Dynamic End-Effector for Rendering Hardness and Stiffness with Encountered-Type Haptics

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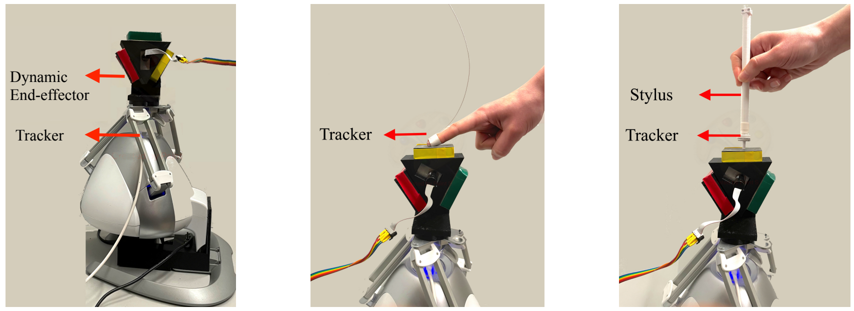
Abstract. We present a novel approach for simulating hardness and stiffness using an Encountered-Type Haptic Display (ETHD) with a dynamic end-effector. Addressing limitations in existing haptic rendering methods, our system allows dynamic adjustment of displayed hardness and stiffness. We conducted two experiments to assess users' perception of virtual blocks' hardness and stiffness using our device. Results indicate that physical hardness is a more salient feature than rendered stiffness. Evidence of stiffness masking was observed, particularly in high-hardness objects. Regardless of touch method (bare finger or stylus), participants were able to discern hardness and stiffness differences, with users finding it easier to distinguish hardness when tapping using a stylus.

Keywords: Haptic Augmented Reality, Encountered Type Haptic Display, Stiffness Rendering, Hardness Rendering

1 Introduction

Rendering hardness and stiffness is a challenging task in displaying realistic virtual objects. Hardness refers to the resistance of an object to indentation, while stiffness refers to the resistance of an object to deformation. However, both of these properties are important in several applications, including surgical simulations [7,2,15], virtual assembly [1,16], and teleoperation of robotic systems [18]. Accurate and realistic rendering of hardness and stiffness is crucial for training medical professionals in performing delicate surgical procedures, manipulating virtual objects with different levels of hardness and stiffness, and ensuring safe and effective control of robots in hazardous or remote environments.

Existing haptic devices and rendering algorithms have limitations such as low fidelity, poor accuracy, and the inability to simulate realistically hard virtual objects [6]. New algorithmic and device-based approaches are needed to address these limitations and provide more realistic hardness and stiffness. Algorithmic methods, which are often event-based, include high-frequency transient force responses [10], hybrid force-moment braking pulse [14], and damping [18]. These studies have shown that tactile cues are superior over kinesthetic cues in increasing perceived hardness [4,10,8]. Device-based methods include haptic augmented reality (AR) and encountered-type haptic displays (ETHD). Jeon et al. introduced a Haptic AR framework that used force feedback to



(a) (b) (c)

Fig. 1: Our ETHD system, (a) the base of our system is a modified haptic device to render stiffness with a custom dynamic end-effector that is used to render hardness. The user interacts with the end-effector through (b) a bare finger or (c) stylus.

modulate a real object's stiffness [9]. However, limitations exist when dealing with highly stiff real objects and uniform dynamic responses. An ETHD contacts the user only when they are touching a virtual object, which reduces the inertia and unwanted haptic noise. Building on this concept, recent research has enhanced ETHD functionality by incorporating surfaces that rotate beneath the user's fingers to increase contact and rendering area [12]. Further advancing this technology, multi-sided end-effectors introduced by Araujo et al. [3] expand the capabilities of ETHDs. These end-effectors render additional surface attributes like temperature and allow for the manipulation of physical objects, enhancing interaction by engaging multiple sides with the user's hand. This innovative approach signifies a leap forward in creating more immersive and interactive user experiences. We previously presented an innovative ETHD approach for displaying combined hardness and stiffness during interactions with an untethered stylus [20]. However, one limitation of this previous system is that the hardness had to be manually changed when rendering different objects.

Multi-modal haptics, such as the combined rendering of hardness and stiffness, aim to create a more immersive user experience by focusing on diverse stimuli like force, vibration, texture, temperature, and pressure. Integration of these modalities introduces challenges such as tactile masking, where the interference between different cues limits distinct perception [22]. We have previously explored the interplay between hardness and stiffness modalities in ETHDs, leveraging tactile masking to create the perception of a harder surface despite limited device stiffness [21].

