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Effects of Haptic interaction on learning performance and satisfaction with 3D collections

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Abstract

Museum learning is beneficial for social inclusion, deepening partnerships between schools and museums, and increasing levels of pupil attainment. While there have been numerous empirical studies on the use of haptics in formal educational settings, few have explored the effect of haptic interaction on learning outcomes in museum learning. This study looks at an interactive 3D artifact simulation using a haptic interface and a non-haptic interface, with one group using 3D hand motions and receiving visual/haptic stimuli, and another group using a mouse and only receiving visual stimuli. Forty individuals majored in arts or social science courses were asked to perform four main interactive tasks about 3D collection. Using a triangulation of assessment scores, investing time, and satisfaction with interactions with the 3D artifact simulation, we explored the efficacy of haptic interaction in improving museum learning. The results showed that in general, the haptic interaction was more helpful in promoting learning performance in relation to 3D collections. However, significant differences only occurred in relation to the volume and material interactive tasks, and not in relation to the contour and color interactive tasks. The Findings reveal that the visual/haptic stimuli provided by haptic interaction in museum learning has a stronger modality effect on human information processing, and the effect of haptic interaction depends on the coupling of interactive tasks and sensorimotor experiences. Further, psychological immersion is more likely to occur when using haptic interaction, and haptically augmented 3D artifacts attract learners' attention, enhancing learner engagement and motivation. Explanations for these results are synthesized from the perceptual symbol, embodied cognition, and immersion theories.

Keywords Museum learning · 3D collection · Haptic interface · Multisensory experience · Psychological immersion

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1 Introduction

Museum learning is beneficial for social inclusion, deepening partnerships between schools and museums, and increasing levels of pupil attainment (Ateş & Lane, 2020). The term “museum” is used to represent various public cultural institutions, including museums, libraries, and archives. As important informal learning environments, these institutions create learning opportunities for both local and remote visitors by providing tangible and intangible historical collections and exhibits. Compared with formal classroom learning, learning in museums (also called museum learning) is usually focused on interesting artifacts from collections or archives (Candela, et al., 2020; Yakubu, et al., 2022). Since the global outbreak of COVID-19, many offline museums have been forced to close their doors or impose restrictions. Therefore, how to create or design engaging experience for learners in digital museums is worthy of attention (Zhang & Hu, 2022).

In order to create more engaging and appealing learning experience, several emerging technologies (Lin, et al., 2022) are incorporated into museum learning. Existing empirical studies (Jędrzejewski, et al., 2020; Castro, et al., 2021) have shown that the adaption of technology in museum learning can significantly improve learning outcomes, not only contributing to the acquisition of knowledge and skills (Sun & Yu, 2019), but also improving emotional attitudes (Schwan, et al., 2018; Lee, et al., 2021). For example, Xu et al. (2021) conducted a meta-analysis analyzing 42 studies on technology applications in museum learning published during 2011–2021; they found interactive technologies are generally used to enhance the virtual interaction between learners and collections, and enrich the learning experience. Zhou et al. (2022) reviewed the relevant studies on virtual reality (VR) and augmented reality (AR) have been used to support museum learning and showed VR and AR have significant positive effects on academic achievement and perceptions in museum learning.

In museum learning, virtual reality simulations have been widely exploited to reconstruct artifacts and relics to provide an interactive, engaging educational context (Belhi, et al., 2023). Currently such 3D or VR simulations mainly provide visual and auditory experiences but, in future, opportunities are likely to increase for the addition of haptic experiences. Haptic is a sensory modality that enables a bidirectional flow information between the real, or virtual, environment and the learners, and affording the ability of touch, grasp, along with force feedback (Magana & Balachandran, 2017). With the advent of haptic technology, haptic interaction is as the input/output modality interface, which could extend virtual interactions with collections beyond the visual and audio realms to include tactile feedback, which simulates the sensation of touching 3D collection. Besides that, visual, auditory, and haptic stimuli can convey information more efficiently than traditional visual or visual/auditory modalities (Zohar & Levy, 2021), with manipulating 3D collections using a haptic interactive channel. Multisensory stimuli or simulations could enrich the learning experience about 3D collections (Petit, et al., 2019).

Although haptic interaction has become a focus in educational studies, most of which concentrate on formal learning settings, few have explored the effect of haptic interaction on learning outcomes in museum learning. Therefore, whether and to what extent haptic interaction could benefit learners in museum learning are questions that still need to be studied. Specifically, it is important to examine how different types of interactive interface affect the perspectives on the learning experience about 3D collections. Moreover, it is also necessary to understand the effect of haptic interaction on museum learning by providing more sensorimotor (or embodied) experiences.

