed a hand-held haptic device that displays force feedback to the index finger and thumb while grasping a virtual object. The grasper part contains a motor that communicates with the ball screw via a central gear. A rigid aluminum body connects the slider portion of the ball screw to the area where the index finger and thumb make contact with the device. To measure the force exerted by the finger on the device, a pressure sensor was placed on the thumb side. An encoder was mounted on the motor to track the distance between the two fingers. Sinclair et al. devised CapstanCrunch [25], a hand-held haptic device with a capstan-based brake whose resistance is controlled with a small DC motor to render compliant virtual objects without any active force control. Choi et al. [26] developed CLAW, a hand-held haptic device that augments the typical VR controller functionality with force feedback displayed to the index finger of the user, enabling grasping of virtual objects and exploring their surfaces.

In summary, the industry and academia have a significant interest in wearable and hand-held haptic devices for VR/AR/MR applications. Easy access to 3D printers nowadays enables the design and manufacturing of wearable and hand-held devices that are low-cost, lightweight, and replicable by others though their small form factor constrains the placement and selection of actuators and sensors utilized for haptic feedback. For the same reason, most of these devices provide only tactile cues composed of low forces. Moreover, even if the net force is the intended haptic feedback, the range of forces that can be rendered by these devices is limited by the design due to their ungrounded nature.

We developed a cable-driven and hand-held device for rendering the net forces involved in grasping and squeezing 3D virtual compliant (soft) objects being held between the index finger and thumb (Fig. 1). Compared to the earlier studies, we focused on the fine control needed to render the reaction forces arising during the squeezing of soft virtual objects. We also aimed to design a hand-held device that is simple and easy to build. For example, compared to the wearable and commercial exoskeleton devices such as CyberGrasp, Dexmo, HaptX, etc. (see Fig. 26 in Dangxiao et al. [1]), our device can display force feedback to two fingers only, but this approach also simplifies the design.

1.2 Multisensory Interactions Between Vision and Touch

Using the proposed device, we demonstrate that the range of object stiffness perceived by the user in VEs can be expanded by manipulating the visual cues. It is already known that an individual's perceptual experience can be altered by manipulating the interactions between vision and touch. Earlier studies on human perception using real objects have shown that visual information can alter the haptic perception of object size, orientation, shape, and texture [27]. In the perception of size and shape [28], when vision and touch provide conflicting information, humans rely on the visual cues more than the haptic ones, whereas in texture perception [29], they appear to use haptic cues as effectively as the visual ones. Moreover, the studies on human perception conducted in virtual environments have demonstrated that manipulation of force cues can also significantly alter our perception of object size, shape, and surface. For example, the direction of the force vector reflected through a haptic device was altered in real-time to generate illusory bumps or troughs on an otherwise flat surface [30], [31]. Using this concept, when force cues of a hole (bump) were combined with the geometric cues of a bump (hole), it has been shown that humans perceive a hole (bump) [32], [33]. It has also been shown that the visual perception of surface orientation can be altered by controlled haptic cues displayed through a haptic interface device [34].

Most of the earlier multisensory experiments conducted in VEs have focused on the visual and haptic interactions for the perception of rigid objects, particularly their geometric and surface properties. Elastic objects, however, have the additional dimension of material properties such as their stiffness. While the deformable behavior of such objects can be rendered by visual displays in VEs (see the applications of this technology, for example, in medical simulation in rendering soft organ tissues with linear [35], nonlinear [36], and viscoelastic [37] material properties), the force cues essential for the haptic perception of their stiffness (or its reciprocal, the compliance) can only be obtained through touch [38], [39], [40]. On the other hand, some earlier studies have suggested that the haptic perception of stiffness depends on if the displacement is fixed or roving [41], can be altered by low-frequency haptic noise [42], and people can infer stiffness from indirect visual information alone [43]. Moreover, when force response changes nonlinearly with displacement, force cues alone may not be sufficient for haptic perception of stiffness [44].

The just noticeable difference (JND) values estimated in the earlier studies for stiffness perception under vision only, haptic only, and vision and haptic together are summarized in the form of a table in [45]. Although there is some variation in these values, the results of these studies suggest that a combination of visual and haptic information leads to a more accurate perception of object stiffness compared to relying solely on one sensory modality [46]. Visual cues, such as the deformation and shape of the objects, provide important information about stiffness. Similarly, haptic cues, such as the force and texture felt during interactions, also play a crucial role in stiffness perception. The brain combines these cues in a way that maximizes the likelihood of the observed sensory inputs [47]. This process involves weighing the reliability or precision of each modality based on its expected accuracy. For example, if vision is known to provide more precise information about an object's stiffness, it may receive more weight in the integration process compared to haptic cues. The combination of visual and haptic cues is achieved by calculating a weighted average or by considering the joint probability distribution of the two modalities. By maximizing the likelihood of the combined sensory inputs, the brain aims to obtain the most accurate estimate of the object's properties.

