Practice Report

Introduction of 3D Printing Technology in the Classroom for Visually Impaired Students

Wonjin Jo, Jang Hee I, Rachel Ananda Harianto, Ji Hyun So, Hyebin Lee, Heon Ju Lee, and Myoung-Woon Moon

As the importance of visual aids increases, textbooks are including more figures and images to help with students' understanding. These visual aids enable students to learn concepts more effectively by hearing and seeing them simultaneously. However, for students who are visually impaired (that is, blind or have low vision), reading and understanding a textbook poses challenges. Teachers of students who are visually impaired have difficulty teaching with textbooks because they are compelled to explain and describe the complex figures and content verbally. Even after being explained, the image or concept might still remain nebulous for the student. Therefore, to help both students and their teachers, instructional materials should be prepared with easy, cheap, and customizable methods such as three-dimensional (3D) printing. Instead of seeing and hearing, students can use their sense of touch to recognize the 3D tactile aids, which might improve their learning and memory processes.

Recently, 3D printing technology has emerged as an exciting technological tool for creating sophisticated and custom-made objects with relatively low-cost materials (Melchels, Feijen, & Grijpma, 2010; Peltola, Melchels, Grijpma, & Kellomäki, 2008; Pham & Gault, 1998). 3D printing is the process of fabricating 3D objects by building up materials layer by layer with a specific layer thickness in the range of 100 to 400 micrometers (μm). The most important advantage of 3D printing is its ability to build new objects in a customized way. Thus, 3D printing can be a powerful tool to make tactile patterns or objects related to textbooks. Stangl et al. tried to make 3D-printed picture books for visually impaired children (Stangl, Kim, & Yeh, 2014). They transcribed the images of the classic book *Goodnight Moon*, by Margaret Wise Brown, by printing features with different plastic layers. However, this study presented only plane-based shapes and not complete 3D objects.

In this research, we investigate how 3D printing technology could be utilized for instructional materials that allow visually impaired students to have full access to high-quality instruction in history class. Researchers from the 3D Printing Group of the Korea Institute of Science and Technology (KIST) provided the Seoul National School for the Blind with tactile instructional materials and resizable braille made by 3D printers as shown in Figure 1. The teacher provided side-by-side hands-on instruction to guide students in understanding the characteristics of the shapes and their meanings. Students also used their hands to independently explore the 3D materials, allowing them to appropriately feel the historical pictures, maps, or relics. This procedure reinforced delivery of the lecture immensely since it clarified potential misunderstanding of text descriptions. The resulting implication was that the 3D instructional materials were beneficial and more suitable to help visually impaired students successfully comprehend content taught in the classroom.

Methods

Three different types of 3D printing methods were utilized: (1) fused deposition modeling (FDM); (2) three-dimensional printing (3DP);

