Graphical Tactile Display Application: Design of Digital Braille Textbook and Initial Findings

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Abstract. According to WHO statistics in 2020, there were approximately 253 million visually impaired people worldwide, including 36 million blind individuals. Blind students learn the same knowledge as ordinary students do in their schools, but they lack a lot of graphical and image information as a learning aid. With the development of electronic graphical tactile display, in this paper, a digital version of Braille textbook is proposed and designed. It not only displays the paper-based Braille texts, but also includes related tactile images and illustrations, therefore the blind students can read texts and images in pair. A serial of initial design guidelines and principles for digital Braille textbook are discussed, followed by the five typical design examples. Twelve blind students in a primary school experienced five lessons of digital Braille textbook, and most of them showed positive responses. Our findings pave the way for future work on improving the user experience of tactile interface design that support the learning by digital Braille textbook.

Keywords: visually impaired people · graphical tactile display · digital Braille textbook · design guidelines

1 Introduction

According to the *World Report on Vision* released by the World Health Organization (WHO) in 2020, there were 253 million people with moderate to severe visual impairment in the world, including 36 million people who are totally blind [1]. In China, the *Disability Profile Report* released by China Disabled People's Federation in 2012 announced that the number of visually impaired people was 17.63 million [2]. Meanwhile, according to the *2019 Yearbook of the Ministry of Education of China*, only about 40,000 children with visual disabilities are covered by the national education system [3, 4] and able to enter schools and other institutions for the blind in the whole country. In blind schools, blind students learn the same knowledge as ordinary children do in their schools, including Chinese, mathematics, physics, chemistry, etc. It is known from a comparative study between Braille textbooks and ordinary ones, that texts are basically the same, but most illustrations disappear in Braille textbooks (Fig. 1). Moreover, for

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some graphical knowledge involved in science, it would be reduced or even deleted directly, such as some geometric parts in mathematics and circuit parts in physics. Blind students lack a lot of graphical and image information as a learning aid. They need, but it is hard, to understand what sighted people are learning, which brings them serious challenges to the comprehensive knowledge learning.

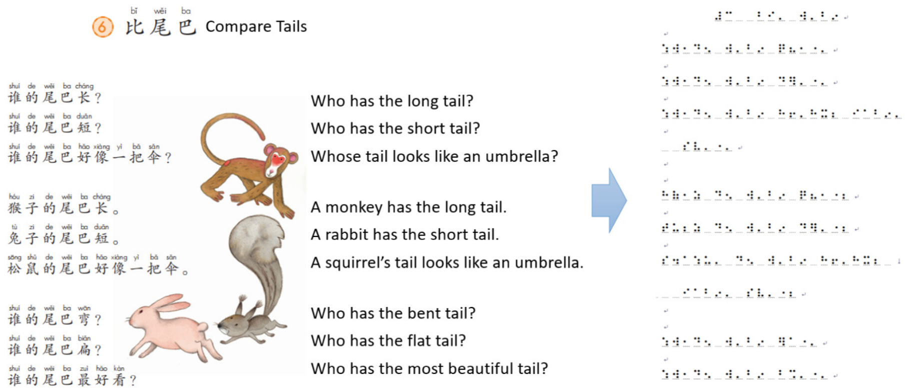

Fig. 1. Comparison of lesson *"Compare Tails"* in ordinary textbook and Braille textbook. Both textbooks are from China People's Education Press and are widely used for the first-grade primary school students.

Besides, apart from Braille reading, blind people can also make use of voice assistant or screen reader software for acquiring text knowledge. However, they extremely lack tools and equipment for learning and understanding graphical information. Typically, in blind schools or Braille libraries, images and pictures are usually handmade with shapeable paper, such as embossing, thermoplastic and braille dot printing, but these methods are expensive and time-consuming. This is one of the main reasons why lots of images and pictures disappear from the Braille textbooks.

In response to this problem, a digital refreshable tactile screen, where the pixels are replaced by tactile pins or dots, can greatly benefit information accessibility for blind people. Recently some graphical tactile display devices have been designed and developed, such as the devices made by Metec.AG, the American Printing House for the Blind and Orbit Research [5]. We also designed and developed a graphical tactile display prototype for the blind [6]. The tactile surface of our device consists of a matrix of 120 by 60 dots that can be raised and retracted dynamically. By controlling these dots through a built-in computing system, traditional pictures can be turned into tactile images. Blind users can read Braille texts and understand images by touching these raised dots (Fig. 2).