Although the visual and haptic perception of purely elastic [48], [49], [50] and viscoelastic materials [45] has already received some attention, their perception under the conflict of vision and touch has not been investigated in depth yet [51]. In this study, we show how manipulated visual cues can be used to expand the range of stiffness perceived by the user in VEs. The physical range of stiffness of a virtual object that can be displayed to a user through a haptic device is typically limited by its resolution, bandwidth, and workspace. We show that the range perceived by the user can be effectively increased or decreased by altering the associated visual cues. In order to overcome the limitations of active haptic devices and render soft objects in VEs, the earlier studies utilized physical objects for passive haptics, also known as "pseudo-haptics" [52]. Using this concept, Weiss et al. [53] modulated the ratio between the actual and virtual hand movements of the user in VR and found that the participants perceive the objects to be up to 28.1% softer and 8.9% stiffer. Bouzbib et al. [54] conducted a series of grasping experiments using a VR system that allowed participants to interact with virtual objects with varying levels of pseudo-stiffness. As stated by the authors, pseudo-haptics create a discrepancy between the physical and virtual interactions, and are thus subject to a perceptual threshold, up to which this visual-haptic illusion is not efficient anymore. The results showed that pseudo-haptics can simulate stiffness beyond k = 24 N/cm. Hu et al. [55] focused on manipulating the timing of haptic and visual feedback to understand its impact on stiffness perception and grip force adjustment. By introducing delays in force feedback and visual feedback, the natural relationship between these modalities was disrupted. The results of their experimental study showed that the visual delay led to a slight overestimation of stiffness, while the delay in force feedback had a mixed effect on perception, causing some participants to underestimate stiffness and others to overestimate it.

In this study, we particularly focus on the effect of displaying conflicting visual and haptic cues in VEs on our perception of object stiffness. We show that a single variable,

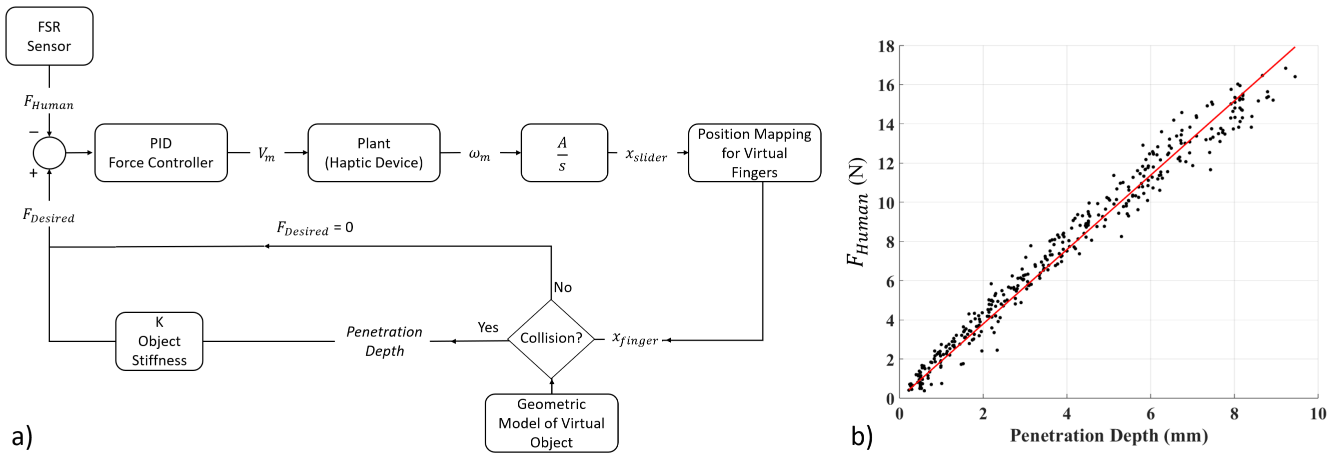

Fig. 2. a) The closed-loop control system used in our psychophysical experiments for rendering the stiffness of virtual objects. b) Scatter plot depicting the user's squeezing behavior while freely (with no displacement constraints) interacting with a virtual object having an intended (desired) stiffness of 2 N/mm for 10 seconds. A linear regression model with no intercept was fitted to the acquired force-displacement data to estimate the actual stiffness of the virtual object. The slope of the line is 1.9 N/mm, which corresponds to 5% error in the rendered stiffness. The R^2 value of the fitted model is 0.98.

named Apparent Stiffness Difference, can predict the pattern of human stiffness perception under manipulated conflict, which can be used for rendering a range of soft objects in VEs larger than what is achievable by a haptic device due to its physical limits.

