Master's Thesis

# Exhibit Upcycling by Digital Augmentation: A Case Study in a Science Museum

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# 디지털 증강을 통한 전시물 업사이클링: 과학관에서의 사례 연구

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# ABSTRACT

Exhibits in science museums must be capable of attracting and holding visitors' attention, but there are always some exhibits neglected by visitors. In this paper, we propose *exhibit upcycling* as a practical approach for reusing an unpopular physical exhibit to create a better exhibit. As a case study, we selected an old physical exhibit at a local science museum. We designed a digital companion that accompanied the physical exhibit to provide more interactive and enjoyable learning experiences. Our design strategy was user-centered and iterative, pairing the digital and physical exhibits step by step. Field studies showed that upcycling increased the attracting power of the exhibit by 9.54 times while significantly improving learning experiences, engaging behaviors, and positive emotions. These research results confirm the potential of combining the unique advantages of physical and digital exhibits for synergy, especially to improve unpopular, outdated exhibits.

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# I. Introduction

In science museums, exhibits are designed and implemented to stimulate visitors' interest and curiosity about science and technologies. Good exhibits prompt visitors, interact with them, and reinforce their own learning [1]. A particular difficulty arises because visitors have complete freedom in choosing the exhibits. Any boring or confusing aspects in the exhibits, maybe minor at a glance, can make visitors go away [2]. This nature of the learning environment in science museums requires exhibits to catch and retain the attention of visitors [3]. Exhibits incapable of doing so possibly waste valuable space in the science museums with no positive contributions to the visitor experiences. Replacing such physical exhibits with new ones may be the best way, but it is not always be feasible for small, local science museums.

In this paper, we demonstrate a concept of *exhibit upcycling by digital augmentation*, which renovates an unpopular physical exhibit in science museums by extending it with digital and programmable components in order to upgrade visitors' learning experiences. This idea was conceived for the special needs of local science museums in small cities in the authors' country. Such science museums have many old physical exhibits that are left unpopular and unvisited, but replacing them regularly with new exhibits is extremely difficult because of their low budgets. According to a statistical report from the authors' country [4], it costs between \$50,000 and \$100,000 to develop and install a new exhibit, but the average annual budget for new exhibits is \$168,000 for each museum. The situation is very poor also because a few central science museums use most of the budget for new exhibits. Local science museums, although their visitors account for the 70% of total visitors in the authors' country, are allocated with only 10%

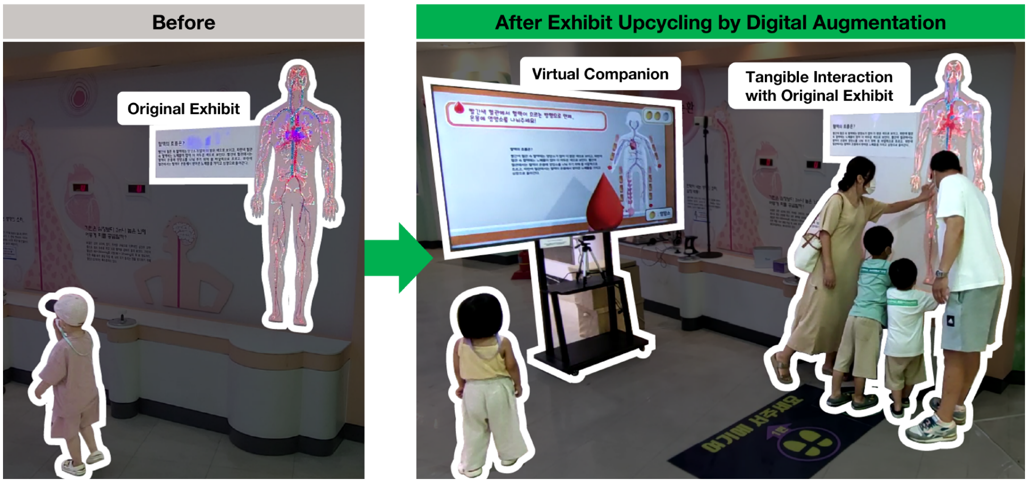


Figure 1.1: An unpopular physical exhibit on the wall (left) and its upcycled exhibit by digital augmentation using a virtual companion (right). The upcycled exhibit now attracts visitors and provides substantially better user experiences.

of the total budget for new exhibits on average [5]. What's worse, the suppliers of physical exhibits are very small and even go out of business quite often, which makes upgrading old physical exhibits themselves hopeless in some cases. Under these circumstances, a practical and viable approach can be to reuse old physical exhibits as much as they are while improving their attractiveness and educational value by digital augmentation. While doing so, we can use off-the-shelf hardware, and the content is programmable for upgrade, both for low cost.

For a proof of concept, we conducted a case study with a physical exhibit called "Blood Flow," one of the unpopular physical exhibits in a local science museum. By unpopular exhibits, we mean the exhibits that visitors do not stop on (*i.e.*, low attraction power), do not use long (*i.e.*, low holding power), and do not engage in (*i.e.*, low engagement level) [6]. We made discussion with educational experts at the museum and established main design goals, also based on visitors' opinions (Section III, Formative Study). We then designed and evaluated our upcycling strategies using digital augmentation in iterative manner over six months (Section IV, Iterative Design Process).

The final design of the digitally-upcycled exhibit of the Blood Flow consists of the original physical exhibit and a digital (virtual) companion displayed on a large TV, as illustrated in Fig. 1.2. The physical exhibit itself is left intact, but its interaction modality is upgraded to promote tangible interaction using an inexpensive camera-based external motion tracker. The upcycled exhibit invites visitors to interact with it in three steps. First, the virtual companion attracts and holds visitors by providing easy, enjoyable, and interactive learning experiences. Second, the virtual companion guides visitors' attention to the original exhibit. Last, visitors play a tangible educational game with the original exhibit. Usual digital augmentation techniques add text, audio, video, or other virtual elements to physical exhibits to append relatively simple information, such as supplementary materials or use guides [7, 8, 9]. Our design moves one step toward exhibit upcycling by providing a virtual companion that starts with an independent system and leads to collaboration with the original exhibit.

Experimental and observational studies performed with the upcycled exhibit at the museum validate its higher attraction, engagement, enjoyment, and educational effects than the original exhibit (Section V, Final Evaluation). We also provide discussion on the results and design implications of our case study (Section VI, Discussion).

The main contributions of this paper are as follows. First, we propose a new concept of *exhibit upcycling by digital augmentation*, which improves an unpopular physical exhibit to provide more engaging and better educational experiences to visitors by pairing it with a virtual companion. Exhibit upcycling is economical to preserve resources and greatly less expensive than replacing existing exhibits with new ones. Second, we share design recommendations for upcycling the exhibit based on the design strategies we followed for six months of user-centered

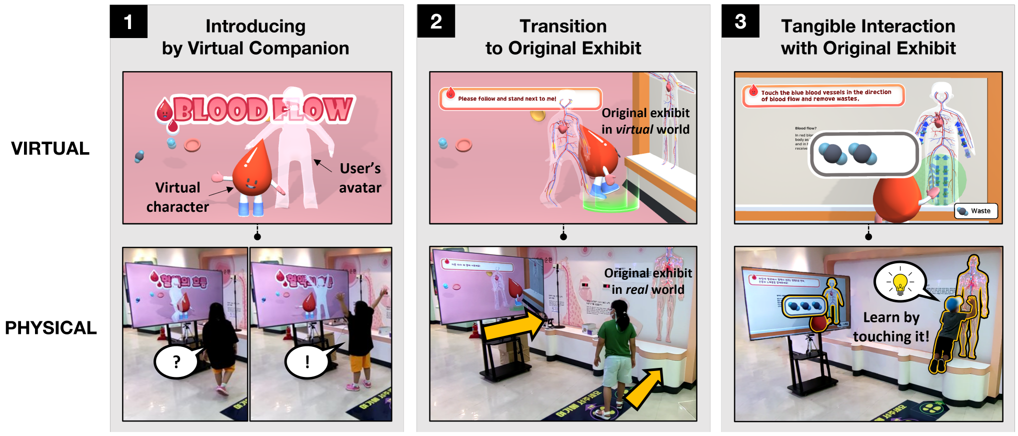


Figure 1.2: Overview of the upcycled exhibit for "Blood Flow." Interactions occur in three steps: 1) with the virtual companion, 2) transition, and 3) with the original exhibit.

design. This procedure demonstrated its effectiveness in field studies and can be easily applied to upcycling other physical exhibits. We hope our research results present a useful approach to renovating numerous outdated and unpopular physical exhibits in science and other museums.

# II. Related Work

In this section, we discuss previous research on digital augmentation in museums, embodied learning in informal settings, and how to design and evaluate museum exhibits.

## 2.1 Digital Augmentation in Museums

Science museums have been introducing exhibits using interactive technologies, such as Augmented Reality (AR) [10, 11] and haptics [12, 13]. These technologies have many advantages, e.g., interacting naturally with visitors, allowing them to experience scientific concepts through multiple modalities, and allowing content to be changed. One branch of utilizing digital technologies is *digital augmentation*, which leaves existing exhibits intact and augments them with text, audio, video, or other virtual elements to convey information lacking or not present in the exhibits [9]. Digital augmentation is also useful when it is difficult or not desirable to fully replace existing exhibits, so it is often brought into history or archaeology museums [14, 15, 16, 17]. Roberts et al. [15] investigated how digital augmentation using interactive displays help visitors appreciate existing authentic objects in a history museum. They compared three different strategies and showed that digital augmentation significantly changed visitor experiences of the same exhibit.