Therefore, with the recent development in electronic graphical tactile display devices, now is the time to consider adapting more learning contents, both texts and images to blind people, especially the Braille textbooks for the young blind students in primary and middle schools. We aim to digitize Braille textbooks, and put images and illustrations which are in the ordinary textbooks for sighted people back to blind people's learning contents. In this way, the blind students can read the Braille texts and tactile images

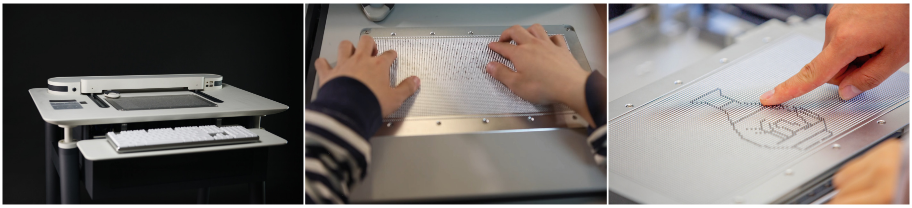

Fig. 2. The graphical tactile display prototype. It can display Braille text and tactile images.

in pair. “A picture is worth a thousand words”, so we believe it can hugely improve information accessibility for these young blind students.

In our research, in order to digitize the Braille textbook and contain the images and illustrations, we made a serial of design principles and methods of Braille textbooks digitalization for a better user experience of Braille textbook learning, followed by several typical design examples of digital braille textbook in Chinese and Mathematics. Then twelve blind students in a primary school were invited to experience our braille textbook demonstrations. Our initial results with twelve participants have been very promising. In the rest of this paper, we present the background for our design research followed by design examples and user evaluations. We conclude the paper for guidelines for effective learning of digital Braille textbook with texts and images in pairs by the electronic tactile display device.

2 Related Work

There is a long history of research on the development of tactile displays as well as Braille and tactile images design as assistive technologies for visually impaired people (e.g., see reviews [5, 15]) that continues to the present day.

Braille is widely used to convey text information for blind people. There are two columns of three dots arranged longitudinally in a Braille cell, with a total of six dots. The distance between each dot is 2.5 mm, and the neighboring Braille cells are 3.5–4 mm apart in order to discriminate each cell. This different spacing standard between dots and cells is valid both in paper-based Braille books and Braille electric displays. However, most of the Braille displays can only show one line of Braille (typically 20 or 40 cells), so the blind can only read a single line of text at a time, which leads to low reading efficiency.

In terms of tactile images, it is urgently needed yet challenging in recognizing and understanding spatial information for blind people. Although the channel capacity of haptics is significantly smaller than that of sight (compared with the sighted people) [13], lots of progresses have been made to assist blind people learn graphical and two-dimensional spatial information [7, 16] summarized several factors affecting tactile images recognition in terms of tactile images design: image geometrical characteristics, image symmetry, image size and perspective. Meanwhile a serial of multi-level coding and quantification scheme criterion [7] was made to evaluate tactile images recognition performance.

In related to tactile interface design with combination of Braille texts and tactile images, one common idea is to keep the conventional interaction paradigm: Window-Icon-Menu-Pointer (WIMP) in graphical user interface (GUI). In this way, a transformation schema from GUI to tactile websites with scalable vector images was developed [8], opening a new way for browsing of web pages for blind people. Further studies begin to focus on the user experience and usability of tactile interface [9] defined four regions segmenting the tactile space to header, body, structure and detail region, while [10, 11] proposed six rectangular regions, allowing the user to perceive the given content at different modes of presentation and levels of detail.

These previous works laid the basis for designing better digital Braille textbook with texts and images in pairs in this paper. Based on the literature, we explored the tactile interface design of digital Braille textbook with the perspective of user experience.

3 Tactile Interface Design of Digital Braille Textbook

In order to achieve good user experience of digital Braille textbook learning, we spitted the design into three parts: typesetting design of Braille texts and tactile images, tactile images design and contextual knowledge learning design. Figure 3 shows the three parts that describe the tactile interface design.