2 Literature review

2.1 3D collections, interactive interfaces, and engaging experience

Digital collections have become the foundation of cultural institutions that deliver essential public services and social education (Tamborrino, 2012). To improve accessibility and support the provision of engaging experiences for diverse groups (Gil-Fuentetaja & Economou, 2019), these institutions have expended considerable effort to provide versatile local or online access to their collections. In recent years, 3D collections and panoramic video using photogrammetry and 3D digitalization have been applied to museum learning(Espina-Romero & Guerrero-Alcedo, 2022; Carvajal, et al., 2020), with 3D collections being used as tools for learning in humanities and social science classrooms. Hannah et al. (2019) contended that it was critical to build the necessary infrastructure to support 3D collections to keep pace with innovative pedagogies and scholarship. Castro et al. (2021) analyzed the impact of 3D models on teaching, learning, and motivation and found that learners using 3D models showed equivalent motivation and a significant increase in learning performance compared with those who only received face-to-face teaching.

In addition to establishing interactive exhibits or virtual exhibition, many museums have begun offering distance learning or online exploration to increase the accessibility of their collections (Ennes, 2021). Numerous studies (Sung, et al., 2010; Confalonieri, et al., 2015) have found that interactive interfaces significantly increased user satisfaction with museum learning by providing an engaging and appealing visiting experience. Web-based interfaces have enabled them to attract new audiences by providing convenient access to their collections. Usman and Antonacopoulos (2019) introduced a visual interface system that made it easier for online users with no domain knowledge to explore museum collections. Cecilia (2021) found that the development of accessible digital content and the provision of access to online collections provided a positive experience for disabled people during the COVID-19 pandemic. In addition, the rise of the immersive technologies, which enables extended reality using VR or AR, has opened new possibilities for interacting with 3D collections (Fujiuchi & Riggie, 2019; Hendery & Burrell, 2020). For instance, Fenu and Pittarello (2018) developed an AR experience to engage visitors in a cultural heritage environment, exploring the relationship between AR, storytelling, and context. Other studies have found that both online and offline AR learning tools (Lee, et al., 2021) can provide a more meaningful experience that motivates children to appreciate the value of cultural/historical artifacts. Oculus Rift and Kinect were also integrated to enable interaction and navigation in a complex 3D or 4D scene (Fernández-Palacios, et al., 2017); these devices can provide an immersive experience using digital reconstructions of heritage scenarios. Xu et al. (2023) verified the positive effects of gamified tangible AR interfaces on users' motivation, engagement, and performance in learning museum artifacts.

2.2 Haptics, embodied cognition, and learning performance

Haptics is generally defined as the sense of touch, and various dermal and hypodermal receptors play important roles in creating the sense of touch (Ucar, et al., 2017). Depending on the differences in these receptors, haptics can be divided into the sense of touch felt through the skin, and the sense of force felt through the joints and ligaments. To simulate these sensations, a series of algorithms related to tactile perception or force feedback have been proposed. Tactile perception is mainly used to simulate surface contact geometry, vibration, and temperature, while force feedback is used to simulate weight, hardness, and friction (Wiebe, et al., 2009). Meanwhile, a series of typical haptic devices, such as stylus haptic devices, haptic gloves, and full body suits, have been invented. These haptic devices and algorithms (Ruspini, et al., 1997; Girard et al., 2016) can apply forces and vibrations to increase our awareness about virtual objects. Some studies have explored the use of haptic interaction in museum or library domains. To address the problem of collection accessibility, Park et al. (2015) used haptic interaction, combined with depth cameras and remote robots, to build a remote collection access system. Using a haptic interface, visually impaired people can remotely explore museum scenes and haptically perceive 3D exhibits. Wójcik (2019) considered that haptic technology had the potential to make library services more accessible or attractive to various groups of people, especially disabled users with special educational and service needs.

Previous empirical studies have examined the use of haptic interaction in formal educational settings. A haptic-enhanced simulation of buoyancy was designed by Minogue and Borland (2016), and their results showed that learners who experienced haptics used "haptically grounded" terms more frequently, leading to the development of a theory of language-mediated haptic cognition. Crandall and Karadoğan (2021) described the two most common cognitive theories, namely, the cognitive load and embodied cognition theories, that can be used to support the implications of the use of haptic technology in learning environments. Embodied cognition is used to explain the positive educational impact of haptics. In other words, this type of learning environment promotes the emergence of tacit embodied knowledge (Reiner, 1999). This type of knowledge is directly (without the mediation of symbols or concepts) related to objects and body movements. Magana and Balachandran (2017) found that students conceptualized electric force through embodied haptic experiences, suggesting that visual/haptic simulations not only helped students to visualize these concepts, but also enriched the learning experience and enhanced retention. Zohar & Levy (2021) developed an embodied learning interactive chemistry environment (ELI-Chem) and found that students' conceptual understanding increased as their degree of bodily engagement through means including movies, simulations, joysticks, and haptic devices increased, with significantly higher learning gains and causal understanding under haptic interaction involving a greater range of motions and forces.