1.1 Contributions

In this paper, we build on prior findings in using an ETHD to render both hardness and stiffness [20,21]. In [20], an ETHD Device was used to increase the realism of virtual haptic interactions and to render both stiffness and hardness. The ETHD was created by disconnecting a haptic device's stylus and attaching plates of varying hardness to the end-effector. An untethered stylus was used to interact with the end-effector, and the haptic device was used to represent stiffness, while the physical hardness of end-effector plates was used to render hardness. Simultaneous and independent rendering of hardness and stiffness allowed us to simulate both transient- and extended-response forces during the haptic interaction. This method helped remove unwanted friction and inertia when simulating free space with a haptic device. Traditional position-based and event-based methods, such as acceleration matching, spring, and spring-damper, were shown to be less realistic than this method for rendering a ranges of materials fro,m soft to hard. In [21], we quantitatively and qualitatively investigated how altering physical hardness changes the perception of the interaction while using an ETHD, which showed higher realism compared to previous methods of rendering. The distinct gap between the stiffness and hardness modalities provided the user with multi-modal cues, which resulted in a tactile masking effect between the two cues. By leveraging the masking effect, we could create the perception of a harder surface despite the device's limited stiffness output. However, these systems were only capable of actively varying stiffness, while hardness remained static and required physical alterations of the end effector. Our novel approach in this paper leverages a dynamic end-effector on the modified haptic device to render both hardness and stiffness. This system allows for simultaneous adjustment of both hardness and stiffness based on the needs of the application and virtual environment, which is crucial for realistic simulations in various fields such as medicine and engineering.

To evaluate the effectiveness of our approach, we conducted two human subject experiments where participants were asked to tap on virtual blocks and sort them based on their perceived hardness and stiffness. The first experiment involved tapping with a stylus, while participants tapped on the blocks using their bare finger in the second experiment. The key results of our study are:

- Participants can easily discriminate between the varying levels of hardness, regardless of the stiffness level of the blocks.
- Stiffness masking was present in this system, confirming the results from [21].
- Participants can accurately differentiate between different levels of hardness and stiffness, regardless of the method of touch used (whether tapping with a bare finger or a stylus).
- The method of touch likely impacts perception, with material properties like hardness and stiffness being easier to distinguish when tapping with a stylus than with a bare finger.

2 Rendering Methods

Our system's design (Fig. 1) modifies a Novint Falcon haptic device into an ETHD for simultaneous rendering of hardness and stiffness. Similar to [21,20], we detach the stylus, making the rest of the device into our system's base. A dynamic end-effector adjusts hardness based on the user's virtual location (Fig. 2). The ETHD's decoupled nature provides tactile cues through stylus-end-effector collisions to generate realistic hardness sensations. Virtual stiffness, controlled by the haptic device, complements this by applying force based on the user's penetration into the virtual object. We discuss the device and control algorithms below.

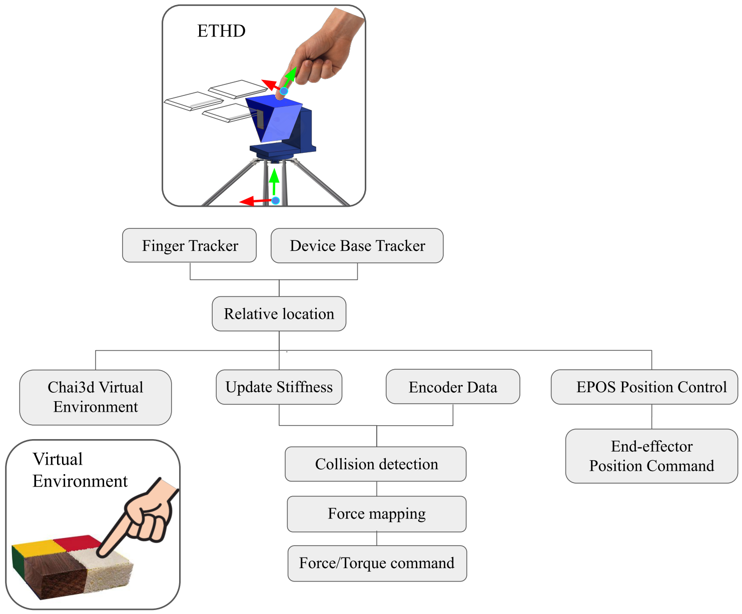


Fig. 2: Control system overview

2.1 Encountered-Type Haptic Display Design

We modified a Novint Falcon kinesthetic haptic device by disconnecting the stylus to allow for free-space, untethered interactions. We also optimize vertical output force by rotating the device 90 degrees, and implement a new X-axis gravity compensator to counteract the end-effector's weight, and reduce friction and inertia. The rendering methods presented in this paper can also be adapted to other devices, such as an admittance device or robotic arm.