Likewise, because most science museums are adopting object-based learning, which encourages interaction with the physical object, as a core pedagogical approach [18], digital technologies were often used to augment the physical object instead of being used alone as a virtual exhibit [9]. In particular, digital augmentation is widely applied in the in-use stage of exhibits in the form of information superposition to reflect use contexts [9]. Overlay of the virtual contents onto the original exhibit can provide the guidelines for the exhibits [19, 20, 21] and visualize the invisible, such as physical force [22], electricity [23], and body organs [24, 25]. Inserting virtual information in the pre-use stage of exhibits has only been attempted using mobile devices to encourage and guide the learning activity. Connaghan et al. [26] used a virtual character called Dr. Ray, which introduced the story and encouraged a user to start an AR activity that displayed a skeleton on the user's body and a toy. This study demonstrated that the virtual character could contribute to making the activity child-friendly and enhancing the educational value of the activity. However, they applied digital augmentation onto a personal toy, not to existing exhibits. In addition, the use of mobile media in science museums is still cautious, as it can distract visitor-exhibit interactions [27, 19] and decrease social interactions [28, 19].

To upcycle unpopular physical exhibits, we apply digital augmentation to both the pre-use and in-use stages of the physical exhibit using a large display. In our design, the virtual companion first provides engaging and motivating experiences in the pre-use stage. Then, the original physical exhibit offers improved experiences in the in-use stage, including tangible interaction enabled by an external camera recognizing the user's touch on the exhibit.

## 2.2 Embodied Learning in Informal Settings

Audiovisual digital simulations are good to show unobservable processes and provide appropriate feedback to users. However, in an effort to make simulations accurate and consistent with concepts in science, visual representations of learning contents tend to be highly abstracted [29]. Also, verbal feedback protocols that are reminiscent of formal instructions may be detrimental to learner agency [30].

Embodied interaction can complement audiovisual simulations by adding a new modality for feedback that directly connects to the actions and perceptions of the learner. Moreover, embodied interaction is well suited to informal learning settings such as science museums where children can physically interact with exhibits.

Embodied cognition theories emphasize that cognitive processes occur in the interaction between one's body and its physical environment [e.g. 31, 32]. Learning methods designed based on embodied cognition are called embodied learning. Its main design rationale is to have learners act out and physicalize the systems, processes, or relationships that they are trying to understand [30]. This activity can create conceptual anchors from which new knowledge can be built.

Many embodied learning studies have been designed for full-body interaction [e.g. 33, 30]. Full-body interaction has the highest level of an embodiment with rich locomotion [34], which can lead the user to be highly engaged and motivated [30, 35]. For instance, in Lindgren et al. [30], participants learned about gravity and planetary motion with a whole-body interactive simulation, which led to a learning gain with high levels of engagement and motivation.

The other large part of the embodied learning literature is concerned with tangible interaction [e.g. 34, 36]. Tangible interaction is a sensing-based interaction modality that enables interaction with a physical object augmented with digital information [37]. One important benefit of tangible interaction is that it can utilize both digital and physical information [37]. For example, Skulmowski et al. [38] augmented a physical heart model with virtual labels showing the names of its parts. They showed that the tangible interface could improve learning outcomes in terms of retention, cognitive load, and motivation than the mouse interface.

We employed full-body interaction in designing the virtual companion to afford visitors high motivation and learning benefits. We also endowed the original exhibit with an additional modality of tangible interaction to enhance the visitor experiences by using both digital and physical information.

## 2.3 Design and Evaluation of Museum Exhibits

User-centered design (UCD) is an iterative design process that involves users throughout the process [39]. UCD can create highly usable and user-friendly products by repeating user evaluations and design improvements. For this reason, UCD is a well-suited design method for products that need to support intended users' existing beliefs, attitudes, and behaviors rather than requiring users to learn and use the system. Exhibits in science museums are one good example.

In science museums, visitors only interact with the exhibits they want. They do not stay with unappealing exhibits for whatever reasons [2]. Exhibit design through UCD allows such undesirable aspects in the design to be removed or replaced in the early stage so that users can easily understand and use them [2]. A case study that applied UCD to designing a virtual reality exhibit showed that the UCD is efficient in developing an exhibit that provides satisfying user experiences [40]. We adopted this design method for the upcycling process.

When evaluating exhibits, researchers should consider that visitors' awareness of being observed can modify some aspects of their behaviors [41]. This phenomenon is well known as the Hawthorn effects. To avoid it, objective observations of visitors' behaviors, such as the number of visitors who stop at the exhibit, holding time, their engagement level, and conversations, are widely used. These measures also provide good insights into how an exhibit encourages interaction and learning [42]. We designed and improved artifacts for digital augmentation based on the experts' and users' opinions and the results of questionnaires, interviews, and visitor observations.

# III. Formative Study

## 3.1 Exhibit Selection

Among the many physical exhibits in the local science museum in the authors' city, we selected the exhibit called "Blood Flow" (Fig. 3.1) for three reasons. First, it covers the human circulatory system, a general education topic in schools and other science museums. Second, most visitors ignored the exhibit, although it was located at the entrance of the exhibition hall. Third, the exhibit appeared to have three characteristics of unpopular exhibits revealed by Boisvert and Slez [6]: complex information presented, abstract presentation, and low interaction.

The Blood Flow was basically a pictograph on the wall. It consisted of a physical model of the human circulatory system and the text explaining it. The human model had the actual size of humans and displayed the heart, arteries, veins, and capillaries. Many LEDs attached along the blood vessels simulated the blood flow with yellow lights. The text located next to the model explained the directions of blood flow and the roles of the artery and vein in the systematic circulation of human bodies.

## 3.2 Background Interview

Before starting the design process, we analyzed the problematic factors that lowered the popularity and capture rate of the Blood Flow exhibit from the users' perspective. Interviewees were randomly recruited among the visitors at the exhibition hall entrance. Once the visitors agreed for interview, they were asked to use the exhibit freely and answer open questions about their experiences and opinions. Twenty children (4-11 y/o; M=6.70; 10 females) and their families

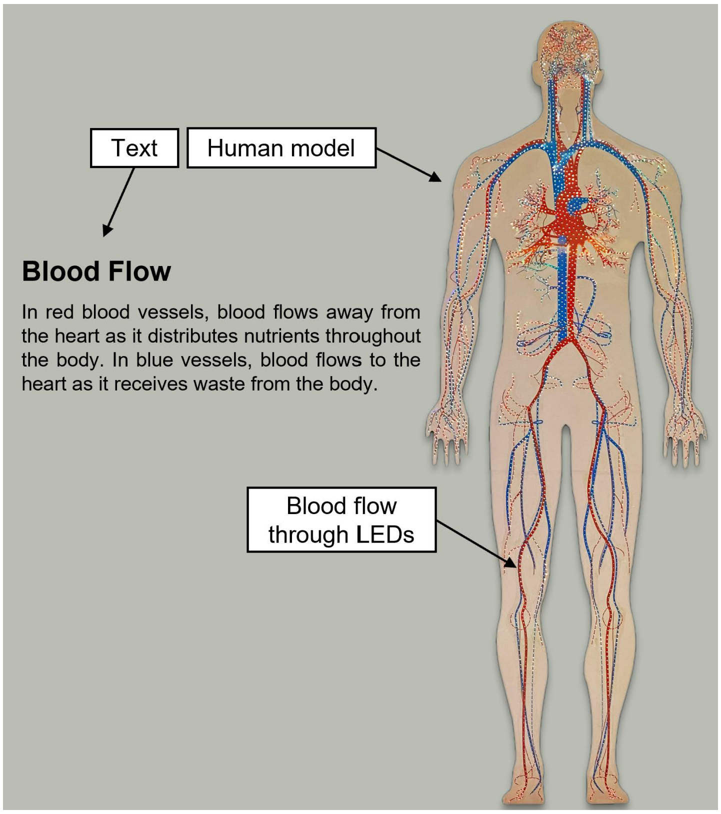


Figure 3.1: The exhibit named "Blood Flow" we chose for the upcycling. The human model on the right shows the circulatory system with blood flowing through LEDs. The text beside it delivers the following learning contents. (1) Blood in red blood vessels flows away from the heart, carrying and distributing the nutrients. (2) Blood in blue blood vessels flows to the heart, carrying and collecting the waste. This exhibit was designed and installed at least 12 years ago.

joined the interview. The interview responses were analyzed through an affinity diagram, and the results are as follows.

- *(Difficulty of learning content)* Two groups said the learning content was too hard for their children.
- *(Unsuitable learning medium)* Children in two groups did not know how to read or did not like to read, and one group wanted to listen to the text through audio.

- *(No interactivity)* Two groups complained about the lack of interactive elements.
- *(Low enjoyment)* Three groups wanted the exhibit to be more enjoyable.
- *(Not interesting)* Eight groups said the exhibit did not have interesting content to attract visitors.

Based on these results, we made the following observations. First, most children visitors of the museum could not easily understand the learning content of the Blood Flow exhibit. The learning content of the exhibit belongs to the national curriculum of 12-year-old students in the authors' country. However, the child visitors were about seven years old on average. Second, the exhibit did not support suitable learning media. Although the exhibit showed the blood flow through the LEDs, the detailed items for learning were in the text form beside the exhibit. Roughly half of the children visitors may not be able to read or understand the text; children start reading and decoding simple texts when they are 6–7 years old [43]. Even if they can read, exhibits with overwhelming texts are not appealing to visitors [15]. Third, the exhibit did not have interactive components, which degraded the enjoyment of using it. These three observations, consistent with the three characteristics of the unpopular exhibit [6], would have caused the exhibit's low popularity.

## 3.3 Brainstorming with Experts

Based on the above mentioned problems, we conducted a brainstorming session to set design directions and find other things to consider for upcycling. This stage involved the director and three researchers working at the science museum. The researchers, including one expert in biology, had in-depth knowledge of the museum and were responsible for inventing new exhibits. The experts were informed of the concept and examples of digital augmentation, and brainstorming was conducted for ideas of how to solve each problem through digital augmentation. The ideas were filtered through strengths, weaknesses, opportunities, and threats (SWOT) analysis and the outcomes (B1–B4) were summarized as follows:

B1. *(Provide prior knowledge-based scaffolding)* Educational scaffolding methods, i.e., assistive steps that support the students' learning [44], will help children visitors learn the difficult content in the exhibit. For example, providing or activating prior knowledge in advance can facilitate the children's learning process during the exhibit.