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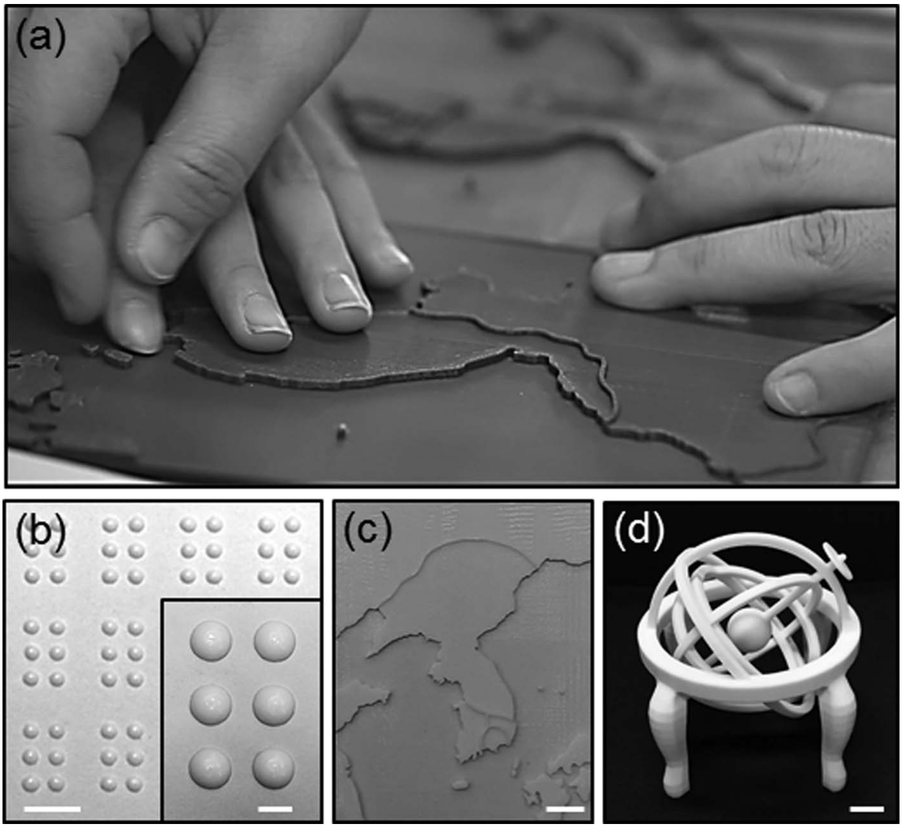

Figure 1. (a) A teacher and a student using the 3D printed tactile instructional map in the fifth-grade classroom of the Seoul National School for the Blind. (b–d) Examples of the 3D printed tactile instructional materials: (b) two differently sized braille patterns, (c) a tactile map, and (d) a historical relic. The scale bars are (b) 5 mm and (c–d) 2 cm.

and (3) digital light processing (DLP). The 3D printing process involves multiple stages, as shown in Figure 2. All 3D printing techniques are based on the use of computer-aided design (CAD) information that describes the geometry and size of the objects to be printed. The CAD data is converted to an STL (STereoLithography) file format which has extensive triangular coordination of 3D surface geometry (Chen, Ng, & Wang, 1999). Once the file is in a printable format, the 3D model is sliced into a series of digital cross-sectional layers of specific thickness. Then the designed structure is built through a layer-by-layer fabrication process with each layer thickness being 100 μm. When the printing is completed, the last step involves post-treatment operations to the object to improve its softness, durability, and safety. In that step, we used the biologically compatible material PLA (polylactic acid, a biodegradable thermoplastic) for the FDM method. The thermal reflow process was conducted for significant improvement in surface smoothness of the objects made by the FDM 3D printer (Jo, Kim, Lee, Lee, & Moon, 2014). In the case of the 3DP and DLP methods, printed objects were coated with a varnish solution that is a nontoxic product made with odorless, environmentally friendly material.

The 3D instructional materials produced were provided for use in a history class for one semester. A group of four fifth-grade students from the Seoul National School for the

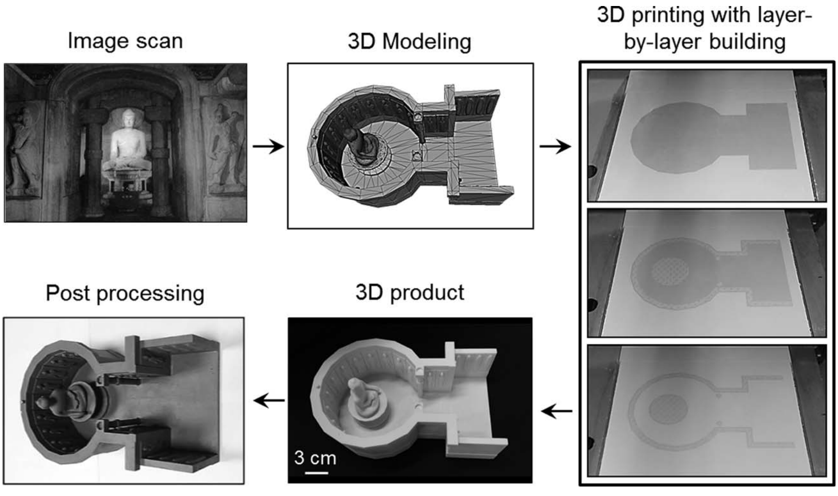

Figure 2. The multiple stages of the 3D printing process.