Given that the Falcon haptic device is operated with an open-loop control system, it is necessary to verify that the force output to the user matches the commanded force. We manually re-calibrated the device by finding the relationship between commanded and output stiffness, based on the procedure in [21], and then used this calibration to adjust the commanded stiffness.

2.2 Dynamic End-Effector Design

Our system utilizes the haptic device's actuators to render stiffness, while the end-effector surface is responsible for rendering hardness, allowing the system to overcome limitations of the low-cost Novint Falcon in simulating hard materials [21,20]. Our dynamic end-effector enables switching between different levels of hardness depending on the user's location. This end-effector consists of a hollow 3D-printed triangular prism drum, with each of its three sides featuring a plate with a different hardness (Figure 1-(a)). Depending on the user's position in the virtual scene, only one of these plates is pointed upwards at a given time and serves as the current interaction point between the stylus and the device.

Our previous study [20] demonstrated that it is possible to simulate a wide range of virtual materials using different stiffnesses and only three different hardness levels (soft, medium, and hard). Therefore, to make this system more generic and to ensure equal time spent rotating the end-effector from one plate to another during an interaction, our system includes three plates with different hardnesses. We use the Shore durometer scale, which measures the indentation depth under a certain load, to determine the hardness of these materials. The selected hardness levels were extra soft (Shore 10 OO), medium (Shore 60 A), and extra hard (Shore 75 D). Each plate is 50.8 mm×50.8 mm in size and 12.7 mm in thickness. The thickness was chosen to prevent the tooltip from reaching the end of the plate when tapping. With this design, we ensure that our system can simulate a range of materials with different hardness levels accurately and consistently. Note that it is always possible to use more plates with different hardness levels or in different ranges based on the resolution of the application.

We placed a DC motor (Maxon, model 344516) at the center of the triangular prism drum to switch between the three plates. This actuator was chosen for its small size, non-backdrivability, and gearbox (16.58:1).Additionally, the actuator has a two-channel encoder and a no-load speed of 11000 rpm at 12V. To drive this actuator, we used a Maxon EPOS4 Compact 50/5 CAN motor driver. To connect the actuator to the device's end-effector, we designed a custom 3D-printed 90-degree joint so that the center of the plates aligned with the center of the end-effector on the X-Y axes. This allowed for precise rotation between the different surfaces, ensuring an accurate and reliable rendering of the different levels of hardness. After we assembled the dynamic end-effector, we used EPOS studio software to tune the PID controller values in order to accurately control the rotation of the drum.

2.3 Device Control

We use the CHAI3D simulation framework for visualizing and rendering the haptic control loop of our device. We integrate external sensors into our ETHD system to allow rendering of hardness and stiffness across the entire workspace. Based on the user's location, the system dynamically adjusts the end-effector's position and orientation, anticipating user interactions with virtual objects to promptly display the appropriate hardness and update stiffness (Fig. 2).

To track the user's position, the stylus includes an Ascension trakSTAR 6 DOF magnetic tracker sensor (Model 180, 0.5 mm resolution, 45 cm range) with 250 Hz update rate positioned at the front of a custom 3D-printed pen-shaped tool (Fig. 1-(c)). The stylus has a hemispherical tip (4 mm diameter, 15 mm length) to interact with the end-effector. Despite its relatively small size, the flat end-effector's surface provided sufficient friction to prevent the stylus from slipping while participants interacted with the target surfaces. For bare-finger interaction, a magnetic tracker sensor (Ascension trakSTAR Model 180) is attached to the user's fingernail (Fig. 1-(b)). The tracker is small (2 mm diameter, 9.9 mm length), offering an intuitive and flexible way to interact without a dedicated tool. Another magnetic tracker sensor (Ascension trakSTAR Model 800) is attached to the center of the haptic device (Fig. 1-(a)) to allow us to calculate the relative position between the device and the user. Calibration ensures accurate relative positioning by accounting for sensor offsets. All position data was low-pass filtered using a single-pole IIR filter with a cutoff frequency at 50 Hz.

