A Comparative Study of Physical and Haptic Exhibits in an Informal Learning Environment

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***Abstract*—Virtual exhibits with haptic feedback offer greater flexibility in diversifying content and providing digital affordance, even at a lower cost, than physical exhibits. However, few studies addressed the value of such haptics-enabled educational systems in informal learning environments. In this study, we investigated the feasibility of a haptic exhibit as an alternative or supplement for a traditional physical exhibit in a science museum. We developed a two-degree-of-freedom cable-driven haptic device to simulate physical interactions on a large visual display. Choosing a seesaw-like physical exhibit available in a local museum, we designed and implemented a virtual lever simulation closely embodying the physics principles that the physical exhibit showcased. Then, we conducted an observational user study with children to compare the exhibit-visitor interaction behaviors, learning effects, and self-reported motivation and enjoyment between the physical and virtual exhibits. The results revealed that the visitors well-received and engaged with the haptic exhibit, instantiating its potential application in diverse learning settings. We hope that our research encourages further exploration of innovative haptic exhibits that enhance users' learning experiences across various environments.**

***Index Terms*—Virtual exhibit, haptic feedback, informal learning, cable-driven haptic device.**

I. Introduction

PHYSICAL interaction offers unique advantages in learning, providing hands-on and multisensory experiences that enable learners to engage with content in meaningful and memorable ways [1]. These advantages are often exploited in informal learning environments, such as museums and science centers [2], [3]. For instance, many physical exhibits in science museums allow visitors to interact with their real mass components to demonstrate the relevant principles in physics. The visitors can directly experience changes in force through their own bodies. However, developing such experiential exhibits is generally expensive, with an average cost as high as $20,000 [4], and updating its content is similarly demanding.

Haptics technology allows users to *physically* interact with virtual objects by creating a bidirectional interface that simulates the physical interaction occurring between real objects. Haptic systems are also more flexible in upgrading the interaction content than physical exhibits, often at a lower cost. These merits motivated researchers to investigate the learning effects of haptic systems; see [5] for a review. However, most focused on the haptic modality's added value, usually compared to the visual and auditory modalities, in formal learning environments, such as schools and universities [6], [7], [8], [9]. Section II reviews the use of haptics technology in learning and interactive exhibits, including their potential advantages and limitations.

This study explores the potential of a virtual exhibit with haptic feedback in improving visitor experiences in an *informal learning environment* under direct comparison to a physical exhibit. We selected a physical exhibit available at a local science museum, which expresses the principle of a lever using a seesaw. We developed a two-DOF (degree of freedom) cable-driven force-feedback device easily attachable to a large visual display (Section III). Using this haptic interface, we implemented a virtual simulation of the lever emulating the seesaw-like physical exhibit (Fig. 1). Then, we carried out an observational user study to compare the exhibit-visitor interaction behaviors, learning effects, and self-reported motivation and enjoyment for children between the physical and virtual exhibits (Section IV). Despite the general unfamiliarity of haptic interfaces, the visitors easily engaged with the virtual exhibit with haptic feedback, thereby demonstrating its potential as a viable alternative or supplement to the physical exhibit (Section VI).

II. Related Work

A. Haptics for Science Education

According to embodied cognition theories, thought and knowledge are shaped by dynamic interactions between the

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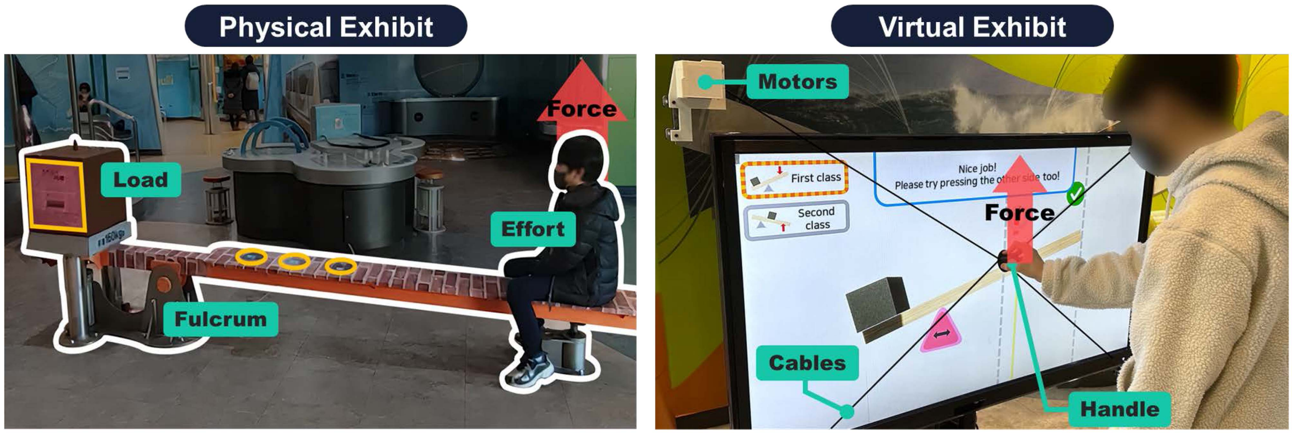