In conclusion, compared with studies examining the effects of the emerging haptic technology on conceptual understanding in formal educational settings, there is yet empirical studies on the effectiveness of haptic interaction in museum learning. To fill this gap in the literature, it is necessary to investigate how haptic interaction can enhance museum learning by providing more embodied experiences. Meanwhile, if the learning topic had been different, whether the embodied experiences make a significant difference in museum learning remains a controversial topic.

3 Research questions

The present study aims to confirm whether and to what extent haptic interaction could benefit learners in museum learning. We need to: (1) design the haptically augmented 3D artifact simulation which blends virtual reality and haptic technology to improve museum learning. (2) investigate whether haptic interaction affected task performance about 3D collections by providing more embodied experiences. (3) examine learner's perspectives on 3D collections by providing engaging experience. Therefore, our research questions are as follows:

Research Question 1 (RQ1): What are the effects of haptic-assisted museum learning versus non-haptic-assisted museum learning on learners' task performances in relation to 3D collections?

Research Question 2 (RQ2): What are the effects of haptic-assisted museum learning versus non-haptic-assisted museum learning on learners' investing time in relation to 3D collections?

Research Question 3 (RQ3): When the learning task or topic changes, do the embodied experiences offered by haptic interaction make a difference to the students' museum learning?

Research Question 4 (RQ4): How do haptic-enabled interface versus non-haptic-enabled interface affect the perspectives (interaction satisfaction) on 3D collections by providing the engaging experience?

4 Research design

4.1 Haptically augmented simulation

3D digitizing of cultural relics, especially artifacts in collections, has been studied extensively. The basic approach involves data sampling of spatial, color, and textural information to achieve a 3D reconstruction of an artifact. However, the data that are collected mainly represent the artifact's visual characteristics, and fail to reflect its haptic and auditory characteristics. Meanwhile, the physical material should be reflected in the roughness, hardness, and temperature of the simulated surface. In our previous study, we presented a haptic computing procedure to enable the simulation of the various characteristics of 3D artifacts (Qi & Zhu, 2018), enabling humans to perceive both the overall nature of and detailed information about virtual artifacts through multiple sensory channels. In addition to multimodal perception, two types of interaction are provided to realize user's operation intention. Rotation interaction allows learners to change their perspective in response to their specific needs, providing multi-view observations of the 3D artifact, while selection interaction enables learners to manipulate and explore the virtual artifact in the simulated learning environment.

We designed the haptically augmented 3D artifact simulation which blends virtual reality and haptic technology to support museum learning. Stylus haptic device was as the user interface of this study, as shown in Fig. 1, and Visual Studio 2013 was used to create a multimodal interactive system. 3D artifact simulation provides two types of feedback, force and visual, that coupled with the simulation. Visual cues are provided via the computer screen. The force feedback was provided by the haptic device. We used the well-known haptic device Phantom Omni (SensAble Technologies Inc., USA), which can track the *x*, *y*, and *z* Cartesian coordinates, as well as the pitch, roll, and yaw of the virtual point-probe that the learner manipulates in a 3D workspace. Above 6 degrees of freedom mainly capture hand motions using the wrist joints as the axis, and the position resolution value is about 0.055 mm. The haptic interface can be programmed to transmit forces via actuators (motors within the device) back to the user's fingertips and arm as it detects collisions with the 3D collections, simulating the sense of touch. Our artifact simulation also supports both mouse and keyboard use for rotation and selection.

The simulation interface takes input from the user and triggers the haptic device using C++programming language. After considering the contact states between the learner and the digital artifact, the multimodal information is generated. The OpenGL toolkit is used to render the visual characteristics of the 3D artifact, and the OpenAL toolkit is used to provide sound effects during interaction with the 3D artifact. The impedance control mode is used as the basic driving mechanism of the haptic rendering. Sensable Technologies' OpenHaptics toolkit is used to trace learners' behavior, such as position and direction information, and render the feeling of force that cannot be seen or heard through a haptic channel. Eventually, information generated from the simulation is passed to the visual and haptic devices.