The end-effector dynamically tracks and follows the user's position, even when in free space. This ensures that the end-effector is immediately available for interaction when the user engages with objects in the virtual environment. After we move the end-effector, we use the magnetic tracker to visually show the tracker's location in the virtual environment (red cursor in Figure 3); the user's position as measured by the magnetic tracker is not used for the rendering calculations in Eq. (1). Instead, to render the haptic surface, we use the encoder data of the haptic device. To align the end-effector with the user's position, the haptic device is temporarily switched to position-control mode, the end-effector is moved to the user's location, and the end-effector is simultaneously commanded to rotate to display the appropriate surface that matches the virtual object to be rendered (with 1000 Hz update rate). The rendered stiffness is also adjusted to match that virtual object.

Our controller adjusts the device's output force based on the user's hand position and its collision with virtual objects:

$$\vec{F} = k\vec{x}. \tag{1}$$

where $\vec{F}$ is the force displayed to the user, k is the stiffness, and $\vec{x}$ is the user's penetration into the virtual object. The controller adjusts the end-effector orientation to provide hardness that matches the virtual object.

3 Experimental Methods

We conducted two experiments to understand how users perceive material properties of virtual objects when both hardness and stiffness are rendered. The user interacted with the device using a stylus in the first experiment and a bare finger in the second experiment. Our hypotheses are: (H1) the perceptual cues used to distinguish different levels of hardness and stiffness will not rely on the method of touch, (H2) the effect of hardness on participants' perception of block properties will be predominant when stiffness differences are minimal.

3.1 Setup

The study was approved by the University of Southern California Institutional Review Board under protocol UP-19-00712, and all participants gave informed consent. Ten participants (4 female, 6 male; 22-36 years old; all right-handed) completed the study. Participants, seated on a chair with headphones to block audio cues, interacted with the device using their dominant hand (stylus or index finger). A keyboard was used to select the blocks using their non-dominant hand. To prevent visual cues, participants were instructed not to look at the device during tapping. The device was positioned below the armrest on a low table to keep the end-effector out of their direct view, ensuring that they focused on the virtual environment displayed on the monitor.

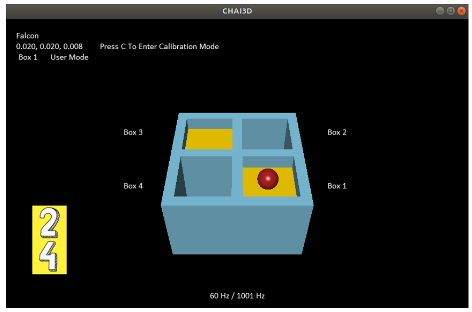


Fig. 3: Visual scene of our experiments consisting of four yellow blocks that represent different levels of hardness and stiffness.

The virtual scene was rendered in OpenGL and displayed to the user on a monitor. It consisted of four virtual blocks (labeled 1–4) with a wall in between (Figure 3). The size of all virtual blocks together was selected to be close to the Falcon workspace range in x-y direction, and centered in z direction (which is 10 cm x 10 cm X 10 cm). The tall walls required participants to lift their finger or stylus off of the end-effector when transitioning between blocks, preventing unintended device interactions during end-effector rotation. All blocks were visually identical to ensure that visual cues did not influence the perception of hardness or stiffness. The blocks did not exhibit any visual deformation when interacted with, avoiding any visual bias that might affect the user's tactile perception as demonstrated in previous studies [5].Stiffness was rendered through our haptic device, while hardness was controlled by the device's end-effector. Notably, the blue box remained stationary, and the red ball's movement corresponded to the user's finger or stylus position relative to the haptic device's center.

In Experiment 1, the user interacted with the end-effector of the haptic device using a stylus that tracked their position. In Experiment 2, the user interacted with the end-effector using a bare finger with a tracker attached to their fingernail; tape was also placed on their fingertip to mask tactile cues from contact with the end-effector. To ensure balanced experimental conditions, participants were randomly assigned to start with either the stylus or the bare finger, and then switched roles in subsequent sessions. A small sphere cursor on the screen indicated the position of the user's stylus or finger relative to the device. Once the position of the stylus or finger was identified to fall within the x-y range of a given virtual block, the end-effector moved to that location and rotated to display the appropriate material on top. However, the end-effector did not move if the relative position of the tracker remained within the x-y limits of the current block.