2 METHODS

2.1 Design of Hand-held Haptic Device

Our hand-held haptic device consists of mainly two parts: grasper and handle (Fig. 1). The grasper can simulate holding a 3D object with the index finger and thumb to display its stiffness to the user in VEs. An electric motor (DCX16S EB KL 6V, Maxon Inc.) and a cable-driven mechanism, made of 4 pulleys (one for tensioning) and a coated steel wire (Fig. 1) were used to control the sliding movements of the thimbles, where the index finger and thumb are inserted, to display force feedback to the user during the grasping of a virtual object. A pressure sensor (FSR 402, Interlink Electronics Inc.) was placed inside the side walls of each thimble (see the zoomed view in Fig. 1) to measure the grasping forces applied by the fingers when squeezing and releasing the virtual object. The thimbles can rotate freely around the vertical axis parallel to the handle to fit over the index finger and thumb of the user easily and also to slide smoothly on two parallel rails when squeezing or releasing forces are applied to them by the user's fingers. Thimbles have a linear motion range of 47.5 mm. The pressure sensors were calibrated by using known weights priori. A PID controller is utilized to minimize the error between the measured and desired forces by adjusting the rotational speed of the motor, which is controlled by a microcontroller (Teensy 4.0 Development Board, PJRC Inc.). The device weighs 225 grams in total.

2.2 Haptic Rendering of Soft Virtual Objects

The closed-loop controller for rendering virtual objects using the proposed force feedback device is shown in Fig. 2a. The forces applied by the index finger and thumb of the user are first acquired by the FSR sensors placed at the side walls of the thimbles and then combined (F_{Human}). This force is subtracted from the desired value ($F_{Desired}$) to calculate the error in force, which is inputted to a PID controller. The PID controller shown in the diagram outputs the voltage signal (V_m) for the DC motor embedded into the handle of haptic device. The rotational velocity of the motor (ω_m) is converted to the translational motion of the sliders (x_{slider}) for grasping a virtual object, where A is the conversion constant. The displacements of the sliders are mapped to the displacements of the index finger and thumb (x_{finger}) in virtual worlds. The desired force to be displayed to the user is calculated based on the penetration depth of the virtual fingers into the virtual object multiplied by its stiffness, K. If there is no penetration, the desired force is set to zero and the user freely moves the sliders till the fingers make contact with the virtual object. Fig. 2b shows the stiffness rendering performance of our device.

2.3 Psychophysical Experiments

We conducted two sets of human psychophysical experiments to investigate the effect of manipulated visual information on the haptic perception of object stiffness in VEs [48], [49], [51]. During the experiments, a pair of virtual objects in the shape of a rectangular box was displayed side by side to the participants visually on a computer monitor and haptically via the hand-held haptic device introduced in this study (Fig. 3). It is assumed that the virtual objects are purely elastic and incompressible, having a Poisson's ratio of 0.5 in each direction. In the first set of experiments, participants were asked to discriminate the stiffness of the objects using haptic cues with and without a visual display of the haptic deformations. In the second set of experiments, the participants were asked to repeat the same task, but the relationship between the visually presented deformation and the haptic deformation of each object was varied among the experimental trials to investigate the effect of manipulated visual cues on the haptic perception of object stiffness.