Fig. 1. Comparison of the physical and virtual exhibits. (Left) A physical exhibit "Strong Lever" in a local science museum, demonstrating the principle of a lever using a seesaw. The yellow box on the load describes the principle of lever using text and figure. The yellow circles on the beam contain text instructions to guide users to lift the load by moving back and forth on the beam. (Right) Our virtual exhibit with haptic feedback. A custom 2-DOF cable-driven force-feedback device is attached to a large visual display. Motors located at the corners of the display generate 2D force and transmit it to a single handle through the cables. Users can learn the principle of lever from both visual and haptic simulations while operating the simulation with the handle.

body and the physical world [10]. The whole body is considered a receptor of perceptual experiences creating mental representations called image schemas [7]. Physical experiences serve as cognitive anchors while freeing up mental capacity and facilitating understanding of abstract concepts [1], [10], [11]. Haptic simulations can contribute to embodied learning by directly connecting learners' percepts to learning concepts [12], especially those related to forces and kinematics [5], [13], [14].

Previous studies showed that combining visual and haptic modalities can enhance interest and comprehension in physics among adult learners [8], [9], [15]. However, the learning effectiveness of haptic simulations for younger individuals remains to be determined. For instance, a haptic simulation using a 2-DOF force-feedback joystick improved recall and transfer test scores for elementary school students compared to visual-only simulations [7]. However, for middle school students, the additional cognitive load of coordinating a 3-DOF haptic interface with visual feedback was detrimental to learning [6].

Effective integration of haptics into education requires a proper understanding of the target users and learning environments. Despite the growing interest in this research space, results are lacking in informal learning environments outside the classroom. Direct comparison results between physical and virtual learning experiences are also unavailable. Our research addresses these gaps in the research of haptics and education.

B. Interactive Exhibits for Informal Learning Environments

Interactive technologies are prominent in science museums, as they enable the exhibits to engage and immerse visitors through various modalities. For example, Augmented Reality (AR) is a popular technology in science museums due to its ability to present complex scientific concepts dynamically; see [16] for a review. AR can enhance understanding of the exhibit content by visualizing invisible things on the exhibits [17] or providing guidance [18]. Full-body interaction is also popular in informal settings, offering a high level of embodiment and locomotion that promotes the users' engagement and motivation [19], [20], [21]. In addition, tangible elements effectively attract and retain visitors, enabled by their multisensory experiences and technical novelty [22], [23].

Interactive education systems with haptic feedback have ample potential for improving learning performance and experiences. However, technological difficulty and high cost are the obstacles to overcome. It requires the use of a simple and low-cost haptic interface, which should also be intuitive to use and scalable to various visual displays. To this end, SPIDAR-type haptic interfaces [24], [25], [26], [27], which use strings for force transmission, can be a good fit for their inexpensiveness and large workspace. Related research has been expanded into wearable forms and more sophisticated force feedback with a greater DOF [28], [29], [30]. However, the potential of string-based force-feedback interface remains to be examined for learning applications. Our research uses a 2-DOF cable-driven force feedback device attachable to a large display, chosen based on a focus group interview with educational experts.

III. Virtual Exhibit

In science museums, exhibits are designed and implemented to stimulate visitors' interest and curiosity about science and technologies. A particular difficulty arises because visitors have complete freedom in choosing the exhibits. This nature of the learning environment requires exhibits to attract and retain their attention [31]. Visitors also freely choose how and for how long they interact with exhibits and engage in learning experiences [32]. Under this context, this section describes the design and implementation of our virtual exhibit that embodies the principle of lever using a haptic interface.

A. Physical Exhibit Selection

For this study, we selected a physical exhibit called "Strong Lever" in a local science museum; see Fig. 1. The exhibit is a seesaw that has a 160-kg concrete block on one end and a seating area for visitors on the other end. As a lever, the concrete block corresponds to the load, while the seating area to the effort point. The pivot point between the two is at the hinge in a fulcrum shape. A sign on one side of the concrete cube explains how the force magnitude changes in response to the load, effort, and fulcrum in a first-class lever. Some visual instructions are printed on the seesaw to guide visitors, such as "Can you lift the concrete block?", "The concrete block on the other side weighs 160 kg." and "Try lifting the concrete block by moving back and forth." This seesaw exhibit allows learning of scientific principles primarily through physical interaction. In particular, the exhibit demonstrates the principle of a first-class lever with only one effort point, which is suitable for haptic simulation using a point-contact force-feedback device.

B. Focus Group Interview

We conducted a focus group interview with experts to garner advice on design choices that would make a virtual exhibit intuitive for children to use with high affordance. The group consisted of the director and three staff members of the science museum, who were all experts in science education and exhibits (three males and one female). The interview began by explaining haptics and introducing a few examples of haptic learning systems to promote the interviewees' understanding of the related concepts.

The resulting design directions were as follows:

- *Use a large visual display:* Using a large display is recommended to attract visitors' attention.
- *Begin with an easy-to-follow user guide:* Most visitors are not familiar with haptic exhibits and are likely to quickly lose interest if the haptic exhibit is difficult to use. Thus, a haptic exhibit should start with an easy-to-follow user guide.
- *Extend the exhibit with advanced content:* An advantage of virtual exhibits is the ability to expand on the original exhibit's content. It needs to be fully exploited.