3.2 Procedure

Participants were asked to sort the four virtual blocks from softest to hardest through tapping, either with the stylus or their bare finger. Note that we are asking participants to rate the perceptual hardness of the blocks, which is affected by an object's physical hardness and stiffness [13]. To select a box, they pressed a key and the corresponding block disappeared from the virtual scene and appeared in the ordered stack on the left-hand side. This process continued until all blocks were sorted; participants then pressed the "enter" button to initiate a new set of hardness and stiffness values. Tapping was chosen as the primary interaction method due to its common use in evaluating material properties [11], facilitating user interaction and feedback of perceived hardness.

During the experiment, participants could freely tap on each block as much as they preferred. Participants were not instructed on how to grasp the stylus, even though it has been shown that grasping styles can affect perception [19,17] because we wanted them to concentrate on perception rather than maintaining a particular grasp. They were advised to hold the stylus vertically, much like a pencil, and were not restricted in terms of how many times they could tap. They were also not instructed on the distinction between the rendered hardness and stiffness to prevent any bias or confusion. Before the experiment, participants were trained on how to tap and with what approximate speed to tap. Although the contact velocity of taps was not controlled during the experiment, an example of tapping speed was shown to participants, and they were instructed to use the same speed for all trials. Additionally, previous research suggests that the way individuals hold the stylus and explore the surface can impact stiffness perception. As a result, we did not impose additional restrictions on tapping styles [17].

3.3 Experimental Conditions

Each trial involved four blocks, each with a unique combination of two stiffness and two hardness levels. We used three different stiffness levels (low (1000 N/m), medium (1500 N/m), and high (2000 N/m)) and three different hardness levels (extra soft (Shore 10 OO), medium (Shore 60 A), and extra hard (Shore 75 D)), which were selected based on previous research [21]. In total, there were nine unique cases, made up of all possible combinations of hardness and stiffness levels. To ensure reliability and validity, each experiment was repeated twice, resulting in a total of 18 trials per experiment. The order of conditions was pseudo-randomized for each participant and the order of Experiments 1 and 2 was counter-balanced across participants to minimize any potential order effects.

4 Results

Below we present the results of our experiments. For simplicity, we denote Hardness as H and Stiffness as S. For each hardness we denote H_l for extra soft (Shore 10 OO), H_m for medium (Shore 60 A), and H_h for extra hard (Shore 75 D). Also, we denote S_l = 1000 N/m, S_m = 1500 N/m, and S_h = 2000 N/m for the stiffness levels generated by the device.

Experiment 1: Stylus. Figure 4 shows the results of Experiment 1 for nine different combinations of hardness and stiffness levels. This result indicates how participants sorted the blocks from soft to hard while tapping with a stylus. The dependent variable represents the accuracy of the sorting. Since in each of the nine cases, the combination of hardness and stiffness levels is different, we ran a separate two-way ANOVA on the sorting results for each case with rendered hardness and stiffness as factors. The results

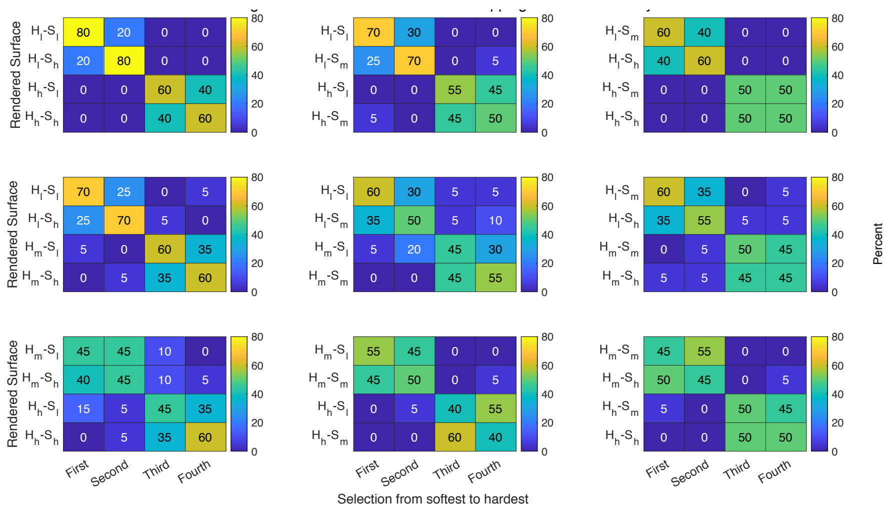


Fig. 4: Confusion matrices indicating how participants sorted the blocks from soft to hard while tapping with a stylus.

of the ANOVAs with hardness as factor are shown in Table 1 and with stiffness as factor in Table 2. In these tables, the yellow cells indicate statistically significant values, while the red cells indicate non-significant ones. This analysis indicated that regardless of the different combinations of hardness and stiffness values, hardness was a significant factor in participants' sorting accuracy (correctness of the sorting). However, stiffness was only a significant factor in less than half of the cases (44%).