B2. *(Support diverse learning media)* Adding an auditory medium to the exhibit will let users see the circulatory system model while listening to the learning content. Supplementing visual media, such as virtual models and animations, can provide an intuitive understanding of the concept.

B3. *(Start with motivating contents)* The primary goal of exhibits is to arouse interest and curiosity, which in turn motivates visitors to seek the advanced content. Starting with easy and fun content will provide a stepping stone for using the original exhibit.

B4. *(Introduce interactivity)* Introducing interactive elements that can be controlled by the user's movement or touch will make the exhibit more enjoyable and increase the learner agency.

The above outcomes were set as our design direction and basis when we made design choices during the iterative design process.

## 3.4 Design Goals

Here we present four high-level design goals, the first representing the purpose of upcycling and the other three goals informed by the formative study. We aimed to design an upcycled exhibit to

G1. Utilize the original exhibit wisely.

G2. Attract visitors and encourage the use of the exhibit.

G3. Deliver the original learning content effectively.

G4. Provide enjoyable and engaging user experiences.

G5. Be affordable at a low cost.

# IV. Iterative Design Process

In this section, we present the design process for exhibit upcycling of the Blood Flow, which was iterated mainly three times over six months with a total of 149 children of the mean age of 6.99 years. The procedure and results of each iteration are described in the following structure. First, we specify the goals based on the results from the formative study or previous iteration. Second, we describe the design rationale that served as the background of our design choices. Third, we illustrate the detailed design and implementation methods of the design alternatives. Fourth, we present the methods and results of a user evaluation. Finally, we discuss the lessons learned through the iteration. The design outputs of the three iterations are summarized in Fig. 4.1, 4.2, and 4.3, respectively.

Common methods used in the visitor evaluations were as follows. The user evaluation procedure started with randomly recruiting participants visiting the science museum. The children who agreed to participate were asked to solve a pre-quiz about the target learning concepts of the design. Then, they freely interacted with the exhibit, and it was recorded by a video camera. After using the exhibit, they solved a post-quiz with the same questions as the pre-quiz and answered a short survey evaluating motivation and enjoyment. Finally, we interviewed the children and their families to obtain feedback on the exhibit's activity. The participants received science museum souvenirs that cost about USD 2.

## 4.1 First Design: Virtual Companion

Following the expert's advice to start with motivating content (B3) and provide prior knowledge-based scaffolding (B1), we set the goal of our first iteration as attracting visitors and providing fun and motivating virtual content in the pre-use stage of the original exhibit. For that, we designed a virtual companion that convey prior knowledge about the circulatory system based on full-body interactions. This decision was made while also considering that a digital companion that can be used independently is preferred when physical exhibits get broken or out of order in science museums (personal communication with a staff in a science museum).

### 4.1.1 Design Rationale

**Drawing the visitors' attention** The original exhibit could not capture visitors' attention alone. Displaying an avatar that imitates the movements of passers-by is widely used to capture their attention and initiate interaction [45]. We chose to display the movements of visitors passing by as avatars to trigger their curiosity and induce them to interact spontaneously with the exhibit. It also corresponds to our design direction to introduce interactivity (B4).

**Scaffolding through prior knowledge** The difficult learning content of existing exhibits lowers the motivation of users to interact with the exhibits. Scaffolding refers to a method that offers a particular kind of support for students to learn new concepts or develop new skills. As experts suggested (B1), the scaffolding activating the prior knowledge in education is known to play an important role in motivating the students [46, 47] and enhancing the learning effects [48, 49]. Thus, we decided to provide prior knowledge about the human circulatory system through fun and engaging activities before children start using the original

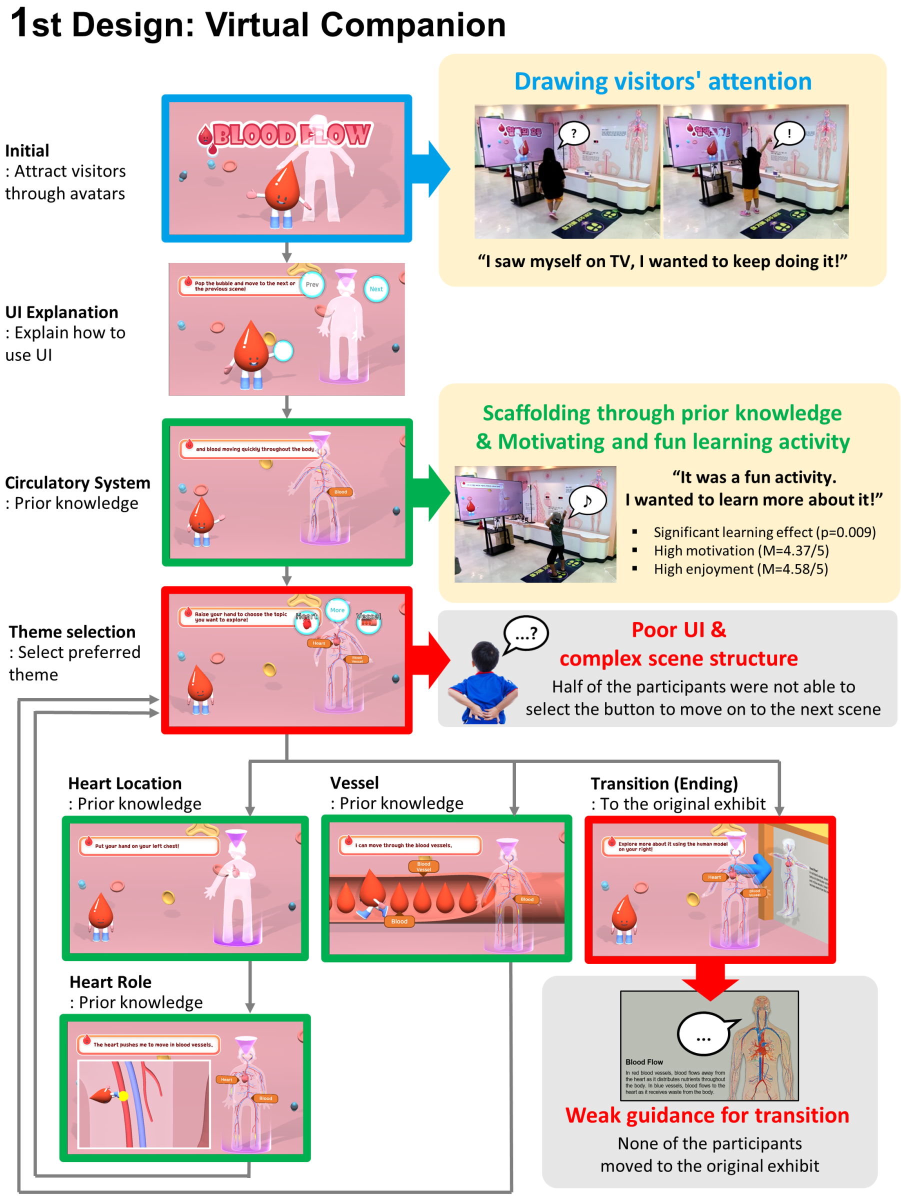


Figure 4.1: The first design output of the iterative design process. The grey arrows represent the scenario of the virtual companion. The scenes with blue or green borders indicate that the scenes contain components related to the design rationale. The arrows connected to them show a brief outcome of the design choices. Scenes with red borders represent the scenes needing improvements, and the arrows connected to them describe the scenes' problems. A video that shows the full interaction scenario is available in the supplemental materials.

exhibit.

**Motivating and fun learning activity** To deliver prior knowledge through enjoyable activities (B3), we adopted two methods: full-body interaction and animation. Full-body embodied interaction has been shown to positively affect the learning experience, such as motivation, enjoyment, and learning gain [e.g. 35, 30]. We decided to overlay the circulatory system structure on the users' avatars to enable learning with their own bodies. Animations explaining scientific concepts can also facilitate an intuitive understanding of the concepts [50, 51]. We used animations to convey prior knowledge by visually depicting concepts that are hard to see, such as the role of the heart. Such full-body interaction and audiovisual animations support diverse learning media (B2).

### 4.1.2 Detailed Designs and Implementation

We implemented the virtual companion using the Unity game engine. It was displayed on a 75-inch TV installed near the original exhibit. We used Microsoft Kinect to track the users' motions in front of the TV. We deliberately chose these commercial devices that are easy to obtain and of low cost.

The scenario and its detailed designs are as follows. First, the initial scene of the virtual companion shows avatars that mirrored the movements of passers-by within 3 m of the display (the *initial* scene in Fig. 4.1). It is to draw their attention so that they would begin an interaction with the exhibit. The avatar's size is rescaled to be proportional to the user's actual height to help users quickly recognize their own avatars. In the next scene, a cute virtual character, which looks similar to a blood drop, briefly explains how to use the UI for interaction (the *UI explanation* scene in Fig. 4.1). The user can select a navigation button by reaching out to one of the bubble-shaped buttons around the user's avatar.

From the next scenes, we designed an enjoyable activity to learn the original exhibit's prior knowledge. We chose four easy concepts about the circulatory system: the structure of the circulatory system, the roles and locations of the blood vessels, the location of the heart, and the function of the heart. In the *circulatory system* scene, users can see the heart and blood vessels superimposed on their avatar to learn the structure of the circulatory system. Then, the user is asked to select a preferred learning theme for the next activity (the *theme selection* scene in Fig. 4.1). Three buttons labeled 'Heart,' 'Vessel,' and 'More,' respectively, are available for selection. Choosing the 'Heart' button moves the user to the scenes teaching the location and role of the heart (the *heart location & role* scene in Fig. 4.1), the 'Vessel' button to the scene about the role and location of the vessel (the *vessel* scene in Fig. 4.1). In the *heart location* scene, users are instructed to put their hands on their left chest. By following the instruction, the user can feel and see the location of the heart superimposed on their avatar. The scenes teaching the role of the heart and vessels require explanations about what is happening inside the circulatory system. Hence, we used animations appearing in a new window to enlarge the details and visualize the concepts. Users can return to the selection scene after finishing each content.