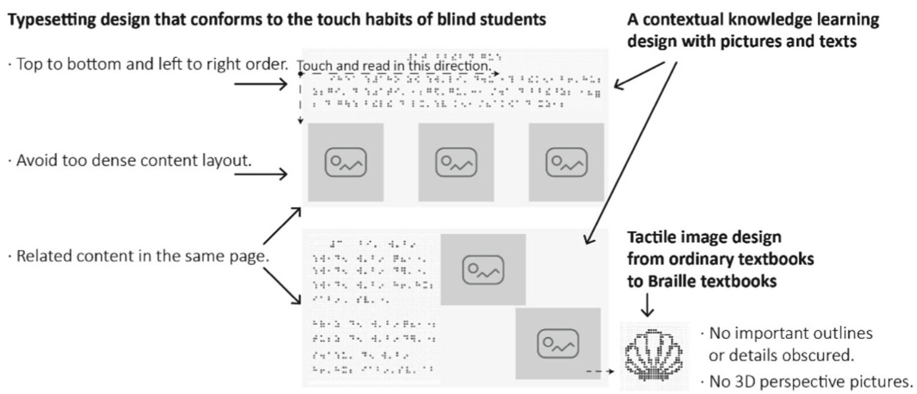

Fig. 3. The three parts that describe the tactile interface design of digital Braille textbook

3.1 Typesetting Design that Conforms to the Touch Habits of Blind Students

At present, the layout of Braille textbook used in blind school is basically the same as that of ordinary textbook. The order of content is both top to bottom and left to right. Such a convention should be considered for showing Braille on the tactile display for the blind.

In the tactile interface with Braille texts and images, several principles should be followed. Firstly, both texts and images should not be arranged too densely due to the much smaller channel capacity of haptics than vision, and the feature of tactile perception would be slow and discontinuous. The interaction design for the blind should be consistent with the concept, metaphors and paradigms of blind users. To make touch-reading easy, improve the accuracy of information expression and avoid causing difficulties or misunderstandings, the principles of Gestalt psychology [14] could be considered to simplify the tactile images in design.

Secondly, relevant content that needs to be read at the same time could be presented on the same page. The discontinuity of tactile perception affects blind people's touch-reading. Relevant content presented should not be separated, so that the reading and thinking will not be interrupted. For example, as the text *Comparing Tails* shows in the fourth example, the images of animals and related paragraphs are arranged on the same page in the Braille version design, so that we can ensure the consistency of the content and facilitates the association and understanding.

Finally, as same as sighted people, the cognitive process of blind people will also be affected by emotions. A touch-friendly layout can help blind people obtain correct information easily and reasonably, enhancing learning confidence and improving learning effect.

3.2 Tactile Image Design from Ordinary Textbooks to Braille Textbooks

To design a tactile image, several principles and methods should be considered to make images recognizable and easy to understand [7] have verified that the effect of tactile recognition can be affected by tactile images' features, including "lines omitted due to occlusion", "Perspective and Viewpoint", "Image Symmetry", "Image Geometrical Characteristic", as well as "Image Size". However, the last three features are about the characteristics of the tactile images themselves, which is difficult to improve the image recognition performance by Braille textbook design.

The other two features, "lines omitted due to occlusion" and "Perspective and Viewpoint", focus on the expression of tactile images, and can make images easy to understand. First, blind people are hard to distinguish the "foreground" and "background", so lines' occlusion affects recognition negatively. Second, their living and cognitive habits of blind people make them unable to understand the perspective relationship of objects well, perspective images would be very difficult to be recognized either.

Based on these two features, we summarized some suggestions on tactile image design:

- Do not obscure the important outlines or details. Keep a complete outline, display important details fully, and avoid confusing the foreground and background. For example, as the text *Understanding 1–5* in the second example shows, images with many animals obscuring each other have been adjusted to a non-overlapping arrangement to avoid misunderstanding.
- Do not use 3D perspective pictures. Parallel perspectives or sections at different angles are suitable ways to present three-dimensional objects. Both two lessons *Zhaozhou Bridge* and *Up and Down, Front and Back*, use single faces of objects to represent them, so that the tactile images would be easy to recognize and understand.

3.3 A Contextual Knowledge Learning Design with Pictures and Texts

Researches of cognitive psychology show that the content of text and images can complement each other, and help learners to integrate visual and language representations psychologically, thereby promoting good understanding of learners or the generation of meaningful learning. In other words, the combination of pictures and texts gives teaching advantages. For blind students, we believe textbooks with pictures and texts are easier to read, study and understand than text-only textbooks.