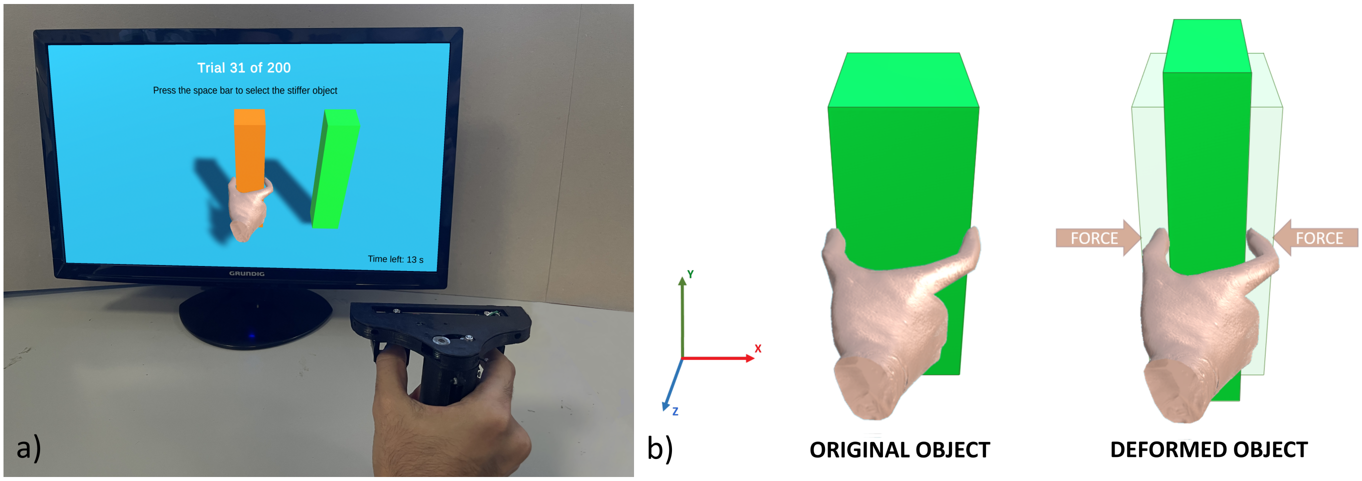

Fig. 3. a) In the stiffness discrimination experiments, two virtual objects were displayed side by side on the computer screen. The participants were asked to select the stiffer object by repeatedly (and freely) squeezing and releasing them. Participants were given 15 seconds to respond in each trial. Note that the device and the holding hand were covered with a cardboard box during the experiments. b) Deformable behavior of the virtual objects displayed in our stiffness discrimination experiments was modeled by a simple linear elastic model, where they were assumed to be incompressible (The Poisson's ratio is equal to ν = 0.5). Hence, when the participant squeezed a virtual object using the index finger and thumb along the x direction, the object expanded along the y and z directions to satisfy the incompressibility condition.

2.3.1 Experiment 1: Stiffness Perception In the Absence of Conflict Between Vision and Haptics

In the first experiment, the stiffness of one of the objects (reference) was kept constant ($K_0 = 2\ N/mm$), while the stiffness of the other (variable) was set to $K_0 + \Delta K$, with ΔK varying from –30% to 30% of K_0. A total of 6 naive participants (2 females, 4 males; the average age is 26 $\pm$ 3 years, with no known physical impairments) participated in the experiment, and they were asked to discriminate the stiffness of the virtual objects by repeatedly (and freely with no constraints in displacement) squeezing and releasing them with their index finger and thumb and judging which one was stiffer. The participants were prevented from seeing their own hands. The experiment was conducted under two conditions: (1) only haptic cues were provided to the participants (H) and (2) both visual and haptic cues were provided together to the participants (VH). The haptic stimulus was generated by the hand-held haptic device, and the visual cues were displayed on a computer monitor. There were in total 7 stiffness pairs ($\Delta K/K_0$ = -30%, -20%, -10%, 0, 10%, 20%, and 30%) $\times$ 2 sensory conditions (haptics only or both vision and haptics together) = 14 cases, with 10 trials for each case. The order of the trials in each case (visual cues present or absent) was randomized, with the same order displayed to each participant.

2.3.2 Experiment 2: Stiffness Perception Under Conflicting Visual and Haptic Cues

A total of 11 participants (7 females, 4 males; the average age is 25 $\pm$ 3 years, with no known physical impairments) participated in the second experiment. This time, the visual display of the deformation of each object was manipulated across the experimental trials. In each trial, the stiffness of one object was always equal to a reference stiffness, $K_0 = 2\ N/mm$. The stiffness of the other was $(K_0 + \Delta K)$, ΔK being $0.25K_0$, $0.5K_0$, $0.75K_0$, or K_0. Trials were randomized so that the stiffness of both objects had an equal probability of having the reference stiffness, and the participant could not have prior knowledge of which object was stiffer. The relationship between the haptic and visual deformation of each object was determined by the following set of equations:

$$X_{h,reference} = \frac{F}{K_{h,reference}} = \frac{F}{K_0} \tag{1}$$

$$X_{v,reference} = \frac{F}{K_{v,reference}} = \frac{F}{(1-\lambda)K_0 + \lambda(K_0 + \Delta K)} \tag{2}$$