Lastly, when users choose the 'More' button in the *theme selection* scene, they can move to the *transition* scene in Fig. 4.1. The transition scene shows the original exhibit in the virtual world that mirrors the physical one. Users were asked to move toward the original physical exhibit through voice and text instructions with an arrow.

### 4.1.3 Evaluation

A total of 19 children (4-10 y/o; M=7.00; 12 females) participated in the evaluation of the exhibit. The children solved a quiz about the circulatory system consisting of the following four True/False (T/F) questions:

Q1. The circulatory system is composed of the heart, blood, and blood vessels. (T)

Q2. Blood vessels are spread only on the legs. (F)

Q3. The heart is located in the right chest. (F)

Q4. The heart pumps the blood throughout the whole body. (T)

The score of each question was one if answered correctly. The participants also answered a short survey about motivation and enjoyment on a 5-point Likert scale. The two survey questions adapted from Lindgren et al. [30] were as follows:

- I wanted to know more about the circulatory system after using the exhibit.
- I enjoyed using the exhibit.

The result of a one-way repeated-measures ANOVA on the scores of prior knowledge was significantly higher ($F(1, 18) = 8.56$, $p = 0.0090$) in the post quiz score ($M = 3.42$, $SD = 0.88$) than the prior quiz score ($M = 2.68$, $SD = 0.98$). The correct answer rate was over 75% for every post-quiz question. In the survey, the average score of motivation was 4.37 ($SD = 0.74$), and that of enjoyment was 4.58 ($SD = 0.82$). However, we observed that only 8 out of 19 children completed the virtual interaction scenario, and none of the participants moved to the original exhibit. It was out of our initial expectations.

#### 4.1.4 Lessons Learned

First, the avatars mirroring the passers-by's movement could attract visitors effectively. The mirroring effect could be easily observed in the comments collected in the interviews, such as "*I saw myself on TV, I wanted to keep doing it.*", "*The avatar that imitated my body was interesting.*", and "*Interactivity with body looked appealing.*" Second, learning with embodied interaction and animation could deliver all learning concepts for the prior knowledge to the user effectively, as demonstrated by the participants' quiz scores. Third, the embodied interaction and animations could encourage the use of the exhibit and elicit enjoyable visitor experiences. The interview comments of "*It was a fun activity. I wanted to learn more about it.*" and "*It was fun to see the veins, the heart, and myself appear on display.*", and the high motivation and enjoyment scores describe the activities' positive effects. Fourth, multiple identical buttons and instructions delivered only through voice and text seem to lead to a low completion rate. From the recorded videos, we observed that ten children were confused with the multiple similar-looking buttons. Another four could not follow interaction instructions in *heart location* scene. These led to stopping the use of the exhibit. Lastly, we showed the original exhibit in a virtual world with verbal and textual instruction for the transition in the *transition* scene. However, no one could move and start interacting with the original exhibit. Voice and text instructions with simple visual cues seem insufficient for complex instructions.

## 4.2 Second Design: Improving User Interface and Guidance

From the first design, we observed multiple buttons confuse children, and instructions through only voice and text are ineffective in guiding them.

Therefore, in this second design, we aim to improve UIs and guidance to increase the completion rate of the virtual interaction scenario and transition rate to the original exhibit.

### 4.2.1 Design Rationale

**Intuitive User Interface for Affordance** Excessive buttons can confuse the user [52], and the multiple buttons in the *theme selection* scene of the first de-

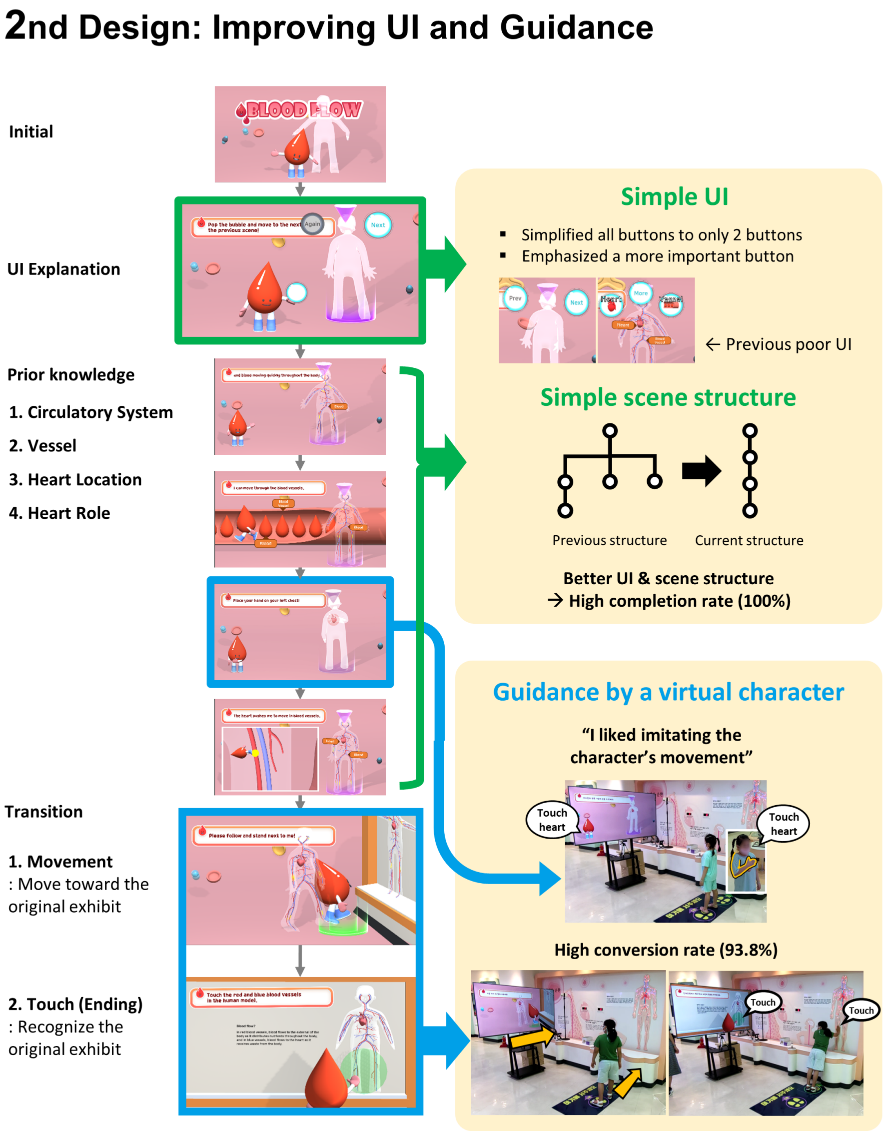


Figure 4.2: The second design output of the iterative design process. The grey arrows represent the scenario of output from the second design. The scenes with blue or green borders indicate the scenes containing components related to the design rationale. The arrows connected to them show the outcome of the design choices. A video that shows the full interaction scenario is available in the supplemental materials.

sign probably harmed the user experience. We decided to reduce the number of buttons by streamlining the scene structure and removing the selection function. Additionally, we controlled the colors and sizes of buttons depending on their importance; an appropriate emphasis on UI can make users quickly aware of what they should do [53].

**Guidance by a Virtual Character** From the first design, we found that voice and text are not enough to guide children for our purpose. While looking for a more powerful guidance method, we observed that some children expressed intimacy with the virtual character in their interviews. They said the following: "*It was nice to study with the virtual character.*" and "*The virtual character taught me the knowledge.*"

Thus, we decided to make the virtual character demonstrate how to do target actions first and encourage children to imitate and learn the actions. We expected this strategy would be viable from the general fact that children are good at imitating others' behaviors and learn quickly by it [54].

### 4.2.2 Detailed Designs and Implementation

We displayed three buttons for branching to multiple learning themes in the first design. In the second design, we did not need them as we simplified and serialized the scene structure (the *prior knowledge* scenes in Fig. 4.2). Instead of choosing the next theme to learn, users could choose between staying on the scene and moving to the next scene so that they could still participate, depending on their interest (the *UI explanation* scene in Fig. 4.2). Additionally, we emphasized the button to move to the next scene to encourage completion. In the first design, there was no emphasis on the important buttons.

To guide the user, we used the animations of a virtual character. In the *heart location* scene, we observed some participants could not follow the interaction instructions. Thus, we made the virtual character put its hand on its left chest to prompt users to do the same action with their body to teach the location of the heart (the *heart location* scene in Fig. 4.2). We also used the virtual character in the *transition* scene to guide the user to move on and interact with the original exhibit. The virtual character showed a motion pointing to the original exhibit in the virtual world. We expected the users to follow the virtual character spontaneously and move toward the original exhibit in the real world (the *movement* scene in Fig. 4.2). Similarly, in the following scene, the virtual character showed an animation of itself viewing and touching the exhibit, encouraging the user to do the same with the original exhibit (the *touch* scene in Fig. 4.2).

### 4.2.3 Design Rationale

### 4.2.4 Evaluation

The second design's evaluation focused on analyzing the users' progress with the exhibit. Sixteen children (4-11 y/o; M=6.81; 8 females) participated in the evaluation. In the results, all 16 participants completed the virtual interaction scenario. The Chi-squared test showed that the completion rate significantly increased ($\chi^2(1) = 13.51$, $p = 0.0002$) compared to the first design in which only 8 out of the 19 participants could finish. Moreover, 15 of the 16 participants successfully moved to the original physical exhibit and continued the interaction activity.

### 4.2.5 Lessons Learned

First, using simple UIs and emphasizing important buttons can allow children to understand how to interact with the virtual companion. No participants expressed difficulties using the UIs from the recorded videos. It enabled the high completion rate of the virtual interaction scenario (100%).