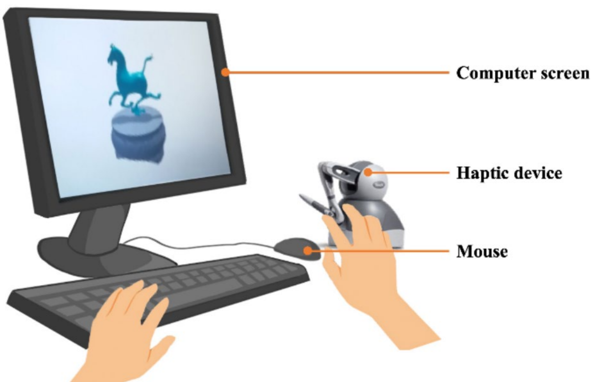


Fig. 1 Elements of the haptically augmented 3D artifact simulation

4.2 Participants

Forty (N=40) healthy Chinese undergraduate students (mean age 26.05 years, 19 males and 21 females) enrolled in arts or social science courses at universities in Nanjing, China, volunteered to participate in this study. None of the participants had previously participated in a museum learning activity involving 3D collections. All of the participants were randomly assigned to either a haptic interaction group or a non-haptic interaction group prior to the commencement of the experiment. Each condition had 20 participants. Both groups undertook four interactive tasks in relation to the 3D artifact. Participants had not prior experience with the haptic device (a Phantom Omni), and all participants signed an informed consent form before any experimental procedure. They all had normal or corrected-to-normal vision and hearing, and no tactile impairment, and were all paid a participation fee after completing the experiment.

4.3 Learning tasks and experimental procedure

For 3D collections, especially those that include 3D artifacts, the two abovementioned interaction interfaces can accurately reproduce low-level features (e.g., contours, colors, textures, and materials) in different ways. After discussions with several experts, we designed four types of learning tasks oriented to the following characteristics of 3D artifacts: a contour (shape) interaction task, a color interaction task, a volume interaction task, and a material interaction task. In the present experiment, some 3D artifacts appeared at a random location on the computer screen and participants were required to navigate a 3-D cursor to the target (using the Phantom Omni). Then, using the interactive 3D artifact simulations, participants made an experimental observation and hands-on manipulation (3D motion and rotation) about the given 3D artifacts. In the contour (shape) interaction task, the participants were required to observe and describe the contour of appeared 3D artifact. In the color interaction task, they were required to rotate, observe and describe the color attribute or pattern about specified zone of the appeared 3D artifact. In the volume interaction task, two 3D artifacts with different volumes were placed in different locations around 3D space, and the participants were required to move, rotate, and compare volumes. In the material interaction task, they were required to identify which artifacts were rougher or harder by observing and touching the simulated surfaces. Participants were also required to perform these tasks with their dominant hand.

Following the design and development of the applications, the abovementioned interactive tasks were undertaken by the participants in the haptic interaction group. Using haptic devices, the participants had the opportunity to touch and virtual manipulate the collections in 3D user interface. The participants in the non-haptic interaction group undertook the same interactive tasks, but were restricted to the use of non-haptic-enabled interfaces operated using the mouse. First, each participant received an introduction to the concept, devices, and usage about 3D artifact simulation. After the introduction, the participants undertook pre-experiment or training activity before we started the lab session, in order to overcome this "novelty effect" in museum learning as much as possible. Then, the haptic interaction group undertook the four interactive tasks using haptic devices, while the non-haptic interaction group performed the same interactive tasks using a mouse and keyboard. The four interactive tasks were randomly presented under constant conditions. During the lab session, participants were informed that they should finish all interactive tasks in 10 min or less. Afterwards, the non-haptic interaction group were introduced to haptic technology and used haptic-enabled interface to explore 3D collections. Finally, the participants filled out a questionnaire on learner satisfaction. Experimental procedure is as shown in Fig. 2.

4.4 Study measures

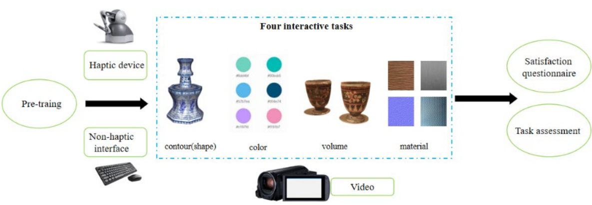
A video recording was made of each participant's learning performance in relation to the virtual collection. Considering that the interaction interface can simultaneously present multiple low-level features, the participants focused on one interactive task at a time to avoid cross-influence among the various tasks. Immediately following completion of an interactive task, the participants were asked a task-related question, and their responses were electronically recorded. The video recording was analyzed to ascertain the total learning time spent on each interactive task.

In a study on ARI [Augmented Reality Immersion] questionnaire by Georgiou and Kyza (2017), a nine-item learner satisfaction questionnaire was used to evaluate whether there was a significant difference in the level of satisfaction between groups. Cronbach's alpha was used to measure internal consistency, and was 0.73, which was acceptable. More specifically, Cheng et al. (2015) pointed out that immersion or psychological immersion is comprised of three stages in ascending order: engagement, engrossment, and total immersion, respectively. Engagement is the first step of immersion, and "Interest" and "Usability" compose this level. Our questionnaire examined two factors, usability and interest, and the scales showed reasonable reliability (alpha coefficients of 0.78 and 0.70, respectively). Responses were measured using a five-point Likert-type scale ranging from 1 to 5 where 1 = "Strongly disagree" and 5 = "Strongly agree." Prior to constructing the questionnaire items, we evaluated previous studies and selected items based on the advice of the expert committee. While the first group answered questions on the effects of haptic interaction on their attitudes toward 3D collections, the second group answered questions on the effects of non-haptic interaction on their beliefs.