Whether putting the image before the text or after can both benefit learning, yet when combining images and texts in textbooks, it is also necessary to consider the specific connection of the context and arrange the order reasonably. Based on the viewpoint of simplicity to complexity from the elaboration theory of instruction [12], the order should be designed while combining with contextual content associations and factors such as the amount of image and text information, complexity and so on. Images put before text can help blind students to understand texts; while putting texts before can guide blind students to pay attention to the key information in the images.

In a word, tactile images should be fully contextualized, and simple images and textual information should be presented firstly, which can be helpful for Braille learners to understand their textbooks. As some examples in the fourth section show, *"The Story of 'Shell'"*, displays a paragraph of easy-to-understand text before an abstract picture about this Chinese character form evolution, so that the image could be much more understandable. *"Zhaozhou Bridge"* also has such a design purpose. Firstly, it shows a vivid picture of the bridge, with texts explaining more complex structural principles and functions after the image, blind students can therefore learn step by step.

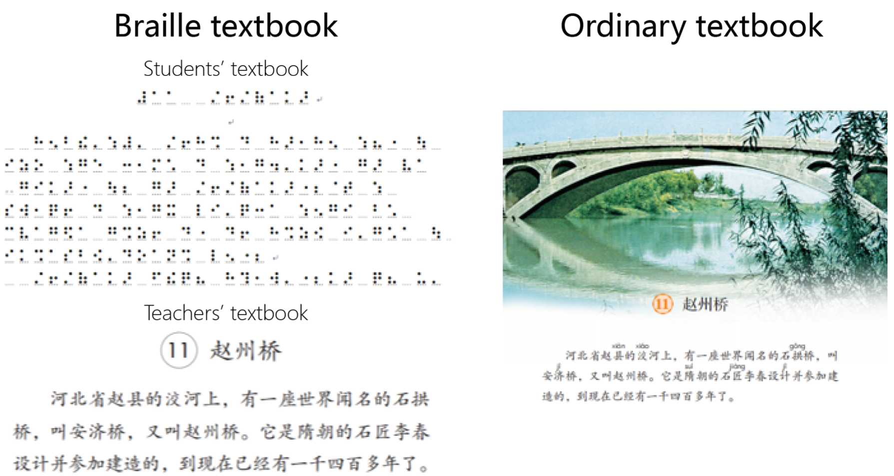

Fig. 4. Comparison of Texts *"Zhaozhou Bridge"* in Braille textbook and ordinary textbook

4 Typical Design Examples of Digital Braille Textbook

4.1 Lesson "*Zhaozhou Bridge*" in Chinese Textbook

As Fig. 4 shows, this lesson introduces the shape and design principles of Zhaozhou Bridge. In the ordinary textbook, a real photo of the bridge in three-dimensional space is displayed above the text, and the shape, location and water reflection of the bridge are presented. With the introduction in the text, sighted students can easily know the ingenious design of the Zhaozhou Bridge.

The question is, in the Braille textbook, only text description retains. Thinking about how complex the construction of the Zhaozhou Bridge is, blind students are not easy to imagine what the bridge looks like.

Our design adds a two-dimensional image to the screen (Fig. 5), allowing students to feel the shape of it. By reproducing the flat image of the bridge, this lesson is designed as follows:

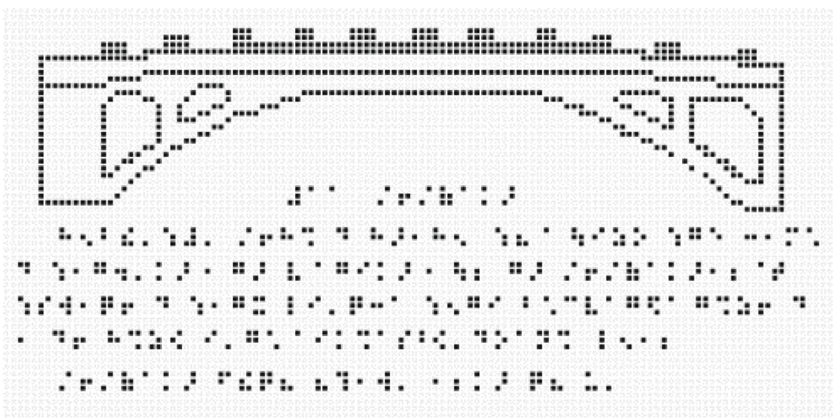

Fig. 5. Lesson *"Zhaozhou Bridge"* in digital Braille Textbook

With a tactile image about the structure of Zhaozhou Bridge that follows the principle of symmetry and no occlusion, the shape of the bridge can become clearer to blind students, and would make the abstract concepts described in the text easier to understand.