Second, animations of the virtual character can guide children to interact with the original exhibit effectively. The high conversion ratio of the users to the original exhibit (93.8%) indicates that the participants could easily follow the character's guidance. The participants' interviews also supported it, , e.g. "*I liked imitating the character's movement.*"

## 4.3 Third Design: Augmenting the Original Exhibit

In the last two designs, we aimed to design the virtual companion and connect them to the original exhibit. Now, we move our focus to renovating the original exhibit for its own learning experiences. From the brainstorming session in the formative study, the experts mentioned the need for adding interactive elements to the original exhibit (B4). Therefore, in this final design, we aim to add a new learning modality to the original exhibit for engaging interactions.

### 4.3.1 Design Rationale

**Augmentation through gamified tangible interactions** One of the good attributes of physical exhibits is that visitors can freely touch them. We chose tangible interaction as a new learning modality to benefit from both physical exhibits and digital augmentation. Tangible interaction is known to positively affect learning experiences [e.g. 55, 56]. Moreover, gamified tangible interaction with learning content has demonstrated its effectiveness on engagement and learning [57, 58].

### 4.3.2 Detailed Designs and Implementation

We augmented the original exhibit to support tangible interaction using the Microsoft Kinect. The system can recognize if users touch on the human model and the direction of the touch motion by capturing the user's motion. This method was simpler and less expensive than alternatives, such as installing a thin, transparent, film-like pressure sensory array all over the human model.

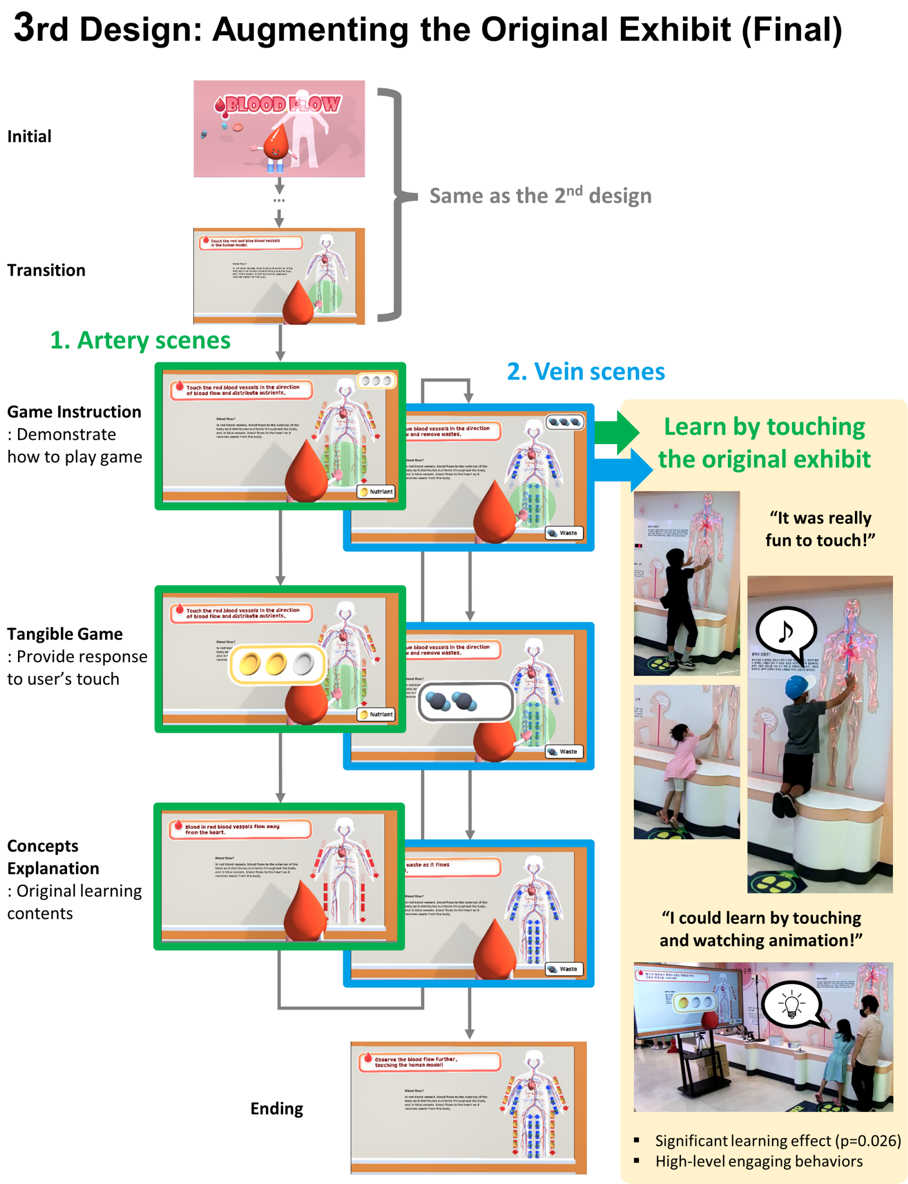


Figure 4.3: The third and final design output of the iterative design process. The grey arrows represent the scene flow of the third design output. The scenes with green and blue borders indicate the artery and vein scenes, respectively. These scenes contain components related to the design rationale: augmentation through gamified tangible interaction. Arrows connected to them show the brief outcome of the design choice. A video that shows the full interaction scenario is available in the supplemental materials.

We gamified the learning content of the original exhibit, the roles and directions of the arteries and veins, as follows. First, the virtual character explained the purpose of the game and demonstrated how to play the game through animation (the *game instruction* scene in Fig. 4.3). In the artery scenes, the virtual character asks the users to help to distribute nutrients throughout the body by touching the human model in the direction away from the heart. Similarly, in the vein scenes, the virtual character asks the users to help collect waste by touching the human model toward the heart.

The game starts when the user follows the instructed movement. Whenever they succeeded in the game task, game effects were given by animation and sound to encourage the user to proceed further (the *tangible game* scene in Fig. 4.3). The game ended after the user made tangible interactions three times with the exhibit. Then, the information about the flow directions and roles of blood for each type of blood vessel is delivered with an animation on the human model of the virtual companion along with voice and text (the *concepts explanation* scene in Fig. 4.3). Finally, after completing both the artery and vein game scenes, further exploration of the original exhibit was encouraged in the ending scene (the *ending* scene in Fig. 4.3).

### 4.3.3 Evaluation

Twenty children (5-10 y/o; M=8.00; 9 females) participated in this evaluation. Because the third design focused on learning the contents of the original exhibit, the quiz questions were related to learning concepts presented in the original exhibit. The quiz had the following four T/F questions:

Q1. In red blood vessels, blood flows away from the heart. (T)

Q2. Blood in the red blood vessels has many nutrients to distribute to the whole body. (T)

Q3. In blue blood vessels, blood flows away from the heart. (F)

Q4. Blood in the blue blood vessels has lots of waste collected from the body. (T)

The score of each question was one if responded correctly. The participants answered a short survey about motivation and enjoyment (the same one used to evaluate the first design).

As a result, the quiz score was significantly higher ($F(1, 19) = 17.08$, $p = 0.0006$) in the post-quiz ($M = 2.60$, $SD = 0.92$) than in the pre-quiz ($M = 1.25$, $SD = 0.89$). The score of every question increased in the post-quiz. In particular, the differences were significant in Q2 and Q4 ($\chi^2(1) = 6.46$, $p = 0.0110$ and $\chi^2(1) = 20.42$, $p < 0.0001$). In the survey, the average score of motivation was 3.70 ($SD = 1.27$), and that of enjoyment was 4.65 ($SD = 0.96$).

### 4.3.4 Lessons Learned

First, the gamified tangible interaction seems to be an effective approach for delivering the learning content to the users. It is based on the numerical results of the quiz and the participants' responses, such as "*I learned by touching it.*" and "*I could learn by touching and watching animation.*" In particular, the learning effect improved significantly in the questions about the role of blood in arteries and veins. It seems that the users well accepted the tangible interaction of touching each blood vessel and the responses emphasizing the roles of blood in arteries and veins. Second, the game with tangible interaction appears to contribute to improving the original physical exhibit to afford enjoyable and engaging user experiences. Participants' positive responses were observed in both motivation and enjoyment scores. Some comments from the interviews were also relevant; e.g., "*It was nice to touch the blood vessels, it was fun,*" "*I felt better when I touched it,*" "*I liked to touch it along with it, and I was curious about the inside of the* *body.*"

## 4.4 Design Outputs: Upcycled Exhibit

Finally, we present the upcycled exhibit, composed of three main parts, as refined and completed by three iterations of design, user evaluation, and improvement. As shown in Fig. 1.2, the virtual companion attracts passers-by and motivates them to continue using the exhibit. Full-body interaction attracts the visitors to start using the exhibit, and enjoyable learning activities using embodied learning and animation encourage them to move forward. Second, the friendly virtual character guides the users' attention to the original exhibit. The virtual character encourages them to start interacting with the original exhibit by demonstrating its movement toward and touching the original exhibit in the virtual world. Third, the original physical exhibit, renovated with new external interaction components of tangible interaction and gaming, offers interactive and engaging experiences of learning. Lastly, in the whole process, the virtual character delivers the learning contents and exhibit use guidance through the voice and text on the display.

The design process of upcycling costed a total of $12,000, including for payments for developers and researchers ($9,000), equipment ($2,500), and user studies ($500). It is cost-effective because the cost corresponds to only about 16% of the average development price of $75,000 per physical exhibit. Moreover, future designers could be able to shorten the upcycling design process substantially based on our trial-and-error process and design guidelines presented in Section VI, Discussion.

# V. Final Evaluation

We conducted two field studies in the science museum: (1) an experimental study to investigate the learning experiences of the upcycled exhibit and (2) an observational study to explore the practical effectiveness without intervention from the researchers. A total 152 children with the mean age of 7.26 participated in these final evaluations.

## 5.1 Experimental Study

In this study, we compared the motivation for learning and the learning effect between the upcycled exhibit condition (UPCYCLED) and the original exhibit condition (ORIGINAL).