$$X_{h,variable} = \frac{F}{K_{h,variable}} = \frac{F}{K_0 + \Delta K} \tag{3}$$

$$X_{v,variable} = \frac{F}{K_{v,variable}} = \frac{F}{(1-\lambda)(K_0 + \Delta K) + \lambda K_0} \tag{4}$$

where, $X_{h,reference}$ ($K_{h,reference}$) and $X_{v,reference}$ ($K_{v,reference}$) are the haptic and visual displacements (stiffnesses) of the reference object respectively. Similarly, the relations for $X_{h,variable}$ ($K_{h,variable}$) and $X_{v,variable}$ ($K_{v,variable}$) represent the haptic and visual displacements (stiffnesses) of the variable object respectively. It can be observed from the Equations (1) and (3) that actual displacement for a given force is simply equal to the force divided by the stiffness of the object. On the other hand, the Equations (2) and (4) show that the displacements that are visually rendered on the computer monitor are equal to the applied force divided by a weighted average of both stiffnesses. The influence of each stiffness depends on the scaling factor, λ. Hence, λ is a parameter that manipulates only the visual deformation, and its value was equal to 0,

TABLE 1
Each cell of the table tabulates the stiffness values ($K_{h,reference}$, $K_{v,reference}$, $K_{h,variable}$, $K_{v,variable}$) used in Eqs.(1)-(4) for Experiment 2 in units of N/mm.

λ \ ΔK	$0.25K_0$	$0.50K_0$	$0.75K_0$	$1.00K_0$
0.00	2.0000	2.0000	2.0000	2.0000
	2.0000	2.0000	2.0000	2.0000
	2.5000	3.0000	3.5000	4.0000
	2.5000	3.0000	3.5000	4.0000
0.25	2.0000	2.0000	2.0000	2.0000
	2.1250	2.2500	2.3750	2.5000
	2.5000	3.0000	3.5000	4.0000
	2.3750	2.7500	3.1250	3.5000
0.50	2.0000	2.0000	2.0000	2.0000
	2.5000	2.5000	2.7500	3.0000
	2.5000	3.0000	3.5000	4.0000
	2.2500	2.5000	2.7500	3.0000
0.75	2.0000	2.0000	2.0000	2.0000
	2.3750	2.7500	3.1250	3.5000
	2.5000	3.0000	3.5000	4.0000
	2.1250	2.2500	2.3750	2.5000
1.00	2.0000	2.0000	2.0000	2.0000
	2.5000	3.0000	3.5000	4.0000
	2.5000	3.0000	3.5000	4.0000
	2.0000	2.0000	2.0000	2.0000

0.25, 0.50, 0.75, or 1 in the experiment. In this way, λ ranged from zero conflict (λ = 0), that is, the visual deformation of each object corresponded to its haptic deformation, to a case of a complete conflict (λ = 1), where the visual displacement of the object with the stiffness of K_0 was equal to the haptic displacement of the other object with the stiffness of $K_0 + \Delta K$ for the same force F and vice versa.

Participants were asked to discriminate the softness of the objects as in the first experiment, by judging which one was stiffer. There were in total 4 stiffness pairs ($\Delta K/K_0$ = 25%, 50%, 75%, and 100%) $\times$ 5 different settings of λ (0, 0.25, 0.5, 0.75, and 1) = 20 cases with 10 trials for each case per participant. The stimuli order was randomized among ΔK and λ, with the same order displayed to each participant. Table 1 tabulates all the stiffness values utilized in Experiment 2 based on the selected ΔK and λ values.

3 Results

3.1 Experiment 1: Stiffness Perception In the Absence of Conflict Between Vision and Haptics

The results of the first experiment (Fig. 4), plotted as the percentage of trials in which the variable object was perceived to be stiffer than the reference object versus stiffness increment ΔK (expressed as a percent of K), show that when $|\Delta K|$ was greater than 30%, the participants could discriminate the stiffnesses of two objects at almost 100% correct through haptics with or without the supporting visual information. The Just Noticeable Differences (JND) under the H and VH conditions were estimated from the psychometric curve as 10.41% and 7.24%, respectively. These values are in agreement with the ones reported in the literature [41], [56], [43], [45], [52]. We conducted a two-way ANOVA analysis by taking the percent difference in stiffness with respect to the reference, $\Delta K/K_0$ (-30%, -20%, -10% 0%, 10%, 20%, 30%), and the sensory conditions (H, VH) as the independent variables and the participants' responses