These interview results provided general requirements for the subsequent design of a haptic device and a virtual lever simulation.

C. Force-Feedback Device

Commercial rigid-linkage haptic interfaces with large workspaces are available, but they are expensive and not scalable to different screen sizes. Haptic interfaces featuring low cost, easy maintainability, and size scalability are appropriate for informal learning environments. These considerations motivated us to develop a 2-DOF cable-driven force-feedback device attachable to a large planar visual display; see Figs. 1 and 2. Its handle, operated by a user, is in contact with the visual screen, and the handle's 2D position is collocated with the visual content. These features make the device much more intuitive and easier for children to learn and use than 3- or higher-DOF devices. Our device uses strings rather than rigid links, which minimizes screen occlusion, lowers the device cost, and improves the device's scalability to visual screen size. The robustness of this cable-driven platform was validated by many previous examples [24], [25], [26].

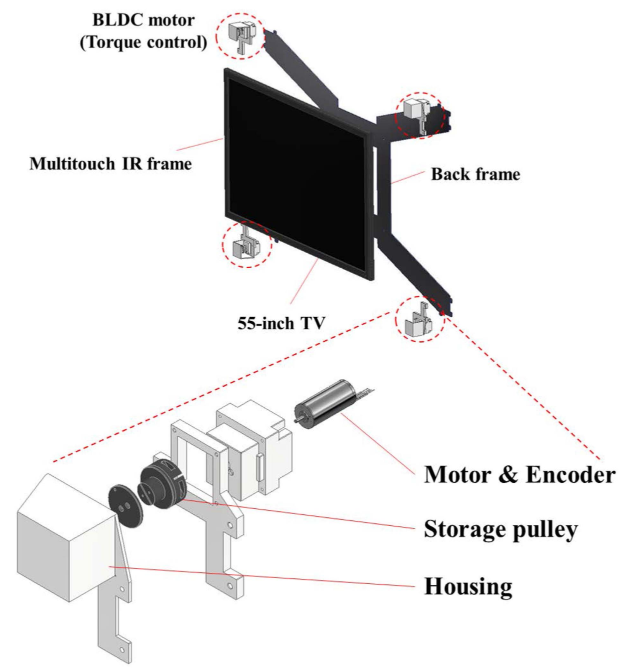
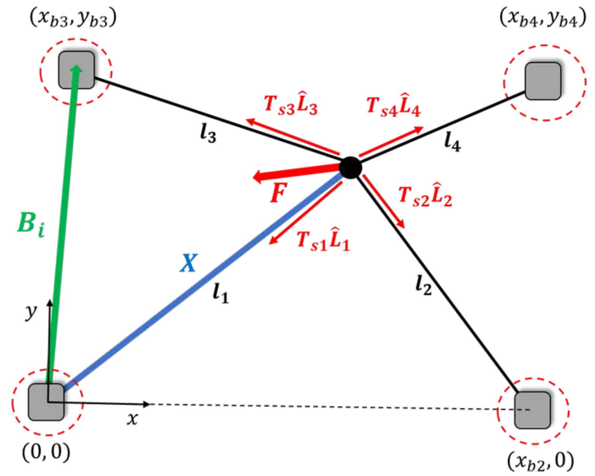


Fig. 2. Hardware structure of our haptic interface.

The hardware structure of our haptic interface is presented in Fig. 2. We used a 55-inch TV as a visual display and a multitouch IR frame (FC-55, Xintai touch) to detect a user's touch. The haptic device was assembled onto the display through a back frame (1400 mm $\times$ 900 mm $\times$ 3 mm). Four BLDC motors (DCX 12 L, Maxon) were mounted to the four corners of the back frame, one each, with a 3D-printed housing. The motors were connected to the device handle using a wire (stainless steel; 7 $\times$ 7 820-0300, Carl Stahl). Each motor module contained an optical encoder, motor driver, MCU, and LiPo battery. The motor angle was measured by the encoder to compute the handle position through the device kinematics. Motor drivers (EPOS4 50/5, Maxon) controlled each motor, and MCU (Nucleo-F767ZI, STMicroelectronics) calculated the desired torque. The MCU and the motor driver exchanged data through CAN communication. Communication between the PC and the MCU was done through USB. LiPo batteries (22.2 V, 2500 mAh, Enrichpower) were used as a power supply for the motor drivers instead of an SMPS (switching mode power supply) to prevent reverse current flow that may occur when the wire is pulled counter-direction of the motor.

Fig. 3 details the kinematics and statics of the 2-DOF force feedback device. Kinematics calculates the handle position vector $\boldsymbol{X}$, which is a displacement of the handle from the original coordinate. $\boldsymbol{X}$ can be calculated using the motor module position vector $\boldsymbol{B}$ and the cable length l_i. To determine the length l_i