### 5.1.1 Procedure

We randomly recruited visitors to the science museum to participate in this experiment. We first informed visitors of the purpose and procedure of the experiment. Visitors who agreed to participate signed the consent form. They were invited to use either the upcycled or original exhibit. After they finished experiencing the upcycled or original exhibit, children were asked to complete a survey and take a test about the knowledge they learned respectively from the upcycled exhibit and the original exhibit. Finally, we conducted a semi-structured interview with both children and parents. We asked them what elements of the exhibits were interesting, motivating, and helpful for learning. A video camera recorded the actions and conversations of the participants and their interviews. As a token of appreciation, the participants received science museum souvenirs (worth approximately USD 2).

### 5.1.2 Participants

Twenty-five children participated in ORIGINAL (4-11 y/o; M=6.92; 12 females) and twenty-four participated in UPCYCLED (4-11 y/o; M=6.71; 9 females) in a between-subjects design. The maximum age of the participants was limited to 11 years because students in the authors' country learn the original exhibit's content at the age of 12, according to the official curriculum from the Ministry of Education. There were no significant differences in age ($F(1, 47) = 0.16$, $p = 0.6889$) and gender ($\chi^2(1) = 0.55$, $p = 0.4578$) between the two groups.

### 5.1.3 Data Analysis

To measure the motivation for learning, we adapted the questionnaire from the Modified Attitudes towards Science Inventory (mATSI) [59], as follows. Children answered these questions on the child-friendly 5-Likert scale [60].

- Learning about blood flow is something that I enjoy very much.
- I have a real desire to learn about blood flow.
- Blood flow is one of my favorite science concepts.
- I would like to read something on blood flow that has not been assigned to me.

The knowledge test contained eight T/F questions that were similar to those used in the design process. The first four questions (Q1-Q4) were about the circulatory system, vessel, heart location, and heart role, respectively, and related to the prior knowledge provided by the virtual companion of the upcycled exhibit. The latter four (Q5-Q8) were about the blood flow direction in the artery, the role of blood in the artery, the blood flow direction in the vein, and the role of blood in the vein, respectively, and related to the contents of the original exhibit.

Table 5.1: Comparison of the learning effects between the original and upcycled exhibits in the experimental study.

| | Prior Knowledge | | | | | Original Learning Contents | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | Q2 | Q3 | Q4 | Overall | Q5 | Q6 | Q7 | Q8 | Overall |
| ORIGINAL | 48% | 64% | 52% | 60% | 56% | 40% | 80% | 36% | 12% | 42% |
| UPCYCLED | 71% | 79% | 83% | 67% | 75% | 58% | 83% | 75% | 38% | 64% |
| $\chi^2(1)$ | 2.64 | 1.38 | 5.47 | 0.23 | 6.99 | 1.65 | 0.09 | 7.53 | 4.31 | 8.27 |
| p-value | 0.104 | 0.2401 | **0.0194**$^*$ | 0.6284 | **0.0050**$^{**}$ | 0.1994 | 0.7632 | **0.0061**$^{**}$ | **0.0380**$^*$ | **0.0024**$^{**}$ |

The participants could learn the original educational content in both conditions, but only the upcycled exhibit provided the prior knowledge.

### 5.1.4 Results

**Motivation for Learning** A one-way between-subject ANOVA was performed on the average scores of the four motivation questions. The result showed that the motivation in UPCYCLED ($M = 3.95$, $SD = 0.80$) was significantly higher than in ORIGINAL ($M = 3.37$, $SD = 0.91$; $F(1, 47) = 5.51$, $p = 0.0232$).

**Learning Effect** We performed a Chi-squared test on the correct rates of each T/F question. The results are summarized in Table 5.1. For all the four questions (Q1-Q4) related to prior knowledge, UPCYCLED had higher correct rates than ORIGINAL, but it was significant only for the question regarding the heart location ($\chi^2_{Q3}(1) = 5.47$, $p_{Q3} = 0.0194$). The overall correct rate of the four questions was significantly higher in UPCYCLED than in ORIGINAL ($\chi^2(1) = 6.99$, $p = 0.0050$).

Similarly, UPCYCLED had higher correct rates for all the four questions (Q5-Q8) about the educational contents of the original exhibit than ORIGINAL, but it was statistically significant only for the two questions (Q7 and Q8) regarding the vein ($\chi^2_{Q7}(1) = 7.53$, $p_{Q7} = 0.0061$; $\chi^2_{Q8}(1) = 4.31$, $p_{Q8} = 0.0380$). The overall correct rate for the four questions was also significantly higher in UPCYCLED than in ORIGINAL ($\chi^2(1) = 8.27$, $p = 0.0024$).

Additionally, we analyzed the correlation between the correct rates and the participants' age. There was no clear correlation between the age and the scores of the two learning contents (prior knowledge: $r(23) = 0.19, p = 0.3475$, original learning contents: $r(23) = 0.05, p = 0.8304$) in ORIGINAL. However, in the case of UPCYCLED, there were positive moderate correlations with both contents (prior knowledge: $r(22) = 0.55, p = 0.0045$, original learning contents: $r(22) = 0.48, p = 0.01650$).

## 5.2 Observational Study

A science museum is an informal learning space without any restrictions. The upcycled exhibit must be effective by itself without any intervention from the researchers. Thus, we unobtrusively investigated the practical effectiveness of the upcycled exhibit (UPCYCLED) in terms of attraction, engagement, and enjoyment in comparison to the original exhibit (ORIGINAL).

### 5.2.1 Procedure

We installed cameras and voice recorders around the tested exhibits with a "recording" sign. Then, we recorded the visitors' behaviors and conversations around the exhibits. ORIGINAL was recorded for 12 days including 3 holidays, and UPCYCLED for 3 days including 1 holiday.

### 5.2.2 Participants

From each video, we counted the number of visitors entering the exhibition room and the number of exhibit users. As the two exhibits had different characteristics, we considered a child who stopped and saw or touched the original exhibit for more than 1 s as a user for ORIGINAL. We regarded a child who directly interacted with the upcycled exhibit as a user for UPCYCLED. In UPCYCLED, 233 children entered the room, and 84 (estimated age: M=7.48, SD=2.42; 38 females) used the upcycled exhibit. In ORIGINAL, 515 children entered the

Table 5.2: Children's behaviors of engagement and enjoyment in the experimental and the observational study. *Italic texts* indicate behaviors that are unique to one exhibit.

| | | Upcycled Exhibit | Original Exhibit |
|---|---|---|---|
| Engagement | Level 1. Passive contact | Look at the physical body model<br>Listen to explanations from family or friends<br>*Watch or listen to the virtual contents* | Look at the physical body model<br>Listen to explanations from family or friends |
| | Level 2. Active manipulation | Touch the physical body model<br>Answer questions from family or friends<br>Express positive emotions<br>*Move their body while looking at their avatar on the screen*<br>*Manipulate UIs or perform tasks* | Touch the physical body model<br>Answer questions from family or friends<br>Express positive emotions<br>*Look at the text description* |
| | Level 3. Exploratory behavior | Touch their own hearts or vessels voluntarily<br>Touch the physical body model voluntarily in the direction of blood flow<br>Ask or explain the learning contents | Touch their own hearts or vessels voluntarily<br>Touch the physical body model voluntarily in the direction of blood flow<br>Ask or explain the learning contents<br>*Read the text description* |
| Enjoyment | | Smiling, laughing audibly, *dancing, jumping, clapping, over-acting, running in place* | Smiling, laughing audibly |

room, and 19 (estimated age: M=7.47, SD=3.02; 11 females) used the original exhibit. We attempted to gather as many users in ORIGINAL as in UPCYCLED, but doing so was very difficult for ORIGINAL; a simple estimate is that it would have required approximately 40 more days of data collection, as an average of 1.6 visitors used the original exhibit per day.

### 5.2.3 Data Analysis

To measure how each exhibit attracts visitors effectively, we calculated a capture rate, which is the number of exhibit users divided by the number of visitors who entered the exhibition hall.

We classified children's behaviors into three levels of engagement. We adapted the coding schemes used in Van Schijndel et al. [61] and Rennie and Howitt [62] to our exhibits, as shown in Table 5.2. Engagement level 1, called passive contact, refers to a starting point in learning, which is not yet specific or dynamic behavior. Engagement level 2, called active manipulation, refers to specific activities that are determined based on actions and the outcomes of those actions. Children in 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 are more committed to meaningful learning.

Two researchers in our team classified the users' behaviors as observed in the videos, counted the number of children, and measured the duration of each behavior, as in [42, 61, 62]. They used videos from the experimental study to make an initial coding rule and then adjusted the details to arrive at the final coding rule. Their final video coding results for the observation study were highly consistent with a high intraclass correlation coefficient (ICC) [63] of 0.97.

Similarly, we adapted the method used in Bai et al. [64] to measure how much the children enjoyed the exhibits. This method recorded the type and duration of expressive behaviors for positive emotions, such as smiling, cheering, and clapping. The two evaluators also classified the participants' behaviors of positive emotions, counted the number of participants who showed each behavior and measured the duration of the behavior. The two evaluators practiced using the videos from the experimental study and then achieved a high ICC of 0.97 for the videos of the observational study. The final coding rules for engagement and enjoyment are described in Table 5.2.