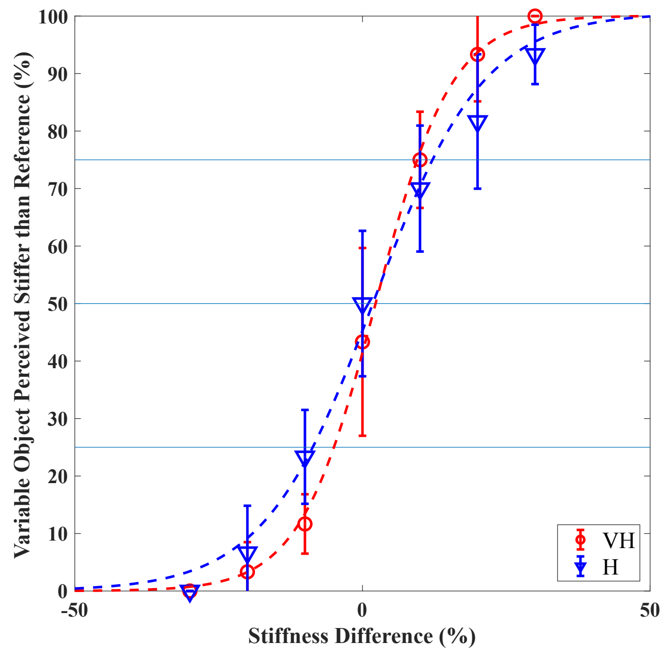

Fig. 4. The results of the stiffness discrimination experiment when there is no conflict between visual and haptic cues. The dashed blue and red colored curves represent the mean percentage responses of the participants under H and VH conditions, respectively. The error bars show the standard deviations. A sigmoid function of the form $A/(1+e^{-B(x-C)})$ was fitted to the average data with ΔK as the independent variable and A, B, and C are the constant coefficients. R^2 value for both curves is 0.99.

(i.e. the variable object perceived stiffer than the reference object in percentage) as the dependent variable. The two-way ANOVA showed a significant effect of $\Delta K/K_0$ ($F_{6,70}$ = 56.66, p $<$ 0.0001) and the sensory conditions ($F_{1,70}$ = 5.88, p = 0.018) on the participants' responses, and no interaction between the two ($F_{6,70}$ = 1.74, p = 0.125). Our post-hoc analysis showed that the differences in the participants' responses were significant for all pairwise comparisons of $\Delta K/K_0$ (p $<$ 0.05), except for the following pairs: -30% and -20%, -30% and 30%, -20% and 20%, -20% and 30%, -10% and 10%, -10% and 20%, and 20% and 30%.

3.2 Experiment 2: Stiffness Perception Under Conflicting Visual and Haptic Cues

The results of the second experiment (Fig. 5a) showed that the percentage of correct responses decreased significantly as the conflict between visual and haptic cues was increased. For example, at full conflict (λ = 1) when the visual displacement of the object with the stiffness of $K_0 + \Delta K$ at a given force was equal to the haptic displacement of the object with the stiffness of K_0 and vice versa, the participants were wrong more than 70% of times in their judgments. Freyberger et al. [57] report that the illusion breaks when compliances by both modalities differ more than 55%. This total reversal of results compared to their performance, when there was no conflict (λ = 0), is unexpected, considering that the ΔK values used in the second experiment were such that the participants would be able to