Kinematics	Statics
Given value:	**Given value:**
$l = [l_1 \quad l_2 \quad l_3 \quad l_4]^T$ $B_2 = [x_{b2} \quad 0]^T$ $B_3 = [x_{b3} \quad y_{b3}]^T$	$S = \begin{bmatrix} \hat{L}_{1x} & \hat{L}_{2x} & \hat{L}_{3x} & \hat{L}_{4x} \\ \hat{L}_{1y} & \hat{L}_{2y} & \hat{L}_{3y} & \hat{L}_{4y} \end{bmatrix}$ $F = [F_x \quad F_y]^T$
Equation for position calculation:	**Equation for target tension:**
$X = [x \quad y]^T$ $x = \frac{x_{b2}^2 + l_1^2 - l_2^2}{2x_{b2}}$ $y = \frac{x_{b3}^2 + y_{b3}^2 - 2x_{b3}x + l_1^2 - l_3^2}{2y_{b3}}$	$T_s = [T_{s1} \quad T_{s2} \quad T_{s3} \quad T_{s4}]^T$ $T_s = S^+F + (I - S^+S)\,z$ $(T_{min} < T_s < T_{max})$ S^+: Pseudo-inverse of S z: Arbitrary vector

Fig. 3. Kinematics and statics of the 2-DOF force feedback device.

between each motor and the handle, we include an initialization process, in which the handle is positioned at each other sequentially. l_i is computed by reading its encoder afterward. Given the force vector $\boldsymbol{F}$ received from a haptic simulation, the static tension T_{si} for each cable toward the $\hat{\boldsymbol{L}}_i$ direction is calculated using the cable direction matrix $\boldsymbol{S}$ derived from the kinematics. It is enabled by using S^+, the pseudo-inverse matrix of S. The tension values can be adjusted while generating the same force feedback by modifying an arbitrary vector $\boldsymbol{z}$; the tension values change in the null space of the force mapping. The motor tensions are confined between 1 N and 9 N using this principle. The MCU performs kinematics and statics calculations at 1 kHz to improve the stability of haptic interaction [33]. When a user grasps the handle and makes 2D exploratory motion sliding on the visual screen, the four motors generate appropriate torques to provide force feedback. Further details on the system kinematics, force computation, and control can be found in our previous work [34].

D. Virtual Lever Simulation

The virtual lever was designed to emulate the existing physical exhibit. The beam of the lever is fixed to the top point of the fulcrum. A constraint is applied to allow rotation at the top

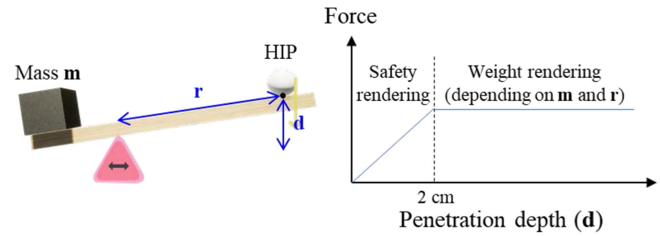


Fig. 4. Virtual lever and force rendering method to demonstrate the principles of lever.

point around only the single axis perpendicular to the visual display's screen. The load on the lever is made in the shape of a cube and fixed to one end of the beam using a constraint. The handle position in the virtual environment, i.e., the haptic interface point (HIP), is represented by a white sphere. When a user manipulates the handle and the HIP presses the beam, force feedback is applied to the handle by the haptic device.

Fig. 4 shows our virtual lever and force rendering method to demonstrate the principles of lever. Force rendering was initiated when the physics engine detected a collision between the HIP and the lever's beam. The magnitude of the force was calculated based on the principles of lever: 1) multiplying the distance between the fulcrum and the load by the mass of the load m and 2) dividing the result by the distance r between the fulcrum and the effort point. The following safety measures were also added to the force rendering. The force magnitude was linearly increased until the handle penetrated the lever beam by 2 cm to prevent a sudden change of force, similar to the general offset surfaces used for haptic rendering [35]. The force magnitude was limited to the haptic device's maximum force of 9 N.

We implemented the virtual environment for lever simulation on Unreal Engine. The PC and our haptic device serially communicated with the USB protocol at a sampling rate of 1 kHz with a latency of less than 10 ms. The haptic device sent the handle position to the PC, and the PC computed the force command and sent it to the haptic device. We used an open-source physics engine supported by Unreal Engine to reduce the developmental cost as in [36].

E. Interaction Scenes

Visitors can interact with the virtual exhibit in three scenes: *Tutorial video*, *Use guidance*, and *Free exploration*. The scenes were designed assuming that visitors would have no prior experience with force-feedback haptic interfaces. A video showing the three scenes in detail is available in the supplemental material. The first interaction scene for a visitor is a *tutorial video*, which shows a video of a person holding the haptic device handle and pressing a lever. The visitor can watch the tutorial video and learn how to use the exhibit correctly. Our program supports two classes of levers, classes 1 and 2. Interaction for each lever class consists of two interaction scenes: use guidance and free exploration.

The *use guidance* scene guides a user to self-learn how to use the lever simulation, similar to the instructions in the physical

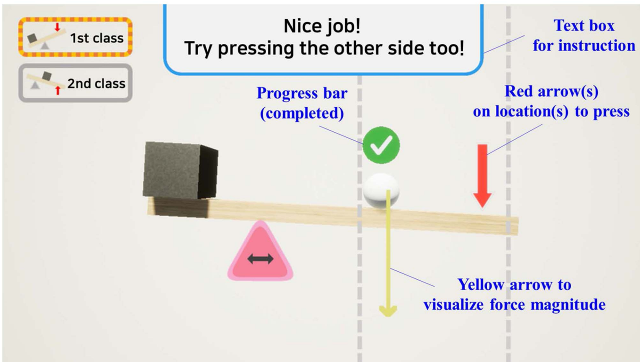


Fig. 5. Screenshot of the use guidance scene of our virtual lever simulation. Blue texts indicate digital affordance to help visitors use the virtual lever.