### 5.2.4 Results

**Attraction** Data about the attraction of ORIGINAL and UPCYCLED are summarized in Table 5.3. The capture rate of ORIGINAL was 3.69%, computed from the 19 children who used the original exhibit out of 515 children who entered the exhibition room. UPCYCLED showed a 9.54 times higher capture rate of 36.05%. Out of the 233 children who entered the exhibition room, 84 were captured by the virtual companion of the upcycled exhibit. Among the 84 children, 38 (45.24%) interacted with the augmented original exhibit. In addition, none of the passers-by observed the users using the original exhibit, whereas 29 passers-by observed

Table 5.3: Numbers of visitors interacting with the original and upcycled exhibits in the observational study.

| ORIGINAL | Enter | Using Original Exhibit | |
|---|---|---|---|
| (12 days) | 515 | 19 (3.69%) | |
| UPCYCLED | Enter | Captured by Virtual Companion | Using Original Exhibit |
| (3 days) | 233 | 84 (36.05%) | 38 (16.31%) |

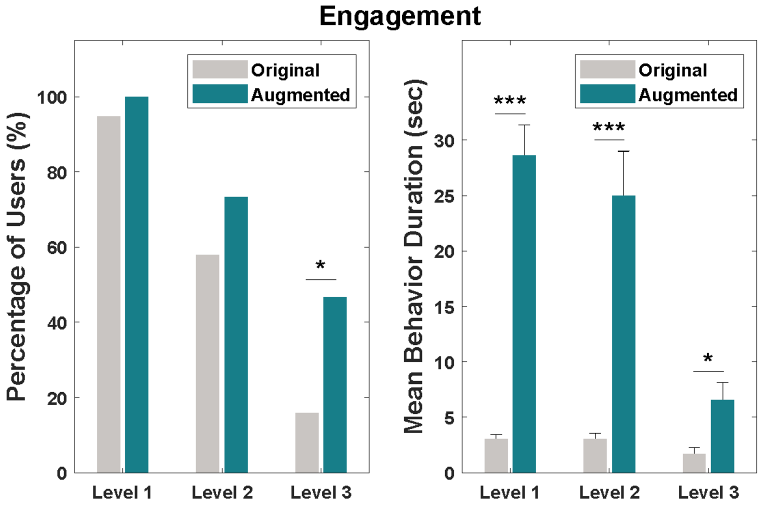


Figure 5.1: Comparison of engagement between the original and upcycled exhibits in the observational study; (left) percentage of users who showed behaviors of each engagement level; (right) mean behavior duration at each engagement level.

the users using the upcycled exhibit.

**Engagement** We compared the engagements of visitors between UPCYCLED and ORIGINAL in Fig. 5.1. At all engagement levels, the durations in UPCYCLED were significantly higher than in ORIGINAL according to Welch's $t$-test ($p_{level1} = 0.0000$, $p_{level2} = 0.0000$, $p_{level3} = 0.0105$). The percentage of visitors at every engagement level in UPCYCLED was higher than in ORIGINAL, in particular, with a significant increase at level 3 ($\chi^2(1) = 4.90$, $p = 0.0269$).

We also measured the children's engagement in the virtual companion in UPCYCLED. The times spent at every engagement level were low in the *Vessel*

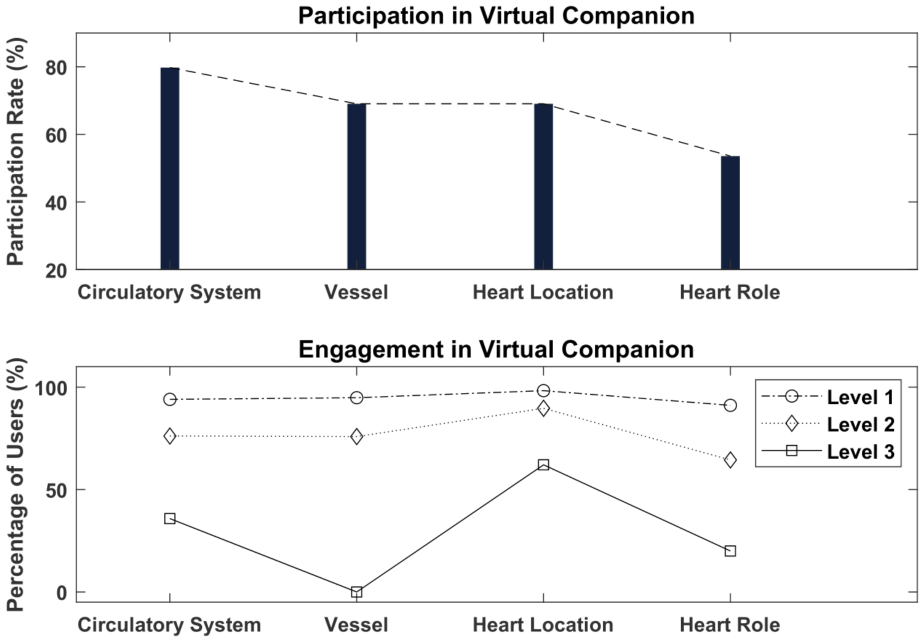


Figure 5.2: Engagement and participation in the virtual companion of the upcycled exhibit in the observational study; (top) percentage of users who participated in each scene; (bottom) engagement of users in each scene.

and *Heart Role* scenes (Fig. 5.2 (bottom)). A similar tendency was observed with the percentage of users who participated in each scene of the virtual companion (Fig. 5.2 (top)). Unlike the other two scenes, the participation rate decreased by 13.43% in the *vessel role* scene and decreased again by 22.41% in the *heart role* scene.

**Enjoyment** We compared the participants' enjoyment between UPCYCLED and ORIGINAL (Fig. 5.3). In ORIGINAL, only 1 of the 19 children (5.26%) expressed positive emotions only for 1 s. In UPCYCLED, 47 of the 84 children (55.95%) expressed positive emotions when interacting with the upcycled exhibit for an average of 15.5 s. All these children danced or smiled while watching their avatars for an average of 15.2 s in the virtual companion. Four of them (8.51%) danced or smiled while using the augmented original exhibit for an average of 3 s.

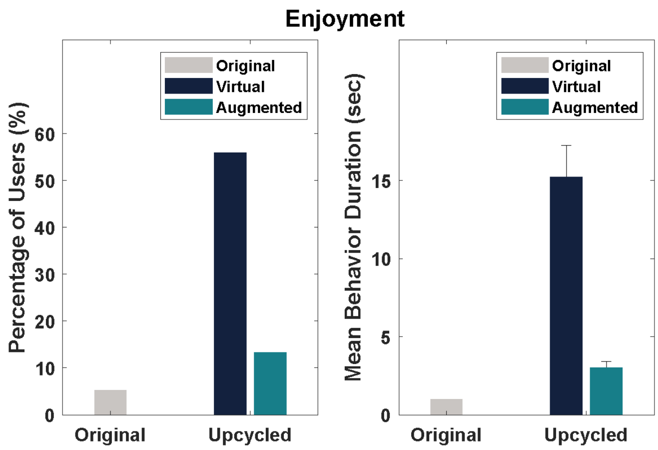


Figure 5.3: Comparison of enjoyment between the original and upcycled exhibits in the observational study; (left) percentage of users who expressed behaviors of positive emotions; (right) mean behavior duration of positive emotions.

Finally, the evaluation results can be summarized as follows. In the experimental study, the motivation for learning in UPCYCLED was significantly higher than in ORIGINAL. UPCYCLED also had higher correct rates for all eight questions than ORIGINAL. Overall, the average correct rate for prior knowledge significantly improved from 56% to 75%, and that for the original learning contents improved significantly from 42% to 64%. The learning effect of UPCYCLED was moderately correlated with the participants' age, which appears to result from children's intelligence development with age [65].

In the observational study, UPCYCLED attracted passers-by more effectively than ORIGINAL. That is, UPCYCLED showed a capture rate of 36.05% , which is 9.54 times higher than 3.69% of ORIGINAL. For engagement, children in UPCYCLED showed significantly longer engaging behaviors at every engagement level. In particular, at level 3, the percentage of users who showed engaging behaviors was also significantly higher than in ORIGINAL. Lastly, children in UPCYCLED expressed various positive emotions, such as dancing, jumping, and over-acting, more frequently for a longer time than in ORIGINAL.

# VI. Discussion

The primary goal of this study was to upcycle an unpopular exhibit to renovate it into a more useful one. In this section, we discuss the final evaluation results and analyze the effects of our design choices. Then, we provide design recommendations for exhibit upcycling by digital augmentation.

## 6.1 Trade-off between Scaffolding and Holding Power in the Virtual Companion

The virtual companion played an educational role by providing or activating prior knowledge about the human circulatory system. By doing so, we assumed that children would be motivated to learn the advanced learning contents of the original exhibit. In our first design, children who interacted with the virtual companion showed high motivation scores for learning more about the circulatory system. The experimental study of the final evaluation also showed that the upcycled exhibit significantly increased the motivation level of children. Some participants said, "*I didn't know much (about the circulatory system) at first, but now I want to know more about the circulatory system.*" Such prior knowledge motivated children and led to a learning scaffold. Some participants who completed the virtual interaction scenario said the following while interacting with the augmented original exhibit: "*There is a heart over there. What flows out of the heart and what flows in?*" and "*The blood goes back to the heart!*" These instances imply that the prior knowledge about the heart's location led to a concrete understanding of the blood flow.

However, some users stopped at informative scenes, especially at the *Vessel* and *Heart role* scenes (Fig. 5.2). Because these scenes focused on explaining prior knowledge via educational animations, children were observed to be less interactive. It is well known that low interactivity decreases the attracting and holding power of exhibits [66, 6]. This implies a trade-off between holding power and educational value in our virtual companion.

## 6.2 Educational Efficacy of Embodied and Tangible Interaction

The virtual companion increased the correct answer rates of all four questions about prior knowledge, but the increase was significant only for one question regarding the location of the heart. In the *Heart Location* scene, the user should perform a specific embodied task in which the user touches their left chest, unlike in other scenes where the virtual companion explains the contents through animation. The result is acceptable in that embodied learning is effective under a condition in which movements map onto particular concepts to learn [67, 33].

We also found that children learned the original educational contents better when they used the physical body model as a tangible interface rather than as the original visual display. However, the correct answer rates significantly increased for only two questions regarding the veins for the augmented physical exhibit in the final evaluation. There seemed to be an order effect because the artery scenes always preceded the vein scenes. In the experimental study, the average time spent at engagement level 1 was higher in the artery scenes, and that of level 2 was higher in the vein scenes. It is possible that users became accustomed to using the tangible interface through the artery scenes, and consequently, they could grasp the learning content more effectively in the vein scenes. Therefore, when introducing a tangible interface, we can consider placing easy learning content in front to minimize the degradation of learning experiences.