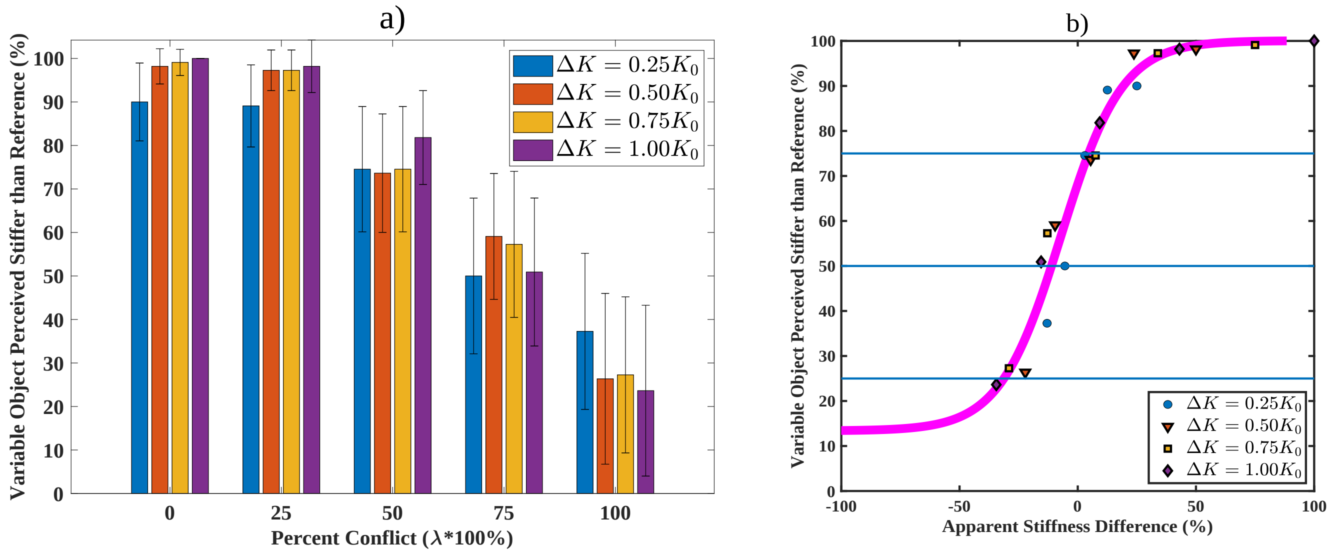

Fig. 5. a) The results of the stiffness discrimination experiment when there is a variable conflict between visual and haptic cues. The results show that the discrimination performance of the participants was strongly affected by visual cues even for ΔK values much larger than those for which participants performed at almost 100% correct levels when there was no visual conflict. The error bars show the standard deviations. b) A single-variable empirical model can successfully predict the results of the second experiment. The solid line represents the fitted curve.

discriminate the stiffnesses correctly at 100% even with the haptic information alone, as indicated by the results of the first experiment.

We conducted a two-way ANOVA analysis by taking the percent difference in stiffness with respect to the reference, $\Delta K/K_0$ (25%, 50%, 75% 100%) and the parameter quantifying the percent conflict between vision and haptics, λ (0, 0.25, 0.50, 0.75 1), as the independent variables and the participants' responses (i.e. the variable object perceived stiffer than the reference object in percentage) as the dependent variable. The two-way ANOVA showed a significant effect of λ ($F_{4,200}$ = 211.0, p $<$ 0.0001), no effect of $\Delta K/K_0$ ($F_{3,200}$ = 0.6, p = 0.61) since the selected $\Delta K/K_0$ values were all larger than the JND values calculated in the first experiment, and no interaction between the two ($F_{12,200}$ = 1.6, p = 0.10). Our post-hoc analysis showed that the differences in participants' responses for all pairwise comparisons of λ are significant (p $<$ 0.05) except for λ = 0 and λ = 0.25. There were no significant differences in participants' responses for any pairwise comparisons of $\Delta K/K_0$.

The strong dependence of participants' stiffness discrimination on the visual information suggests the following analysis. By definition, the computation of the stiffness of an object requires the determination of the ratio of the force applied to the resulting deformation. In the discrimination experiments involving visual and haptic cues, the force information has to necessarily come from the haptic channel whereas the deformation information has two alternative paths: the displacement of the real fingers sensed kinesthetically, and the displacement of the virtual fingers sensed visually. The results of the second experiment then suggest the following hypothesis: when there is a conflict in the displacement information from the two paths, the participant relies on visual displacement and associates it with the applied force sensed haptically, while paying less attention to the haptic displacement information sensed kinesthetically. In this regard, we could reformulate the discrimination problem as follows. The stiffness of the reference object perceived by the participant ($K_{reference}$) will be the applied force (F) divided by the visual displacement of the reference object ($X_{v,reference}$) and the stiffness of the variable object perceived by the participant ($K_{variable}$) will be the applied force, F, divided by the visual displacement of the variable object ($X_{v,variable}$). However, as seen from the error bars in Fig. 5a, the uncertainty in the response of participants increased as the conflict between vision and touch was increased. To address this issue, we update λ by taking the standard error of the means of the participants' responses into account. Hence, λ' is defined as:

$$\lambda' = \frac{(100 - \bar{\sigma})}{100} \times \lambda \tag{5}$$

where $\bar{\sigma}$ is the average of the standard error of means of the different ΔK values for a given λ.