4.5 Data analysis

The data gathered from the questionnaires and achievement tests including assessment scores and investing time were analyzed using the SPSS 20.0 software package.

Fig. 2 Experimental procedure



To examine the effects of haptic interaction on learning performance and participants' level of satisfaction with 3D collections, means and standard deviations were calculated and chi-squared tests and Mann–Whitney U tests were performed with a predetermined significance level of 0.05.

5 Experimental results

In this section, we present the experimental results based on inferential statistical analyses. Subsection 5.1 analyzes differences in task performance between the haptic and non-haptic interaction groups, Subsection 5.2 compares the investing time of the two groups, Subsection 5.3 analyzes the learning assessments related to the different interactive tasks in both groups, and Subsection 5.4 presents the results of the learner satisfaction questionnaire survey.

5.1 Task performance

The participants' responses were scored and the overall item score for each of the learning tasks (contour, color, volume, and material) was calculated to allow for comparison across treatment groups (see Table 1). Multiple-choice questions were considered to access the learners' performance of interactive tasks. The responses were scored with 0–1 (incorrect and correct answer, respectively). Then, we calculated the total scores for the four interactive tasks. These data were analyzed using the chi-squared test. Scores on the volume and material tasks varied significantly between the groups, with the haptic interaction group outperforming the non-haptic interaction group (volume $p = 0.000 < 0.01$; material $p = 0.011 < 0.05$). Conversely, the non-haptic interaction group performed slightly better on the contour assessment, although the difference was not significant, and there was no significant difference between the two groups in relation to the color assessment. Overall, the haptic inter-

Table 1 Differences between treatment groups based on the chi-squared test

Testing question type	Learning mode	Number of learners	Mean	Std. dev	X^2	Sig.
Contour type	Haptic interactive group	20	0.90	0.31	2.105	0.147
	Non-haptic interactive group	20	1.00	0.00		
Color type	Haptic interactive group	20	1.00	0.00	1.026	0.311
	Non-haptic interactive group	20	0.95	0.22		
Volume type	Haptic interactive group	20	0.90	0.31	25.600	0.000**
	Non-haptic interactive group	20	0.10	0.31		
Material type	Haptic interactive group	20	0.75	0.44	6.465	0.011*
	Non-haptic interactive group	20	0.35	0.49		
Total score of four question types	Haptic interactive group	20	3.55	0.69	18.443	0.000**
	Non-haptic interactive group	20	2.40	0.60		

Notes: Items were scored dichotomously, where 1 = correct and 0 = incorrect

* indicates $p < 0.05$, **indicates $p < 0.01$

action group displayed significantly higher task performance than the non-haptic interaction group.

5.2 Time investment

Given the small sample sizes and the non-normality of the data, Mann–Whitney U tests were used to test for differences. Table 2 shows the time invested on the different learning tasks by the two treatment groups. The haptic interaction group needed significantly more training time in the pre-experiment phase to master the basic usage. We compared the time invested on each learning task by the haptic and non-haptic interaction groups, and Mann–Whitney U tests revealed that there was no significant difference in time investment in relation to the color and contour (shape) tasks. However, there were significant differences in the average investing time in relation to the volume and material tasks ($p=0.011<0.05$ and $0.000<0.01$, respectively). In particular, the mean investing time of the haptic interaction group for the material task was nearly six times that of the non-haptic interaction group. Therefore, it is clear that investing time differed significantly across treatment groups.

5.3 Analysis of learning assessments with different interactive tasks in both groups

An analysis of learning under the different interactive tasks revealed a consistently higher level of learning performance using the haptic interface (see Fig. 3a). It can be seen from Fig. 3a that the mean score using the non-haptic interface was affected more obviously declined rapidly when the learning task or topic changed, whereas this did not occur when the haptic interface was used. Figure 3b shows the time invested on the various interactive tasks by the treatment groups. When facing a

Table 2 Comparison of time investment (seconds) between treatment groups based on Mann–Whitney U tests

Testing question type	Learning mode	Number of learners	Mean	Std. dev	*U*	Sig.
Operation pre-learning	Haptic interactive group	20	45.30	28.40	48.50	0.000**
	Non-haptic interactive group	20	17.65	9.64		
Contour type	Haptic interactive group	20	17.45	20.62	180.500	0.596
	Non-haptic interactive group	20	8.50	2.93		
Color type	Haptic interactive group	20	1.25	0.64	192.000	0.706
	Non-haptic interactive group	20	1.75	2.92		
Volume type	Haptic interactive group	20	15.95	6.14	102.000	0.008**
	Non-haptic interactive group	20	11.25	6.78		
Material type	Haptic interactive group	20	50.40	38.21	13.500	0.000**
	Non-haptic interactive group	20	8.80	5.33		
Total time of four question types	Haptic interactive group	20	85.05	57.03	18.443	0.000**
	Non-haptic interactive group	20	30.30	13.20		