We also measured each trial's completion time, but there was no correlation between the time and the various combinations of hardness and stiffness.

Experiment 2: Bare Finger. Figure 5 shows the result of Experiment 2 for the same nine combinations of hardness and stiffness as Experiment 1. This result indicates how participants sorted the blocks from soft to hard while tapping on these blocks with a bare finger. Since in each of the nine cases, the combination of hardness and stiffness levels is different, for each case we ran a two-way ANOVA on the sorting results with rendered hardness and stiffness as factors. The results of the ANOVAs with hardness as factor are shown in Table 3 and with stiffness as factor are shown in Table 4. In these tables, the yellow cells indicate statistically significant values, while the red cells indicate non-significant ones. This analysis indicated that regardless of the different combinations of hardness and stiffness, hardness was a significant factor in the accuracy of participants' block sorting. However, stiffness was only a significant factor in 1/3 of the cases.

We also measured the time of completion for each trial, but there was no correlation between the time and various combinations of hardness and stiffnesses.

Hardness: L and H	**Hardness: L and H**	**Hardness: L and H**
Stiffness: L and H	**Stiffness: L and M**	**Stiffness: M and H**
F(1,77) = 366.67	F(1,77) = 173.95	F(1,77) = 311.11
$p < 0.001$, $\eta^2 = 0.80$	$p < 0.001$, $\eta^2 = 0.69$	$p < 0.001$, $\eta^2 = 0.80$
Hardness: L and M	**Hardness: L and M**	**Hardness: L and M**
Stiffness: L and H	**Stiffness: L and M**	**Stiffness: M and H**
F(1,77) = 152.23	F(1,77) = 77.24	F(1,77) = 105.97
$p < 0.001$, $\eta^2 = 0.65$	$p < 0.001$, $\eta^2 = 0.48$	$p < 0.001$, $\eta^2 = 0.58$
Hardness: M and H	**Hardness: M and H**	**Hardness: M and H**
Stiffness: L and H	**Stiffness: L and M**	**Stiffness: M and H**
F(1,77) = 74.74	F(1,77) = 200.34	F(1,77) = 168.12
$p < 0.001$, $\eta^2 = 0.48$	$p < 0.001$, $\eta^2 = 0.72$	$p < 0.001$, $\eta^2 = 0.69$

Table 1: Results of a 2-way ANOVA, examining main effect of hardness and its interaction with stiffness when interacting with rendered blocks using a stylus.

Hardness: L and H	**Hardness: L and H**	**Hardness: L and H**
Stiffness: L and H	**Stiffness: L and M**	**Stiffness: M and H**
F(1,77) = 14.67	F(1,77) = 3.18	F(1,77) = 0.78
$p < 0.01$, $\eta^2 = 0.03$	$p = 0.078$, $\eta^2 = 0.01$	$p = 0.38$, $\eta^2 = 0$
Hardness: L and M	**Hardness: L and M**	**Hardness: L and M**
Stiffness: L and H	**Stiffness: L and M**	**Stiffness: M and H**
F(1,77) = 5.76	F(1,77) = 6.51	F(1,77) = 0.37
$p < 0.05$, $\eta^2 = 0.03$	$p < 0.05$, $\eta^2 = 0.04$	$p = 0.55$, $\eta^2 = 0$
Hardness: M and H	**Hardness: M and H**	**Hardness: M and H**
Stiffness: L and H	**Stiffness: L and M**	**Stiffness: M and H**
F(1,77) = 3.81	F(1,77) = 0.14	F(1,77) = 0.49
$p < 0.05$, $\eta^2 = 0.02$	$p = 0.71$, $\eta^2 = 0$	$p = 0.48$, $\eta^2 = 0$

Table 2: Results of a 2-way ANOVA, examining main effect of stiffness and its interaction with hardness when interacting with rendered blocks using a stylus.