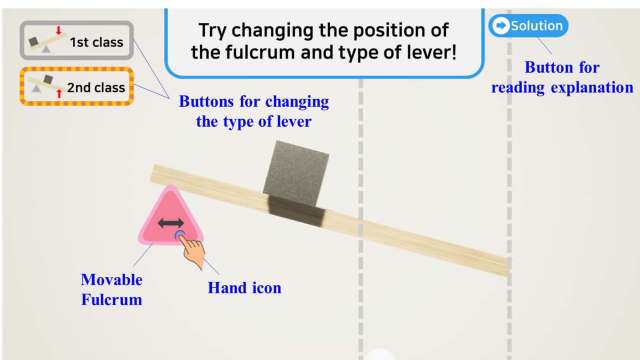


Fig. 6. Screenshot of the free exploration scene of our virtual lever simulation. Blue texts indicate digital affordance to help visitors use the extended content of the virtual lever.

exhibit. Fig. 5 shows a screenshot of this scene. Two red arrows appear on the lever beam, and the simulation asks the user to press each location using the haptic interface through speech and texts. When the user presses the beam, a green loading bar appears and then is gradually filled up. The user is also provided with force feedback. If the pressing lasts 3 seconds, the loading bar is filled completely and changes to a check icon to indicate completion. This scene ends when the user completes the pressing task for both the red arrows. A yellow arrow next to the HIP represents the magnitude of the force feedback through its length. We removed a numerical value of the fore magnitude because child visitors did not check it or did not understand its meaning in a pilot study.

Then, the simulation moves to the *free exploration* scene as illustrated in Fig. 6. Here, the user can use the lever simulation freely and learn about the principles of levers. In addition, the user can also move the fulcrum and experience the second-class lever simulation, i.e., the two extended options from the physical exhibit. It is encouraged by showing a blinking hand icon near the corresponding object. Users can also read the detailed explanation of the principles of lever, similar to the physical exhibit.

IV. User Study

We conducted a user study to compare the learning experiences between our virtual exhibit (`VIR`) and the physical exhibit (`PHY`) at a science museum. Visitors to the museum participated voluntarily in the user study.

A. Methods

The virtual exhibit was placed next to the physical exhibit. We adopted a between-subjects design. While one exhibit was tested, the other was covered with an opaque cloth. Each exhibit was tested on weekends (when the science museum usually has the most visitors) for two days.

1) Participants: We recruited 28 children to participate in `VIR` (16 males and 12 females; age 4–10 years, mean 6.46). We also recruited 26 children to participate in `PHY` (12 males and 14 females; age 4-11 years, mean 6.38). None of the participants reported any known sensorimotor abnormality.

2) Procedure: When evaluating exhibits, visitors' awareness of being observed can affect their behaviors [37]. To minimize such biases, we conducted an observational user study. We installed cameras and voice recorders around the two exhibits with a recording sign at unnoticeable positions. After visitors finished interacting with the exhibit, we approached them and asked for a simple survey about their experiences with the exhibit.

The visitors who agreed to participate were guided to another place. Only child participants were asked to complete a survey and answer a semi-structured interview to measure learning effects. As a token of appreciation, the participants received science museum souvenirs (worth approximately USD 2). We used the video recordings of only the agreed participants for data analysis.

3) Measures: Unobtrusive measures, such as attraction ratio, holding time, and visitor engagement level, are widely used to assess visitors' learning experiences in informal learning environments [38], [39]. Here, a *Holding Time* refers to the amount of the time visitors spend at the exhibit, which can serve as a low-level precursor to their interest and knowledge acquisition [40]. We estimated the holding time of each exhibit by analyzing the recorded videos.

Visitor engagement level represents the degree to which the visitor pays attention to the exhibit. This is closely tied to how the designer planned the exhibit to function [40]; the closer the visitor gets to the design's intended objective, the better the quality of their perceived experience [41]. For this measure, we adapted the coding schemes used in previous exhibit studies [42], [43], which classify visitor behaviors into three levels and count the time spent in each level. Engagement level 1, called passive contact, represents a starting point of interaction. Visitors encountered the exhibit but have yet to engage in specific and active behaviors. Engagement level 2, called active manipulation, represents specific activities determined by the visitor's actions and outcomes. Visitors at level 2 are becoming more committed to the learning experience. Engagement level 3, called exploratory behavior, indicates specific and proactive behaviors that take advantage of learning opportunities and reflect a greater commitment to meaningful learning. While

TABLE I
BEHAVIORS INDICATIVE OF ENGAGEMENT LEVELS

Engagement Level	Children Behavior
Level 1. Passive contact	Look at the exhibit or the exhibit being used by others
Level 2. Active manipulation	Use the body to press the physical lever Grab the haptic handle and operate the virtual lever Listen to explanations on the exhibit from others
Level 3. Exploratory behavior	Ask or explain the learning content Read the explanation about the principle of a lever

watching the recorded videos, we classified the participants' behaviors into one of the three engagement levels and measured the duration during which behaviors for each engagement level were observed. We use this *Engagement Duration* for each level as measures for visitor engagement.