Blind participated in the project. Their visual conditions, learning aptitude, and primary medium of reading and writing are described in Table 1. The social studies textbook selected covers the history of Korea from the prehistoric age to the 20th century (Korean Ministry of Education, 2014). In this study, we created 11 different historical maps and 27 sets of relics by converting the plane images from the original textbook into 3D materials. The images selected by the teacher were determined based on aspects such as their his-

Table 1
Information on the participants in the study.

Variable	Participant A	Participant B	Participant C	Participant D
Visual condition	4th-degree visual impairment; aniridia; 24pt font is readable	1st-degree visual impairment; congenital retinal damage	1st-degree visual impairment; congenital corneal opacity; weak eyesight due to 5 eye surgeries; 40pt font is readable	1st-degree visual impairment; Norrie disease, both eyes are artificial; total blindness
Learning aptitude	Good vocabulary, comprehension, and judgment; weak memorization	Very weak vocabulary and comprehension	Good comprehension; weak vocabulary	Weak vocabulary and comprehension
Literacy aptitude	Able to read and understand the meaning of sentences at the appropriate speed; able to write his thoughts in a diary accurately despite many spelling errors	Able to read, take dictation, and write braille in syllabic units; able to write a diary entry of 5 sentences	Able to read, listen, and write braille in word-phrase unit; able to write a diary entry in simple form	Able to read sentences in braille with ease; able to take dictation exactly; able to write his thoughts in a diary

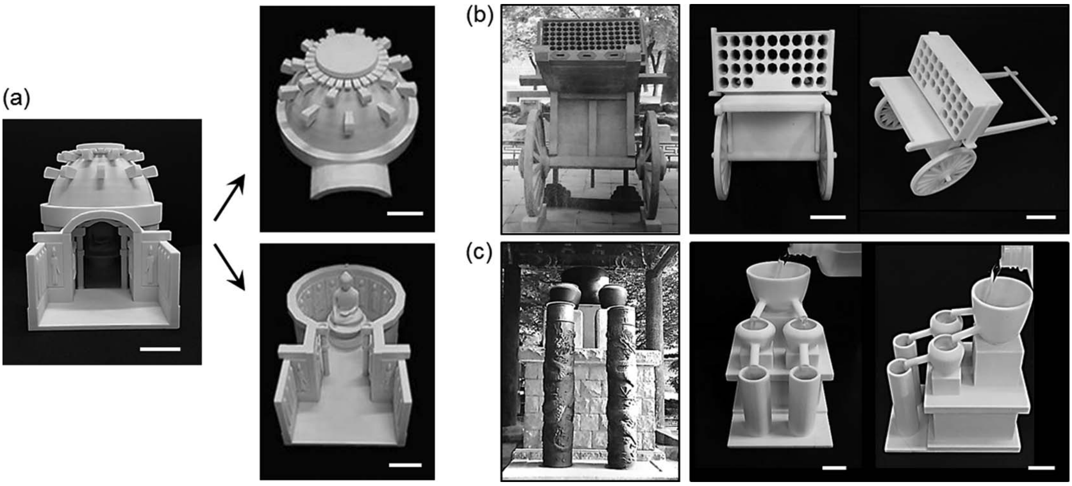

Figure 3. 3D versions of: (a) Buddhist grotto, Seokguram; (b) multiple rocket launcher, Hwacha; and (c) rain gauge, Cheugugi. The scale bars are 4 cm.

torical value and importance, difficulties of buying reproductions of them, or site access limitations. The institutional review board of KIST approved the process before the 3D tactile instructional materials were shown to the students of the Seoul National School for the Blind.