5 Discussion

The experiment results reveal a statistically significant difference in the accuracy of participants' block sorting based on hardness. This distinction persists across various combinations of hardness and stiffness levels, regardless of whether participants use a bare finger or a stylus. Participants were more accurate at correctly sorting the blocks when hardness varied than when stiffness varied, suggesting hardness's greater perceptual salience in object perception. This emphasizes the potential role of tactile feedback in users' material perception and categorization.

Interestingly, participants struggled to differentiate between blocks with varying stiffness levels, with easier sorting observed for combinations of low and high stiffness. The impact of stiffness on accurate sorting only arises when the difference between

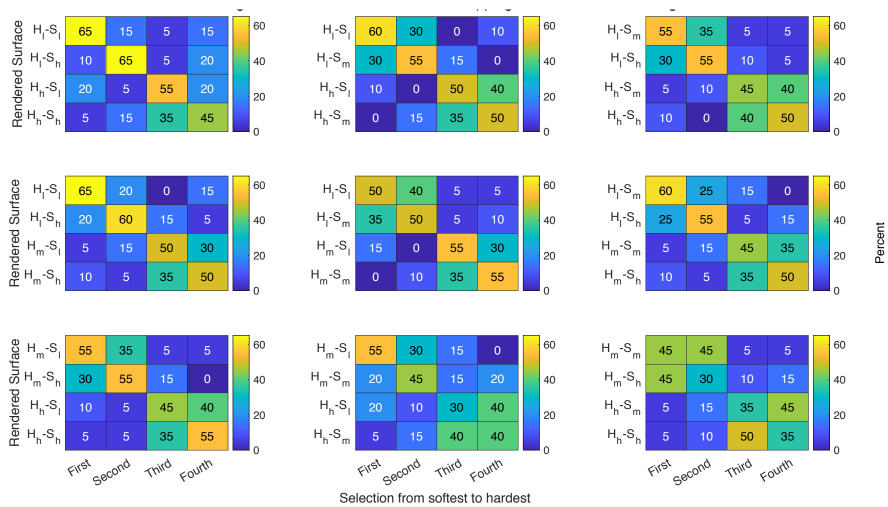


Fig. 5: Confusion matrices indicating how participants sorted the blocks from soft to hard while tapping with a finger.

Hardness: L and H **Stiffness: L and H**	**Hardness: L and H** **Stiffness: L and M**	**Hardness: L and H** **Stiffness: M and H**
F(1,77) = 18.31 p <0.001 , η^2 = 0.18	F(1,77) = 72.33 p <0.001 , η^2 = 0.48	F(1,77) = 63.93 p <0.001 , η^2 = 0.45
Hardness: L and M **Stiffness: L and H**	**Hardness: L and M** **Stiffness: L and M**	**Hardness: L and M** **Stiffness: M and H**
F(1,77) = 85.06 p <0.001 , η^2 = 0.51	F(1,77) = 58.34 p <0.001 , η^2 = 0.42	F(1,77) = 45.95 p <0.001 , η^2 = 0.36
Hardness: M and H **Stiffness: L and H**	**Hardness: M and H** **Stiffness: L and M**	**Hardness: M and H** **Stiffness: M and H**
F(1,77) = 72.98 p <0.001 , η^2 = 0.48	F(1,77) = 23.27 p <0.001 , η^2 = 0.22	F(1,77) = 44.33 p <0.001 , η^2 = 0.36

Table 3: Results of 2-way ANOVA, examining main effect of hardness and its interaction with stiffness when interacting with rendered blocks using bare finger.

stiffness levels is substantial. Otherwise, the effect of hardness on participants' perception of block properties remains more pronounced.

Our results indicate the presence of stiffness masking, which is consistent with [21]. Confusion matrices in Figs. 4 and 5 support this phenomenon, suggesting that high hardness levels may mask perceived differences in stiffness. These findings highlight the complexity of object perception influenced by multi-modal cues.