In a post-survey, we presented the children with a picture showing a first-class lever and two points on the lever. We asked the children which of the two points should be pressed to lift the heavy mass with less force. We assigned a score of 1 point for a correct answer and another 1 point when accompanied by an explanation of their reasoning. We use this *Learning Score* as an index of learning effects.

We also measured the participants' self-reported motivation for learning and enjoyment about the exhibits by adapting the questionnaire from the Intrinsic Motivation Inventory (IMI) [44] and the Modified Attitudes Towards Science Inventory (mATSI) [45]. For *Motivation*, we asked two questions: "I have a real desire to learn about the principles of a lever." and "I would like to read something on the principles of the lever that has not been assigned to me." For *Enjoyment*, we also asked two questions: "I enjoyed using the lever exhibit very much." and "I would describe the lever exhibit as very interesting." Children answered these questions on the child-friendly 5-point Likert scale [46].

Virtual exhibits provide a distinct advantage over physical exhibits in their flexibility to present additional content. It led to a question if users who were interested in the first-class lever simulation would also be interested in exploring the variations of the same topic. The *Content Diversity* of the virtual exhibit was evaluated as the ratio of the participants who interacted with the extended content, moving the fulcrum of the first-class lever and trying the second-class lever, to the total number of participants.

B. Results

To calculate the holding times and engagement durations, two researchers in our team watched the recorded videos, classified the users' behaviors, and measured the duration of behaviors at each engagement level. To this end, they made initial coding rules while watching the videos recorded during two-day pilot tests. They refined the initial rules using the videos recorded in the main study and obtained the final coding rules. These final coding rules for the engagement levels are described in Table 1. The final video coding results between the two coders were highly consistent with a high intraclass correlation coefficient (ICC) [47] of 0.97 for VIR and 0.95 for PHY. We determined the engagement duration for each level by computing the average time spent by only the participants who had exhibited each level of behavior.

The data for *Holding Time* and *Engagement Duration* were tested for the normality using the Shapiro-Wilk test. Results showed that the data were not normally distributed ($p < 0.001$), but positively skewed. *Motivation* ($p = 0.006$) and *Enjoyment* ($p = 0.001$) scores were also not normal, but negatively skewed. Therefore, we used the Kruskal-Wallis test to compare the four measures between VIR and PHY at a significance level of $\alpha = 0.05$. We also performed the Kruskal-Wallis test on *Learning Score*, which included three categorical values (0, 1, or 2). Finally, we divided the participants in VIR into those who used the extended content and those who did not to investigate the impact of extended content on learning experiences.

Fig. 7 shows the mean scores and standard errors of the *Holding Time* and *Engagement Durations*. The *Holding Time* of VIR including the extended content was significantly higher than of PHY ($\chi^2(1) = 5.503$, $p = 0.019$, $\eta^2 = 0.104$). In contrast, the difference between PHY and VIR without the extended content was not significant ($\chi^2(1) = 0.874$, $p = 0.350$, $\eta^2 = 0.017$). For *Engagement Duration*, VIR with the extended content showed a significantly higher mean than PHY at level 2 only ($\chi^2(1) = 6.250$, $p = 0.012$, $\eta^2 = 0.123$). However, the difference between PHY and VIR without the extended contents was not significant ($\chi^2(1) = 0.827, p = 0.363, \eta^2 = 0.016$). No significant differences were found between PHY and VIR with or without the extended content at engagement level 1 or level 3. The numbers of child visitors who showed engaging behaviors at each level were 26, 25, and 1 in PHY, 28, 27, and 6 in VIR with the extended content, and 27, 27, and 4 in VIR without the extended content.

Fig. 8 shows the mean scores and standard errors of the post-survey measures, *Learning Score*, *Motivation*, and *Enjoyment*. We found no significant differences between the two exhibits for the survey data: *Learning Score* ($\chi^2(1) = 0.019$, $p = 0.889$, $\eta^2 < 0.001$), *Motivation* ($\chi^2(1) = 0.156$, $p = 0.693$, $\eta^2 = 0.003$), and *Enjoyment* ($\chi^2(1) = 0.275$, $p = 0.600$, $\eta^2 = 0.005$)

For the content diversity of VIR, 15 participants, out of 28, experienced the extended content of the virtual exhibit. Thus, *Content Diversity* was 0.54 ($= 15/28$). Eight among those 15 participants moved the fulcrum of the first-class lever, and 12 participants used the second-class lever.