## 6.3 Multi-User Support for UI Controls

In science museums, children often explore exhibits in groups, for example if they are there on a school trip, with siblings, or simply because they make instant contact with other children at the museum. We observed that, when two or more visitors used the upcycled exhibit simultaneously, the main user who had the right to control the UI used the exhibit actively, while the other users tended to be relatively passively and watch the main user. Considering the nature of science museums where there are many multi-users and the benefits of collaborative learning, the virtual companion should be improved to embrace multi-users. In previous research, Kang et al. [68] presented a whole-body interaction system enabling embodied interaction and collaborative learning to teach the human circulatory and respiratory systems. They designed collaborative activities in which multi-players should move their positions to achieve a common goal. The virtual companion can take collaborative characteristics to control the UIs with multiple users.

## 6.4 Design Recommendations for Exhibit Upcycling Using Digital Augmentation

We finally address how interaction designers can apply our exhibit upcycling experiences to other unpopular exhibits. The following design recommendations can be regarded as specialized ones to exhibit upcycling compared to the many similar recommendations for the digital augmentation of exhibits in general [e.g. 9, 69, 16].

### 6.4.1 Customize the Interaction Steps of an Upcycled Exhibit to the Problems of an Original Exhibit

Our upcycled exhibit has three steps of interaction: 'Introduction by the virtual companion,' 'Transition to the original exhibit,' and 'Tangible interaction with the original exhibit.' Each step deals with some of the three problems of the unpopular original exhibit. For example, an avatar mirroring a user's movement resolves the problem of low interactivity; providing prior knowledge alleviates the problem of complex learning concepts; and modality augmentation by tangible interaction with the original exhibit improves the problem of abstract information presentation.

Other unpopular physical exhibits may have all the three problems or some of them, and interaction steps with virtual companions should be designed accordingly. All three interaction steps may have to be pursued similarly, or only some of them can be sufficient. We still recommend that the designers include at least the first two steps, which can be crucial to attract visitors and direct their attention to the original exhibits empowered by rapidly evolving interactive technologies.

### 6.4.2 Design and Implement an Attractive Virtual Companion

In our case study, we demonstrated the effectiveness of showing or mirroring the appearances and movements of users in attracting passers-by. This luring step should be tailored to the characteristics of the original exhibit for upcycling. According to Boisvert and Slez [6], concrete exhibits that can be experienced through seeing, hearing, or touching are highly attractive, and such high interactivity is a key for holding the visitors. For instance, for an exhibit demonstrating the principle of electromagnetic field, visualizing the invisible field within or around the coil using AR has a good chance to attract users. If the real-time changes of the magnetic field is also visualized when the user relocates the coil, it can improve the visitor-holding power.

### 6.4.3 Provide Prior Knowledge or Examples for Scaffolding

Our virtual companion first presents prior knowledge concepts to users to deliver the difficult concepts in the human circulatory system explained in the original exhibit more easily and also motivate the users to explore the learning topic. If an original exhibit for upcycling contains complex concepts, examples in our daily life or analogies can be an alternative of the prior knowledge. For example, for an exhibit explaining the principle of a lever, the virtual companion can remind the users of the experience of a seesaw or show it as virtual content to increase the interest and understanding of children.

### 6.4.4 Provide Affordance for Transition

According to our experiences in this case study, a transition from the virtual companion to the original exhibit can be done by making children imitate someone familiar to them. Another option for inducing the transition is to rely on affordance. The type of affordance depends on the content of the virtual companion. If a virtual companion has a specific sound source that provides dominant experiences, a rhythmical change or sound source relocation can be effective in inducing the attention transition [70].

### 6.4.5 Augment Embodied Interaction to an Original Exhibit

The last third step is to augment the original exhibit by adding new interaction modalities, preferably using simple and inexpensive means. For example, we can easily upgrade physical objects to tangible interfaces using a camera as an external sensor, as showcased in this paper. If the physical exhibit should not be touched, superimposing additional content on the exhibit and enabling interaction with that augmented information can be a good alternative. Schmidt et al. [71] projected explanations and a 3-dimensional model of a dinosaur on its physical skeleton exhibit using AR glasses. In this case, we can design embodied and tangible interactions by showing a description for the corresponding body part of the dinosaur when the user touches his or her own body.

# VII. Conclusion

In this case study, we have presented a concept of *exhibit upcycling* that reuses an unpopular physical exhibit to create an attractive and useful exhibit by extending the original exhibit with a digital companion. To develop effective upcycling strategies, we selected an existing exhibit, Blood Flow, in a local science museum, identified problems with users, set design directions and goals with experts, and iteratively designed upcycled exhibits. We added embodied interaction elements based on motion mirroring to resolve the low interactivity problem and provided prior knowledge and tangible interaction in the original exhibit to solve the problems of a complex concept and abstract presentation.

The design output consists of three steps of interaction: interaction with the virtual companion, transition, and interaction with the original exhibit (possibly in a new learning modality). In the final field evaluation, we demonstrated that our approach and designs could effectively attract visitors and enhance their learning experiences, including engagement and positive emotions. Through this case study, we shared design strategies found to be effective in solving certain problematic factors of unpopular exhibits and our hands-on experiences.

We can easily find unpopular exhibits that no longer attract visitors' attention in science museums. It can be due to some inherent problems of the exhibits or the ever-rising expectations of children over time. Replacing them with brand-new exhibits is a straightforward solution, but not every museum can afford it. Exhibit upcycling using digital augmentation can be a good alternative, as it is cost-effective and resource-preserving. If well-designed, upcycled exhibits can be as effective as new ones in attracting visitors and enhancing their experiences, as demonstrated in this case study. We expect our approach to be easily applied to other unpopular physical exhibits and enrich public learning opportunities for children.

# 요 약 문

과학관 전시물은 관람객의 관심을 끌고 흥미를 유발할 수 있어야 하지만 이를 잘 해내지 못하는 비인기 전시물이 항상 존재해왔다. 본 논문에서는 사용도가 낮은 물리적 전시물을 재사용하여 더 나은 전시물을 만드는 실용적인 접근 방식으로서 전시물 업사이클링을 제안한다. 개념 증명을 위해 사례 연구로 지역 과학관의 오래된 물리적 전시물을 선택하여 업사이클링 진행했다. 사용자 중심적 반복적 디자인 과정을 통해 물리적 전시물과 동반되어 보다 상호작용적이고 즐거운 학습 경험을 제공하는 가상 동반자를 설계했다. 과학관에서 진행된 현장 평가를 통해 업사이클링은 전시물의 견인력을 9.54배 증가시켰으며, 사용자의 학습 경험, 참여도 및 즐거움을 크게 향상시키는 것을 보였다. 이러한 연구 결과는 인기가 적고, 오래된 전시물을 활용하여 물리적 전시물과 디지털 전시물의 고유한 장점을 결합하는 새로운 디지털 증강 방법의 잠재력을 보여준다.

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석사 과정과 학위 논문을 마무리하며 이렇게 감사의 글을 쓰니 감회가 새롭습니다. 지난 4학기 동안 많은 시행착오들이 함께 했지만, 그 과정에서 새로운 배움을 얻는 것은 항상 즐거웠습니다. 조금이라도 더 많이 가르쳐주시고 도와주시려고 했던 교수님과 배움과 연구에 대한 열의가 가득했던 연구실 구성원분들 덕분에 지금까지 올 수 있었습니다. 그 감사함을 조금이나마 이 지면을 통해 표현하고자 합니다.

우선 2년의 석사 과정 동안 학문적으로 정신적으로 보살펴 주시고, 연구 진행의 처음부터 끝까지 전체적인 틀에서부터 세심한 부분까지 논리적인 사고로 성심성의껏 지도해 주신 최승문 교수님 감사드립니다. 연구 진행이 원활하지 않아 낙담하던 순간들에서도 항상 해결책을 함께 고민하며 아낌없이 격려해 주셔서 연구와 논문을 잘 마무리할 수 있었습니다. 이곳에서 배운 교수님의 귀중한 가르침에 부끄럽지 않도록 저 또한 끊임없이 배움을 놓지 않고, 세상에 도움이 될 수 있도록 노력하겠습니다.

연구실 생활에서 항상 큰 의지가 되어준 연구실 구성원분들 감사합니다. 학업과 학위 과정도 의미가 있었지만, 이렇게 좋은 분들을 만날 수 있었던 것 또한 제게 감사한 일 입니다. 항상 장난치며 먼저 다가와서 격려해준 21학번 동기 재준, 정우, 정은 누나, 항상 좋은 조언을 해주고, 살갑게 대해준 호준이형, 상윤이형, 겨레형, 적극적으로 이야기를 들어주고, 항상 친절하게 도와주었던 승재형, 채용이형, 동근이형, 석사 선배로서 졸업과 졸업 후 진로에 대해 아낌없이 조언해준 지완누나, 민재, 진수형, 학위 과정을 즐거움으로 채워준 준우형, 호석이형, 재혁이형, 희연이, 그리고 마지막으로 석사과정의 모든 산전수전을 함께해주고, 항상 솔선수범해주었던 다진 누나, 모두 감사합니다.

사랑하는 제 가족들에게 감사를 전합니다. 항상 배움과 도전의 자세를 놓지 않고 본이 되어 주시는 아버지, 건강을 걱정해주시고 따뜻한 말로 품어주시는 어머니, 할머니, 부족한 동생에게 다가와 다독여주는 형 모두 감사드립니다. 그리고 모든 학위 과정에서 제 옆에서 함께 고민하고, 웃으며 제 버팀목이 되어준 여자친구 채은이,

채은이의 남은 박사 학위 과정에서 저 또한 버팀목이 되어줄 수 있도록 노력하겠습니다.

마지막으로, 지면에 다 표현하지는 못하였지만, 석사 과정 2년 동안 힘이 되어준 모든분께 감사를 전하고 싶습니다. 그 고마움을 잊지 않고 차근차근 전하겠습니다.

# Curriculum Vitae

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## Education

2016. 3. – 2021. 2. Department of Computer Science and Engineering,Ulsan National Institute of Science and Technology (B.S.)

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## Experience

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