Notably, ANOVA results were consistent between bare-finger and stylus tapping, indicating that perceptual cues for hardness and stiffness are independent of touch

Hardness: L and H Stiffness: L and H	**Hardness: L and H Stiffness: L and M**	**Hardness: L and H Stiffness: M and H**
F(1,77) = 6.14 p <0.05 , η^2 = 0.06	F(1,77) = 1.2 p = 0.28 , η^2 = 0	F(1,77) = 1.14 p = 0.29 , η^2 = 0
Hardness: L and M Stiffness: L and H	**Hardness: L and M Stiffness: L and M**	**Hardness: L and M Stiffness: M and H**
F(1,77) = 4.07 p <0.05 , η^2 = 0.03	F(1,77) = 3.4 p = 0.07 , η^2 = 0.02	F(1,77) = 3.1 p = 0.09 , η^2 = 0.02
Hardness: M and H Stiffness: L and H	**Hardness: M and H Stiffness: L and M**	**Hardness: M and H Stiffness: M and H**
F(1,77) = 5.28 p <0.05 , η^2 = 0.05	F(1,77) = 1.9 p = 0.17 , η^2 = 0.01	F(1,77) = 0.24 p = 0.62 , η^2 = 0

Table 4: Results of 2-way ANOVA, examining main effect of stiffness and its interaction with hardness when interacting with rendered blocks using bare finger.

method. However, differences in statistical significance and effect size suggest that tapping with a stylus may offer more accurate and consistent haptic feedback, influencing sorting decisions. The observed differences may also relate to kinesthetic movement and joint dynamics, affecting participants' responses. Completion time did not significantly correlate with sorting accuracy, suggesting that it did not impact participants' ability to differentiate between block properties.

These findings highlight the complex nature of object perception and how multimodal cues can work together to influence our perceptions and judgments. It also emphasizes the importance of considering multiple factors when designing studies or interventions aimed at improving object perception or haptic discrimination abilities.

6 Applications

Our device has practical implications in fields such as medical simulation, online shopping, and gaming, where understanding how users perceive and interact with different materials is crucial. For medical training, our ETHD device could be used to simulate different tissue types for palpation practice, providing feedback on diagnostic skills. In online shopping, it can enhance consumer experiences by allowing users to feel the hardness and stiffness of products, improving satisfaction and reducing returns. In gaming, it could add realism and immersion by giving tactile feedback corresponding to the physical properties of virtual objects, enriching player interaction and engagement.

6.1 Limitations and Future Work

There are some limitations to our experiments that should be acknowledged. First, because of the limitation of our workspace, we were only able to render four blocks, and it is possible that the results could differ with a larger set of blocks. It would be great to use a haptic device or robotic arm with a larger workspace or even put the robot on a Cartesian rail as a low-cost method of extending its workspace. The current system primarily facilitates interactions from the top, limiting its use in scenarios requiring multi-directional tactile feedback. To extend its capabilities, integrating a robotic arm could be a viable solution. A robotic arm would allow for precise control and movement in multiple directions, vastly increasing the system's versatility, especially in applications like virtual reality and complex simulations. Currently, the surfaces are all flat and the results could differ if we change the shape or if there is curvature. Also, the use of a prism-shaped end-effector to switch between hardness levels introduces potential limitations. A concern is whether users might feel the edges of the prism and attached plates during transitions, potentially disrupting immersion during these changes. To address this, we included a visual barrier in the virtual environment and instructed users to lift the stylus or finger to avoid touching the wall during transitions. This method is intended to prevent direct contact with the edges during hardness changes, but further user studies are necessary to assess if this effectively maintains immersion and user experience. Future designs could explore more integrated transition mechanisms to further minimize any perceptible disruption. Finally, the study only looked at how users sorted the blocks based on hardness and stiffness and did not explore other factors that may influence how users perceive and interact with materials, such as texture or temperature.

Future research could address these limitations and further explore how users perceive and interact with different materials. Additionally, future studies could also examine how individual differences in cognitive abilities, such as visual or audio perception, may influence the ability to differentiate between objects based on their hardness and stiffness. Also, future research could explore the underlying mechanisms driving the differences between tapping with a bare finger versus a stylus and how they might inform design principles for interfaces and products.

We could also explore the physical deformation during tapping with a bare finger versus a stylus.

7 Conclusion

In this paper, we presented an ETHD system with a dynamic end-effector to render different hardness levels based on virtual object locations. Participants effectively distinguished hardness levels, highlighting its salient role in perception, underscoring the prominent role of hardness in perception within this context. However, stiffness differentiation was limited, revealing stiffness masking and emphasizing the complex nature of object perception influenced by multiple sensory cues, including tactile feedback. Moreover, both stylus and bare-finger tapping led to significant differences in material property distinctions. The touch method's potential impact on statistical results underscores the multisensory nature of perception, where our brains likely utilize various information types, including vibrations, to create a perceptual experience.

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