Note: * indicates $p<0.05$, **indicates $p<0.01$

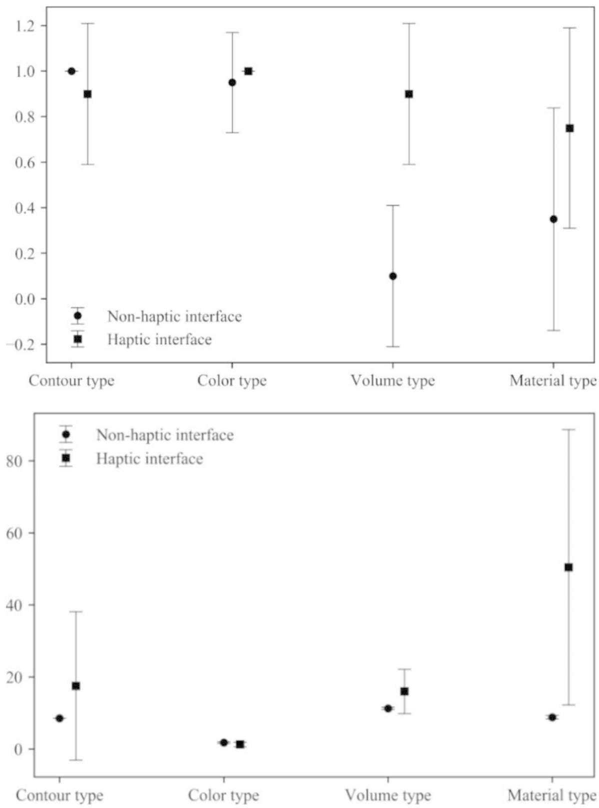


Fig. 3 Means with error bars of the various interactive tasks: (**a**) Learning performance (**b**) Time investment. Error bars represent standard error of the mean

different learning task or topic, the time invested by the haptic interaction group varied, whereas the time invested by the non-haptic interaction group was lower for most tasks and relatively consistent. Our analysis of learning performance and time investment for the four interactive tasks revealed that the only significant differences between treatment groups occurred in relation to the volume and material tasks. This was an interesting finding, as it could be conjectured that if the learning topic had been different, the perceptual experiences of the two groups could have made a difference to the participants' learning performance.

5.4 Comparison of learner interaction satisfaction between treatment groups

In this section, we analyze the differences in interaction satisfaction between the groups based on the participants' responses to the questionnaire. Table 3 shows the results based on Mann–Whitney U tests. A reverse-worded item was included in the survey to identify invalid responses, and 39 valid responses were included in our analysis. Item 1 measured the participants' overall perspectives of interaction satisfaction, items 2, 3, 4, 5, and 6 measured the first factor, usability, and items 7 and 8 measured the second factor, interest. The level of interaction satisfaction in terms of usability was higher among the haptic interaction group than the non-haptic interac-

Table 3 Comparison of learner interaction satisfaction between treatment groups based on Mann–Whitney U tests

Question	Learning mode	Number of learners	Mean	Std. dev	*U*	Sig.
Q1: I think that I would like to use	Haptic interactive group	19	4.68	0.582	304.00	0.000**
this interactive system frequently	Non-haptic interactive group	20	3.80	0.768		
Q2: Complete the tasks without unnecessary	Haptic interactive group	19	4.74	0.562	260.00	0.023*
effort, and I do not feel tired	Non-haptic interactive group	20	4.35	0.587		
Q3: It is easy to use for me, and operation	Haptic interactive group	19	4.47	0.612	226.00	0.259
conforms to natural habits	Non-haptic interactive group	20	4.25	0.639		
Q4: I found it is easy to remember all	Haptic interactive group	19	4.68	0.478	158.50	0.225
operations of the simulation system	Non-haptic interactive group	20	4.85	0.366		
Q5: I think the simulation system operation is easy	Haptic interactive group	19	4.47	0.612	136.00	0.065
to learn	Non-haptic interactive group	20	4.80	0.410		
Q6: I feel that the interaction/controlling	Haptic interactive group	19	4.68	0.582	268.50	0.013*
process is smooth and low-latency	Non-haptic interactive group	20	4.25	0.550		
Q7: I think the presentation of interactive	Haptic interactive group	19	4.53	0.513	261.000	0.021*
simulation system is relatively realistic	Non-haptic interactive group	20	4.10	0.553		
Q8: I think the interactive interface of	Haptic interactive group	19	4.79	0.419	320.000	0.000**
simulation system is very novel	Non-haptic interactive group	20	3.70	0.865		

Note: * indicates $p<0.05$, **indicates $p<0.01$

tion group. There was a significant difference between the two groups in relation to items 2, and 6, which asked participants the perceptions about the usability of 3D artifact simulation. Although the non-haptic interaction group scored slightly higher in terms of learn and remember (mainly in the pre-experiment phase), there were no significant differences. Meanwhile, there was a significant difference between the two groups in relation to items 7, and 8, which indicated that 3D artifact simulation using haptic-enabled interface more attract learners' interest. The responses to item 1 show participants in the haptic interaction group preferred to continue to use the 3D artifact simulation than participants in the non-haptic interaction group. It indicated that haptic-enabled interface affected or enhanced learner motivation on 3D artifact by providing the engaging experience.