In order to explain the results of the second experiment, we introduce the concept of "apparent stiffness". The apparent stiffness of a virtual object is simply the actual applied force divided by the visual displacement of the object (i.e. $K_{v,reference}$ and $K_{v,variable}$ in Eqs. (2) and (4), respectively). Then, the stiffness discrimination judgments made by the participants would be based on *Apparent Stiffness Difference (ASD)*, which is defined as:

$$ASD = 100 \times (\frac{K_{v,variable} - K_{v,reference}}{K_{v,reference}}) \tag{6}$$

To test this hypothesis, the experimental data was re-plotted against ASD (Fig. 5b). To obtain a predictive model, a sigmoid curve of the form $A/(1 + e^{-B(x-C)}) + D$ was fitted to the average data with ASD as the independent variable, and A, B, C, and D are the constant coefficients ($R^2 = 0.96$). The JND was estimated from the psychometric curve as 17.9%. The asymmetry in the psychometric curve can be observed from the difference between the values of upper and lower thresholds (UT = 4.6%, LT = -31.2%). This asymmetry, which needs further investigation, may stem from the fact that the variable object was always significantly stiffer (i.e. above JND) than the reference object in our second experiment and we have not collected data for the opposite case.

4 Discussion

The earlier studies on perceptual integration of visual and haptic modalities have shown that humans integrate these sensory modalities in a statistically optimal fashion, leading to improved discrimination performance [47]. The findings highlight the complementary nature of visual and haptic cues and emphasize the flexibility and adaptability of the integration process. Compared to integration, our decision-making process under visual and haptic conflicts (i.e. a discrepancy between the information received from visual and haptic modalities) has been studied less and it appears that the maximum likelihood estimation approach cannot be applied directly to integrate the sensory data. For example, Kuschel et al. [58] showed that visual and haptic compliance estimates are integrated based on a weighted summation process using weights that are not optimal when there is a conflict. Resolving such conflicts presents a challenge for the brain, which appears to employ Bayesian frameworks [44], [59], consider prior knowledge, contextual cues [60], and the reliability of each modality to make accurate perceptual decisions. The results of our studies suggest that visual position information has a clear dominance over haptic hand position information in the discrimination of object stiffness when there is a conflict between visual and haptic cues. This dominance became more evident as the visual scaling parameter was increased. The participants essentially paid less attention to kinesthetic hand position information regarding object deformation and based their judgment on the relationship between the visual position information and the indentation force sensed haptically. This result has the practical application that while the physical range of stiffnesses of virtual objects that can be displayed to a user is typically limited by the resolution, bandwidth, and workspace of the haptic device, the range perceived by the user can be effectively increased or decreased by altering the associated visual cues. There is, however, an asymmetry in the human perception of such manipulated visual information (as seen in Fig. 5b), which warrants further investigation.

5 Conclusion

We developed a hand-held haptic device to investigate the effect of visual cues on the haptic perception of object stiffness. The results of our psychophysical experiments show that humans rely on visual information more in stiffness discrimination when there is a conflict between visual and haptic cues displayed to them. More generally, all the previous observations on the visual and haptic perception of geometric properties of objects such as size, shape, and orientation and the results described above on the perception of material property, the stiffness (or, equivalently, its reciprocal, the compliance), lead to the following unified explanation: In perceptual tasks that involve spatial perception where information about forces is not essential to the task, visual information supersedes haptic information. However, when the temporal variation of force, a variable that can only be perceived through touch, is essential to the perceptual task, haptic force information is combined with visual-spatial information to arrive at human perceptual judgments. Given that the visual-spatial resolution is superior to that of kinesthesia, this selective retention of haptic force information while throwing away the kinesthetic hand positional information is optimal during the exploration of our natural environment but can go awry when the environmental rules of engagement are altered.

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Cagatay Basdogan received the Ph.D. degree in mechanical engineering from Southern Methodist University. He is a faculty member in the mechanical engineering and computational sciences and engineering programs at the College of Engineering, Koc University, Istanbul. Before joining to Koc University, he worked at NASA-JPL/Caltech, the Massachusetts Institute of Technology, and Northwestern University Research Park. His research interests include haptic interfaces, robotics, mechatronics, biomechanics, medical simulation, computer graphics, and multi-modal virtual environments.

Berke Ataseven received B.S. degree in mechanical engineering from Koc University in 2020. He is currently an M.S. student in the Department of Mechanical Engineering at Koç University and a research assistant at the Robotics and Mechatronics Laboratory. His research interests include mechanical design, haptics, and VR/AR technology.

Mandayam A. Srinivasan received the Ph.D. degree from the Department of Mechanical Engineering, Yale University. He is the founder-director of MIT Touch Lab at the Massachusetts Institute of Technology, USA. He is currently a Professor of Haptics in the Department of Computer Science, University College London, UK, and Vajra visiting professor at the Department of Applied Mechanics, IIT Madras, Chennai, India. His research interests include the science and technology for haptic computation, cognition, and communication in humans and machines, particularly to enhance human–machine interactions in virtual reality and teleoperation systems.