V. DISCUSSION

A. Comparison of Learning Between Physical and Virtual Exhibits

The learning scores of PHY and VIR were similar, but they seemed to induce users to employ different learning principles. Children in VIR tended to rely on the distinct forces they felt at different locations on the virtual lever when solving the quiz. During the video analysis, we observed that 23 out of the 28 participants in VIR pressed multiple points on the virtual lever. For example, P1 talked to his father, "I can feel the difference in the force" while doing so. In contrast, only 13 out of the 26 participants in PHY sat multiple locations on the physical

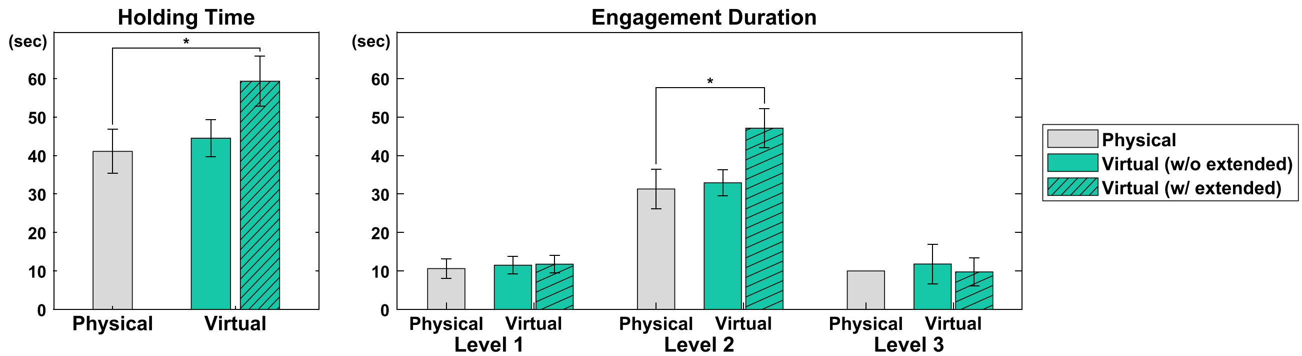


Fig. 7. Comparison of the holding time and engagement duration among the physical exhibit and the virtual exhibit with/without the extended content ($^*: p < 0.05$ in the statistical test).

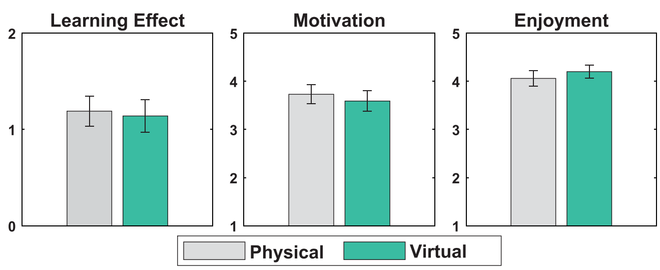


Fig. 8. Comparison of the learning, motivation, and enjoyment scores between the physical and virtual exhibits.

lever. This behavioral difference can be attributed to the digital affordance measures offered by VIR, such as indicating arrows and progress bars. On the other hand, children in PHY were able to draw upon their past experiences of riding seesaws in other places, which facilitated their ability to answer the quiz questions. This is consistent with the previous finding in [48]; reminding a visitor of similar experiences forms the basis for interpreting the exhibit. Children in PHY also said they enjoyed the act of riding on the exhibit like a seesaw in the post-interview.

We also found different engaging behaviors committed to learning, corresponding to level 3, between the two exhibits. In VIR, three participants read the explanations about the principles of lever, and another two made meaningful conversations with their parents. For instance, P2 interacted with the virtual exhibit by herself and then taught her mother how to use it and demonstrated it to encourage her. By contrast, in PHY, no one read the explanations on the exhibit, and only one participant (P3) talked about learning. However, P3's mother proactively asked learning questions to P3, which is relatively passive compared to the case of P2. This difference can also be attributed to the digital affordances available in VIR. Timely instructions and visual indicators could effectively scaffold their learning and encourage users to read the explanations.

VIR, excluding the extended content, had very similar holding times and engagement durations at level 2 to those of PHY. This result contrasts with the previous research that technological novelty (the haptics technology in our case) significantly increases the holding time of an exhibit [31], [49]. One possible explanation is that our study only included young children as participants, who may not have perceived the haptic device as novel. While adult visitors and employees in science museums were amazed and interested in the haptic device, we observed that children were not aware of its novelty as much.

These observations provided valuable insights to improve the design and application of a virtual exhibit. First, it is recommended that a virtual exhibit should incorporate natural analogies that resonate with visitors' prior experiences and knowledge. For example, we can design a virtual lever to resemble a seesaw in a playground and the cube mass to approximate a person sitting on the lever. It is expected to connect visitors' familiar past experiences to haptic experiences, enhancing learning processes.

Second, we suggest leveraging a virtual exhibit as a complement to a physical exhibit rather than a complete replacement. Such a virtual exhibit can provide additional affordances, encouraging visitors to engage more effectively with the learning tasks associated with the physical exhibit. Redundant and synergistic bodily experiences afforded by both exhibits are expected to enhance the overall educational experience.

Finally, adding advanced content would be more appropriate after a virtual exhibit is further improved. In our case, the extended contents offered by VIR can be considered advanced content. VIR with the extended content had a longer holding time by 15 s and a longer level-2 engagement duration 2 by 14 s than VIR without the extended content. However, *Learning Score* of these 15 participants (mean 0.80) was significantly lower than that of another 13 participants (mean 1.54) who did not use the extended contents ($\chi^2(1) = 4.06$, $p = 0.044$, $\eta^2 = 0.150$). We found no significant differences in *Motivation* ($\chi^2(1) = 0.340$, $p = 0.560$, $\eta^2 = 0.013$) and *Enjoyment* ($\chi^2(1) = 0.251$, $p = 0.616$, $\eta^2 = 0.009$).