6 Discussion

The purpose of our study was to investigate whether and to what extent haptic interaction could benefit learners in museum learning. Our haptically augmented 3D artifact simulation supported a haptic interface as well as a mouse and keyboard interface. Differences between the haptic and non-haptic interaction groups in terms of task performance, investing time, and interaction satisfaction were evaluated. Based on our experimental results, several issues such as modality effects and psychological immersion in learning emerged.

6.1 Stronger modality effects of haptic interaction

To address RQ1, the results showed that in general, haptic-assisted museum learning has significant positive effects than the non-haptic-assisted museum learning in promoting task performances in relation to 3D collections. In previous studies (Greenberg, et al., 2021), The modality effect refers to learning increases when information is presented in dual-modality (visual-auditory modalities) rather than in a single modality. Hamza-Lup and Stanescu (2010) found that the quality and amount of information conveyed through the interface was reduced without the haptic modality or channel, resulting in a narrower communication bandwidth and less efficiency during the learning process. In our study, the visual-haptic stimuli provided by haptic interaction had a stronger modality effect on human information processing than non-haptic interaction. Furthermore, several previous studies have indicated that haptically augmented simulation can provide effective perceptual experiences (Magana & Balachandran, 2017).

To address RQ2, there was a significant difference between haptic-assisted museum learning and non-haptic-assisted museum learning with 3D collections in terms of investing time. The task performance of the haptic interaction group was similar to that of the non-haptic interaction group in relation to the contour and color tasks, suggesting that haptic interaction did not induce students to spend significantly more time interacting with the virtual collection. To date, the visual information provided by 3D artifact simulation had been preferred to haptic exploration. A plausible explanation for this is that "modality specificity in perceptual encoding" (Klatzky, et al., 1993) might affect students' interactions with the 3D artifact simulation, and thus ultimately what is learned. This notion has been described as the differential appropriateness of visual and haptic information. Regarding the contour and color tasks, it suggests that haptic exploration might not be invoked when vision is available and sufficient to complete a learning task because of its relatively high processing cost. Additionally, visual recognition of a virtual collection might trigger the retrieval of information stored in memory about its properties.

To address RQ3, the different embodied experiences provided by the two interaction interfaces made a difference to the students' museum learning, which we believe is related to specific learning tasks. Significant differences only occurred in relation to the volume and material tasks, and not in relation to the contour and color tasks. Regarding the volume task, the fact that a monoscopic display of the simulation cannot meet the needs of visual depth perception meant that participants often found it difficult to compare depths and volumes using a mouse. By contrast, hands-on manipulation (3D motion and rotation) enabled by haptic interaction can assist with the volume task, resulting in significantly improved learning and a slightly higher engagement time. This result is consistent with that of Zohar and Levy (2021), who found that participants in the haptic interaction group showed significantly greater learning than those in the non-haptic interaction group as a result of the increased degree of bodily engagement (Zohar & Levy, 2021).

Although haptic interaction led to better performance in terms of volume and material evaluation, we think that the difference in investing time indicates that the working mechanism may differ between the volume and material learning topics. The results of the material evaluation task might be because learners, especially novices, benefit more from haptic sensory feedback in addition to visual and auditory feedback. This finding is like previous findings regarding haptic interaction in the context of learning physics concepts (Minogue & Borland, 2016; Magana, et al., 2019). Perceptual symbol theory (Barsalou, 1999; Ostarek & Huettig, 2019) also suggests that a haptic interface helps learners to create a perceptual grounding by enabling them to physically touch the artifact surface, and the schematic structure of concrete concepts, such as the "hard–soft" tactile structure, is based on perceptual experience.

6.2 Psychological immersion and satisfaction in museum learning

To address RQ4, in addition to analyzing task performance and time investment in relation to interactive tasks, we analyzed the responses to the learner satisfaction questionnaire. The concept of immersion, which is a constant sub-optimal psychological state involving continuous interaction with stimuli in the environment (Brown & Cairns, 2004), was introduced to explain the experimental results. As for the usability factor in the learning satisfaction questionnaire, haptic-enabled interface made a significant difference compared with non-haptic-enabled interface, because the participants felt that the interaction/controlling process was smooth and low-latency, and they complete the tasks with effortless. In addition, as for the interest factor, 3D artifact simulation using haptic-enabled interface more attract learners' interest due to a more realistic presentation and novel interface. Therefore, according to the results of the questionnaire, it is inferred that haptic-enabled interface can help learners overcome some barriers, and engagement is more likely to occur. Then the participants will invest their time, effort, and attention in museum learning how to complete these tasks and getting to grips with the controls. It also explains why haptic interaction group want to invest more time in relation to interactive tasks (RQ2).