Results

One advantage of 3D printing technology is its ability to create customized materials for visually impaired students who have different visual conditions and acuities, learning aptitude, and cognitive abilities (as shown in Table 1). Therefore, we first discussed with the teacher the optimal size and level of detail of the objects based on the recognition ability of the students. As a result, most 3D printed objects were simplified to highlight only core features. For instance, political maps should clearly show territorial borders to depict the relationships among dynasties that existed on the Korean peninsula, but the existing tactile figures made by other methods are limited to highlighting the relationships between regions. These other methods describe borders using braille patterns or by drawing each region with complicated patterns or differently textured fabric. In contrast, the 3D instructional materials can easily be configured to characterize the maps based on the different heights of the plastic contours, as shown in Figure 1. Similarly, 3D printing can translate murals, paintings, or distinctive patterns using a variety of fabrication options such as an embossing technique.

3D printing can also scale down large original relics. When a monument is massively sized, students are unable to comprehend it on site. Figure 3(a) shows the 3D printed Seokguram Buddhist grotto, which was divided to reveal its inner and outer architectures. Seokguram's inner architecture leads into the rectangular antechamber, the narrow corridor, and then finally the round main chamber in which the Buddha statue, more than 362 centimeters in height, is seated. Figure 3(b) shows the original photograph and 3D printed Korean rocket launcher, Hwacha. It contains 100–200 cylindrical holes that simultaneously fire rockets. Students learned about its mechanism using the 3D printed Hwacha and wooden sticks. Figure 3(c) presents the Korean rain gauge Cheugugi. The 3D Cheugugi was built to show how its different levels are connected by channels to prevent an overflow

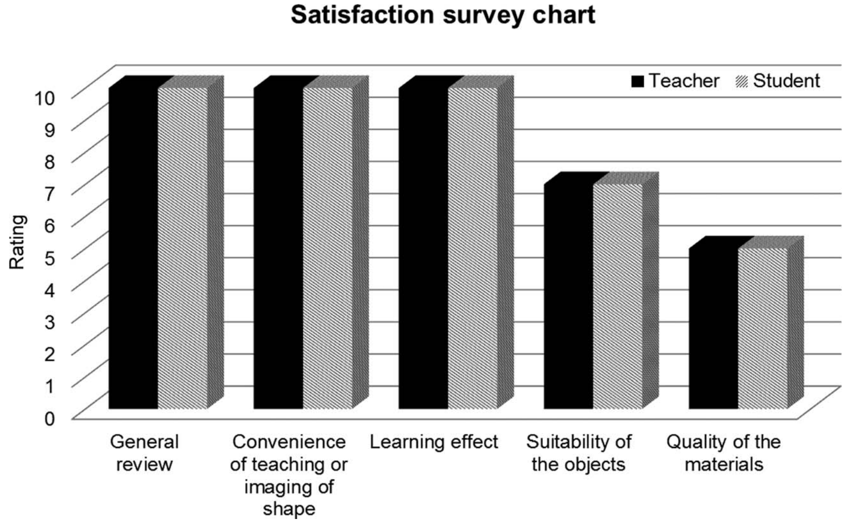

Figure 4. Satisfaction survey chart for the 3D printed tactile instructional materials evaluated by the teacher and students.

of rainfall. Through these 3D objects, students were better able to learn about and appreciate the historical culture of Korea.

We should note that 3D printing cannot represent all images effectively due to the limitations of printing materials and methods. Even though materials have been rapidly developed, the commonly used materials are still limited to plastic, powder, resin, or metal. In addition, sharp or thin structures are difficult to print and easy to break because of insufficient mechanical strength. Therefore, we considered carefully, from the design step forward, the material and structural characteristics and ease of production.

Discussion

After the semester ended, the participants evaluated the effectiveness of the 3D tactile instructional materials based on several criteria, as shown in Figure 4. Both students and teachers acknowledged the importance and usefulness of the 3D materials. The survey showed that students highly valued the 3D objects, since using them improved their memorization and understanding. Although it is still difficult to comprehend the actual size of historical relics, students claimed that the 3D materials delivered a good sense of the shapes and helped to clarify obscure meanings in the textbook. Furthermore, the 3D materials brought liveliness and amusement to the classroom. The teacher stated that the 3D instructional materials enabled her to improve her teaching effectiveness, since the materials enriched the lecture content. Previously, it was difficult for her to describe or explain the historical meaning behind maps or relics using words alone. Although students often felt it hard to grasp the oral explanation, they were better able to understand with the use of 3D materials. The 3D instructional materials directly stimulated the students' imagination and reinforced their understanding and capacity for memorization. It was also effective in maintaining students' interests during class by allowing them to touch the materials continuously.