4.2 Lesson "*Know 1–5, Addition and Subtraction*" in Mathematics Textbook

As shown in the Fig. 6 is the text content of numbers 1–5 in math textbooks. In the ordinary textbook, a picture of the life scene is used for guiding students to recognize and distinguish numbers. Students learn the application of numbers by observing pictures, which also cultivates multi-angle thinking.

Fig. 6. Comparison of Texts *"Know 1–5, Addition and Subtraction"* in Braille textbook and ordinary textbook.

Conversely, in the Braille textbook, vivid pictures are replaced by abstract and regular shapes, which are not interesting and instructive enough for kids (Fig. 7).

The digital Braille textbook can make up for the lack of images, and can provide blind students math learning with pictures and texts that guide thinking. This lesson is designed as follow:

Tactile images can supplement interesting image content. Through this teaching method of combining pictures and texts, it reasonably guides blind students to think and explore numbers.

4.3 Other Digital Braille Textbook Examples

While studying different subjects, tactile images can guide blind students to associate text information and expand their imagination, helping them understand abstract concepts and recognize the world.

For example, the lesson *"The Story of 'Shell'"* adds tactile images to express the evolution of words. Blind students can learn about morphological changes by touching. In the same way, the addition of tactile images of animals in *"Compare Tails"* is also a kind of associative learning with images and texts.

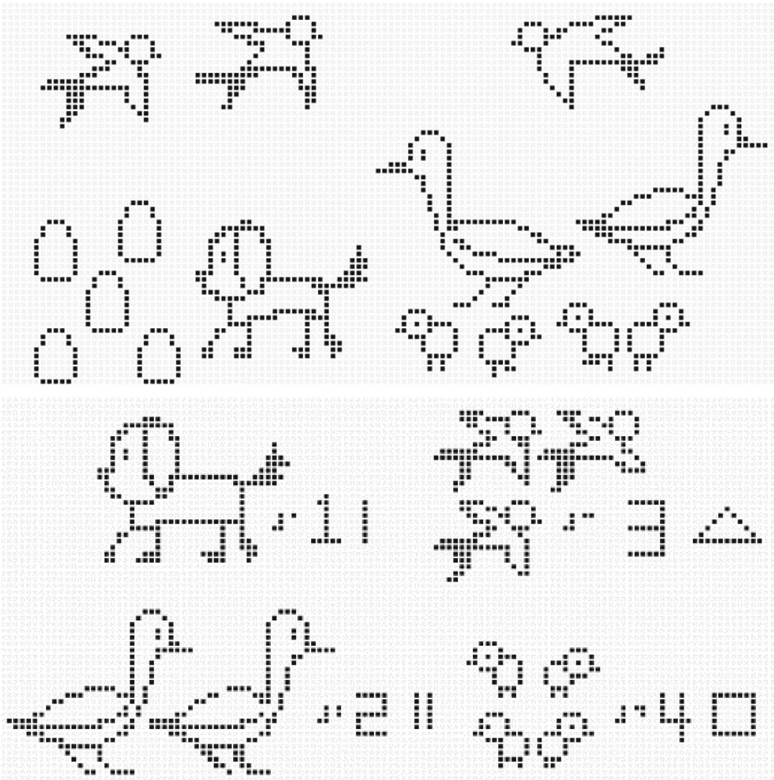

Fig. 7. Tactile images in Texts *"Know 1–5, Addition and Subtraction"*

For mathematics learning, tactile images can also help blind students recognize spatial locations and understand life scenes, and learn mathematics more interestingly (Fig. 8).

5 Evaluation and Discussion

A study with twelve blind students in a blind primary school was conducted, testing the usability of the digital Braille textbook in comparison with current paper-based textbook. Table 1 shows the demographic data of the participants.