It is clear that the haptic interaction group invested more time in pre-experiment phase. Regarding the subjective satisfaction questionnaire in the lab session, there was no significant difference between the two treatment groups in terms of ease of learning and remembering how to use the knowledge gained. A comparison of the quantitative experimental data with the satisfaction questionnaire responses showed that there was a contradiction between subjective self-reporting and objective evaluation. Most of the participants in the haptic interaction group estimated that the time invested on the various learning tasks was less than the actual time spent. This indicates that their attention was focused on the haptic interaction with the virtual collection during the interactive tasks, and they were unaware of the time that had elapsed, resulting in distorted perceptions. Overall, the 3D artifact simulation using haptic-enabled interface provided the participants with a visual-haptic sensory engaging experience, which enhanced the level of engagement and motivational effect. Novak et al. (2020) also found that objects that can be touched are preferred to objects that can only be seen, evoking different emotions, and leading to greater interest and engagement. This could explain why the participants in the haptic interaction group were keen to continue to use the 3D artifact simulation system.

6.3 Suggestions and educational implications

Based on the above findings, suggestions for the design of 3D collections on haptic-assisted museum learning are as follows: (1) Provide multimodal representations including visual, auditory, and haptic stimuli. The design of 3D collections should make full use of haptic technology to reproduce haptic features (e.g., contours, colors, textures, and materials). This requires collaboration between museum education designers and algorithm experts. (2) Allow hands-on manipulation adhere to the intuition. By combining the characteristics of the interactive interface, the design of interaction operations should be according to 3D collections and user bodily engagement. Interaction intention should rely on daily experience, and focus on the coupling of interactive tasks and embodied experiences which providing by interactive operations.

Implications of our study contribute to empirical studies that bring more understanding to the role of hands-on instruction in museum learning. Findings from our research suggest two guidelines for teaching and learning: (1) Add haptic feedback may be more beneficial for learning than only providing visual information. The theories of dual coding and two sensory channels in multimedia learning (Moreno & Mayer, 2007) need to also be validated or revised in order to consider the role of haptic information. (2) Haptic exploration is perceived as an enjoyable learning experience as reported by most of the learners using haptic-enabled interface during the experiment. This finding can be further supported with theories of embodied cognition ascertain the positive effects of engaging learners in use of active manipulation and bodily engagement.

7 Conclusions, limitation and future work

In this study, we developed a haptically augmented interactive 3D artifact simulation, and explored the effect of haptic interaction on learning performance and satisfaction with 3D collections. It was found that the visual/haptic stimuli offered by haptic interaction in museum learning had a stronger modality effect on human information processing than non-haptic interaction, resulting in significantly improved learning performance and slightly greater investing time. Our results suggest that the effect of haptic interaction depends on the coupling of the interactive task and the sensorimotor (or embodied) experience. Significant differences were evident in relation to the volume and material tasks, but not the contour and color tasks, suggesting that there are differences in the working or encoding mechanisms for different learning topics in relation to museum learning. Our analysis of the satisfaction questionnaire responses showed that psychological immersion is more likely to occur when using haptic interaction. In addition, participants in the haptic interaction group indicated that they wanted to continue to use the haptic interaction system. Obviously, touchable 3D artifact could attract the learners' attention, enhancing learner engagement and motivation.

We recognize that one of the limitations of our study relates to the small sample size in each treatment group. A second limitation relates to "novelty effect" what learners encountered the haptically augmented 3D artifact simulations for the first time. Also, the third limitation of the present study is that the questionnaire data could not capture the exact moments when feelings of immersion were experienced.

Several aspects will be further considered in a follow-up study. First, this study focused on the learning process in relation to physical characteristics, which were mainly low-level features, of 3D collections; emotional expressiveness about 3D collections through multisensory interaction is worthy of investigation. Second, we will conduct multiple experiments with the same population using different types of haptic devices, and make the comparison about the experimental results. Furthermore, the haptically augmented simulation components were executed locally, and further research is needed on remote and/or collaborative virtual environments. Finally, regarding the mental state of learners, further evaluation metrics, as well as eye-movement or EEG data, are required to measure and explain aspects such as psychological immersive experience and sense of presence.

Data Availability Data from the corresponding author is available upon reason request.

Declarations

Competing interests The authors declare no competing interests.

Ethical approval The submitted work is original and have not been published elsewhere or submitted to more than one journal for simultaneous consideration.

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