B. Learning and Adaptation With Haptic Interface

Children's age plays a crucial role in knowledge acquisition, aligning with established cognitive development theories [50]. We observed a dependence of learning scores on the participant's age in VIR. We divided the participants into two groups: preschoolers (age 4–7 years) and schoolers (age 8–11 years).

The 8 schoolers (mean 1.63) outperformed the 20 preschoolers (mean 0.95), with a nearly significant difference ($\chi^2(1) = 3.38$, $p = 0.066$, $\eta^2 = 0.125$). On the other hand, PHY showed an insignificant difference in the learning score between the 19 preschoolers (mean 1.11) and the 7 schoolers (mean 1.43) ($\chi^2(1) = 0.862$, $p = 0.353$, $\eta^2 = 0.035$). It is known that children become capable of manipulating objects more dexterously as they transition from preschoolers to schoolers [51]. Therefore, we infer that haptics-enabled virtual exhibits would be more effective for school-aged and older children.

The previous research of Wiebe et al. [6] addressed a similar learning concept, the principles of a lever, but their haptic system was inferior to the visual-only system in learning performance with middle school students. They used a 2D desktop monitor and a PHANToM Omni, which offers 3-DOF force feedback and 6-DOF position sensing in a 3D workspace. Their virtual lever simulation mapped the 6-DOF motion of the device's tip into the 2D plane on the beam of the virtual lever. However, their haptic rendering method could cause a mismatch between the real position of the device's tip and its position mapped into the virtual environment. This mental transformation may require significant cognitive processing, resulting in a learning performance degrade. In contrast, our haptic interface yielded positive results with younger children, with 13 out of 28 participants correctly explaining their reasoning for lifting a heavy mass with less force using a first-class lever. This can be attributed to the correct spatial alignment of visual and haptic information on the display in our system. We also note that our study achieved positive learning effects of haptic simulation with the youngest age group (7-11 years, schoolers) compared to previous studies (11 years above) [6], [7], [12].

They spent 10 s on average, corresponding to engagement level 1, looking at the exhibit or looking at the exhibit being used by others (including the tutorial video in VIR) before active manipulation. These results suggest that our simple 2-DOF haptic interface and tutorial video were sufficiently intuitive for children to initiate interaction.

C. Limitations and Potential Applications

This study has a few limitations that need to be addressed in future research. First, the haptic device should be improved to be safer and more stable for informal learning environments. For example, some children forcefully pulled the handle to the outside of the screen, resulting in wire twisting and deviating from the pulley. To prevent such excessive operations of the handle, we can add physical or virtual fixtures that constrain the handle's range of motion within the display. Second, testing with participants of different body sizes and ages can improve the generalizability of the main findings. We observed some children with small body sizes could not fully explore the virtual lever and had difficulties in manipulating the haptic interface. The low learning scores of preschoolers in VIR could be due to this problem. The workspace of the haptic interface can be adjusted, for example, using movable bases provided in our previous research [34]. Its feasibility and subsequent learning effects should be investigated in future work. Evaluating with a larger number of child visitors in different age groups would provide a more comprehensive understanding of the learning experiences provided by the exhibits.

The interactive and engaging behaviors observed in VIR demonstrate the potential of using cable-driven haptic devices in informal learning settings. Our case study may be extended to other examples that utilize 2-DOF force magnitude and direction, e.g., different learning concepts like electromagnetism and buoyancy. The device's tendon-driven mechanism enables seamless integration into concepts relying on tension, for example, the principles of pulleys. With a large workspace and back-drivability, the haptic interface is also adequate for quick interactions with virtual objects like playing billiards and hockey. This capability expands beyond current educational uses, making it a versatile tool for diverse experiences. For example, Hou et al. [27] used a similar haptic device to amplify gaming experiences with a touchscreen. This opens up opportunities for gamification in informal learning settings, where the fusion of playfulness and education can enhance overall learning experiences for children.

VI. Conclusion

This study investigated the viability of a haptics-enabled virtual exhibit under direct comparison to a traditional physical exhibit available in a science museum. We developed a 2-DOF cable-driven haptic device and implemented a virtual lever simulation that closely emulates the physical exhibit. An observational user study carried out in the science museum revealed that child visitors well-received the virtual exhibit and engaged with the learning content despite the general unfamiliarity with haptic interfaces. Additionally, we found that the virtual and physical exhibits were similarly effective in terms of learning outcomes, although they seemed to be based on different learning principles. Observations in the user study led to ideas for improving the virtual exhibit and using it as a complement to the physical exhibit.

To our knowledge, this study provides the first report on the potential of a virtual exhibit with haptic feedback as an educational tool for informal learning environments. Haptic exhibits offer greater flexibility in updating their virtual content and providing high digital affordance at a lower cost compared to physical exhibits. We hope our research encourages further exploration and development of innovative haptic exhibits that can enhance visitors' learning experiences in various environments.

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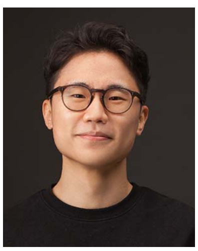

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