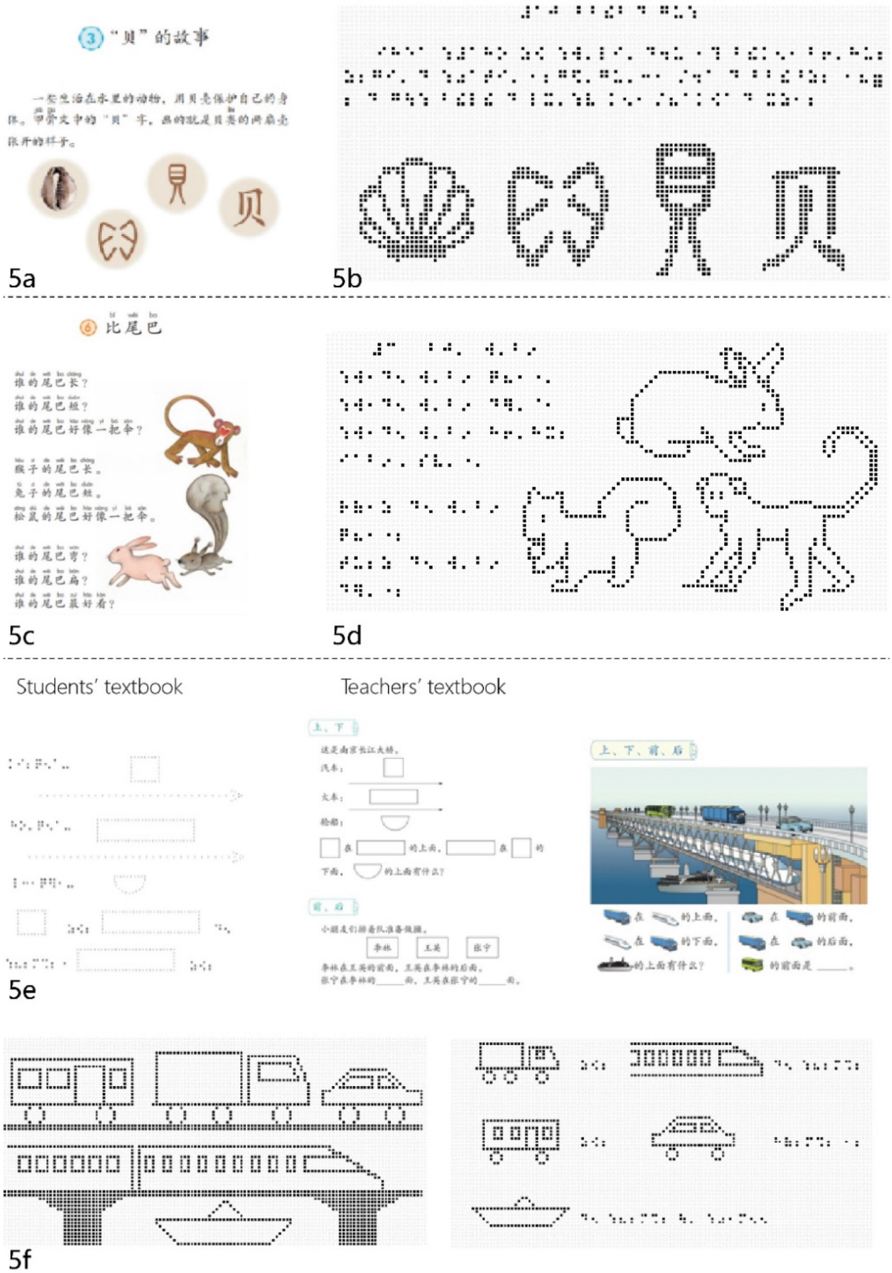

Fig. 8. **a** Lesson *“The Story of ‘Shell’”* in ordinary textbook**.** **b** Digital Braille version of *“The Story of ‘Shell’”*. **c** Lesson *“Compare Tails”* in ordinary textbook. **d** Digital Braille version of *“Compare Tails”*. **e** Comparison of lessons *“Up, Down, Front and Back”* in Braille textbook and ordinary textbook. **f** Digital Braille version of *“Up, Down, Front and Back”*.