The survey results revealed that the teacher and students identified potential areas for improvement, including: (1) determining the optimal size and details of the materials to reduce misunderstanding about actual shapes; (2) enhancing the surface smoothness and durability; and (3) developing more diverse and safer materials with different tactility. Furthermore, providing a 3D printer and its materials at an affordable cost is one of the primary obstacles to 3D printing technology in the education field. And we should note that the survey of teacher and student perceptions shown in Figure 4 provided subjective feedback and that an assessment of student outcomes (for example, with a control group) was not within the scope of the study. Satisfaction research favorably supports the attitude of people who used the materials, but it is based on user opinions and does not necessarily demonstrate a difference in the amount or quality of learning.

Conclusion

We have introduced 3D printing technology to make 3D tactile instructional materials of maps and historical relics that appear as images in textbooks such as a rain gauge, bell, and fortress. We fabricated the 3D tactile instructional materials in appropriate sizes and details. We also used biologically compatible materials for the FDM method, and used varnish coating on the objects fabricated with 3D printing techniques of 3DP and DLP. In the classroom, the 3D materials had a positive impact on both teaching and learning. Although the students and teacher who participated in this project indicated that the material properties and robustness of the 3D printed objects should be improved for further application, they strongly acknowledged the various benefits of 3D tactile instructional materials, including reinforcement of abstract points and content, an increase in students' retention, and the enhancement of students' attention and concentration during class. From this project, we have learned that 3D printing technology could be adapted to other classes such as art, mathematics, or science. A survey of the opinions of four students at one grade level in one type of academic setting may be limited in the generalization of the value of using 3D tactile instructional materials, and it is therefore recommended that additional studies and surveys be made to gather more data related to this study. Demand will grow for appropriate instructional materials for visually impaired students, and 3D printing technology has the potential for helping teachers and students due to its customized and versatile communication method. However, there are several aspects of 3D printing—such as difficulties in design and cost; length of time for fabrication; and limited materials for building diverse 3D objects—that point to the need for improvement in order for this technology to have a wider application.

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Wonjin Jo, Ph.D., *post-doctoral student, 3D Printing Group, Computational Science Research Center, Korea Institute of Science and Technology, 135-791, Seoul, Republic of Korea; e-mail: <wjjo@kist.re.kr>.* ***Jang Hee I, B.S.,*** *master's student, Korea Institute of Science and Technology, 3D Printing Group, Computational Science Research Center, Korea Institute of Science and Technology, 02792, Seoul, Republic of Korea; e-mail: <jhikist@gmail.com>.* ***Rachel Ananda Harianto, B.S.,*** *master's student, Korea Institute of Science and Technology, Seoul, Republic of Korea; e-mail: <514006@kist.re.kr>.* ***Ji Hyun So, B.S.,*** *master's student, Korea Institute of Science and Technology, Seoul, Republic of Korea; e-mail: <chreesteen@gmail.com>.* ***Hyebin Lee,*** *undergraduate student (senior), Kookmyung Women's University, Korea Institute of Science and Technology, Seoul, Republic of Korea; e-mail: <god-6007@hanmail.net>.* ***Heon Ju Lee, Ph.D.,*** *senior research scientist, Korea Institute of Science and Technology, Seoul, Republic of Korea; e-mail: <hlee@kist.re.kr>.* ***Myoung-Woon Moon, Ph.D.,*** *principal research scientist, Korea Institute of Science and Technology, Seoul, Republic of Korea; e-mail: <mwmoon@kist.re.kr>. Address all correpondance to Dr. Moon.*