Table 1. Demographic data of the participants

Participant	age / sex	Level of visual impairment	Grade in primary school
1	9	early blind	1
2	9	late blind	1
3	8	early blind	1
4	10	low vision	2
5	9	low vision	2
6	9	late blind	2
7	10	late blind	2
8	8	early blind	2
9	9	late blind	2
10	10	low vision	3
11	11	late blind	3
12	10	early blind	3

5.1 Method

Five lessons in the digital Braille textbook including three Chinese lessons ("*Zhaozhou Bridge*" "*The Story of 'Shell'*" and "*Compare Tails*"), and two Mathematical lessons ("*Know 1–5, Addition and Subtraction*" and "*Up, Down, Front and Back*") shown in Sect. 4 were displayed individually by our graphical tactile display prototype. Meanwhile, the current paper-based Braille textbook with the same five lessons was also prepared.

In the experiment, each participant spent around five minutes touching and reading one lesson of digital Braille Textbook or paper-based Braille textbook, and another five minutes doing the same task in another version of textbook in random sequence. Then the same procedure was followed for all five lessons. After all lessons were learned, the participant was required to answer several subjective questions with the score of 7 Likert-scale (see Table 2).

5.2 Results

Table 2 shows the score results of subjective questions by twelve participants.

From Table 2, Q1 is about the transfer barrier between paper textbook and digital one, and all the participants gave non-negative scores. Q2–4 asked about the usability of digital textbook, and 11 participants (not including P3) showed positive feedback. Q5–6 care about the future use, and all the participants were optimistic about the future promotion in terms of textbook learning.

Table 2. Score results of subjective questions by twelve participants. The scores represent: 1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = neutral, 5 = slightly agree, 6 = agree, 7 = strongly agree

Questions\Participants	1	2	3	4	5	6	7	8	9	10	11	12
Q1: There are no barriers to transfer from paper textbook to digital textbook	6	7	4	5	7	6	6	6	6	7	6	7
Q2: The digital Braille textbook is easier to read and understand than paper textbook	6	7	4	6	7	6	6	5	6	7	6	7
Q3: The digital Braille textbook conveys more knowledge than paper textbook	7	7	7	7	7	7	7	7	7	7	7	7
Q4: the tactile images in the digital Braille textbook are easy to understand	6	7	3	5	7	6	6	5	6	7	6	7
Q5: I would like to use digital Braille textbook for other Chinese and Mathematics lessons	7	7	5	6	7	7	6	6	7	7	7	7
Q6: I would like to recommend this learning tool to my friends	7	7	6	6	7	7	7	7	7	7	7	7

5.3 Discussion

Although most of the participants expressed their interests and positive feedback, there is one participant (P3) facing challenges for tactile image learning. "*I barely touched tactile images and it is always difficult for me to understand them*" said by P3, "*I can read Braille, but sometimes I cannot fully understand, nor imagine what it is. I know it is tough for blind people, so I get along with it*". That means tactile images are still a challenge for some blind people, but this is why they may need to be further educated to build up more space related abilities.

The other eleven participants are fond of digital version of textbook with Braille texts and tactile images in pairs. They feel that the tactile images include much more information as a nice addition of Braille texts. Moreover, P2, P5, P10–12 mentioned that Braille texts were abstract, while tactile images were concrete, and it was a perfect pair for knowledge learning. They would all like to have more classes with this digital textbook.

Last but not least, this experiment only includes five typical lessons which are related to graphical information. For other lessons, the inclusion of tactile image as illustration may need careful thinking. We suggest that the Braille text in a lesson should be fully kept and transferred to electric display as the main part, while leaving the choice of tactile images as a flexible feature. We believe with the help of the electric tactile display device and the digital Braille textbook, it would benefit blind students to study and live.

6 Concluding Remarks

The present study offers evidence to support the claim that a digital version of Braille textbook with Braille text and images in pair would be beneficial for the blinds' knowledge learning. With the development of electric refreshable tactile display, more spatial knowledge as tactile images and illustrations could be displayed and acquired by blind people.

In view of this, a serial of tactile interface design guidelines and principles for digital Braille textbook are discussed, including typesetting design, tactile image design and contextual knowledge learning design. With these guidelines, some typical design examples are proposed and explained, followed by a twelve participants' experiment. With the experience of five typical lessons, most of the blind students gave very positive responses. It is proved that there are nearly no barriers to transfer from paper textbook to digital one, and the content with Braille texts and tactile images is easier to read and understand. Our initial results with twelve participants have been very promising.

In the future, we will continue to improve the user experience of digital Braille textbook and haptic interactions. With the help of more amount of electric tactile displays, we hope that blind people can easily read both text and image, expand their knowledge and lead a better life.

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