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Understanding what you feel: A Mobile Audio-Tactile System for Graphics Used at Schools with Students with Visual Impairment

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ABSTRACT

A lot of information is nowadays presented graphically. However, students with blindness do not have access to visual information. Providing an alternative text is not always the appropriate solution as exploring graphics to discover information independently is a fundamental part of the learning process.

In this work, we introduce a mobile audio-tactile learning environment, which facilitates the incorporation of real educational material. We evaluate our system by comparing three methods of interaction with tactile graphics: A tactile graphic augmented by (1) a document with key index information in Braille, (2) a digital document with key index information and (3) the TPad system, an audio-tactile solution meeting the specific needs within the school context. Our study shows that the TPad system is suitable for educational environments. Moreover, compared to the other methods TPad is faster to explore tactile graphics and it suggests a promising effect on the memorization of information.

Author Keywords

Access technology; blind; visually impaired; tactile graphics; touch screen devices.

CSS Concepts

• **Human-centered computing~Accessibility systems and tools** • **Hardware~Tactile and hand-based interfaces**

INTRODUCTION

Today, information is increasingly presented in graphic form. Infographics are commonly used in everyday life for instance to show the weather in newspapers, public transportation maps, site plans, and other general-purpose maps. Generally, the aim of graphics is to present information quickly and clearly by displaying the data in a compact and structured way.

The ability to read and understand graphical representations is even more important for those who study or work in fields such as economics, science, technology, engineering and mathematics. Thus, it is essential to learn this ability at an early stage.

However, students with blindness do not have access visual information. The main question is how to make graphics accessible to blind people at an early stage in school [30]. There are two aspects which need to be considered: (1) the perspective of students with blindness who need to learn how to read and understand graphics and (2) the teachers' perspective who have to provide this information. A basic requirement that graphics are made accessible for students with blindness at school is a procedure which is easy and intuitive to use for both students and teachers.

The most frequently used solution to make graphics accessible is to provide an alternative text, which contains the description of the graphic. In some cases, these descriptions are the only possibility to make complex graphics accessible. Although several approaches are trying to generate alternative text automatically for images [3, 29], these models are not currently available for lecture material and at the moment the descriptions are produced manually by experts. A second possibility to make graphics accessible are tactile graphics which are images with raised surface that can be felt with the fingertips or part of the hand. The production methods vary from thermoform, swell paper or embossing on thicker paper. As mentioned by Zebehazy et al. [30], the presentation of textual descriptions together with tactile graphics is the best format for visually impaired persons at school. In this study, the authors also show the importance of tactile graphics to the learning outcome for students with visual impairment. The ability to explore tactile graphics, discover information, and answer questions about the information independently is regarded as a fundamental part of the learning process [1, 30].

Transforming lecture material in tactile form for blind students, however, comes with different problems. First, tactile graphics are labor-intensive to produce and it is not easy for teachers to incorporate the material in class [25]. Second, compared to visual graphics the space for incorporating text in Braille is extremely limited as it needs a lot of space. The space problem is usually solved by two

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strategies: the first one is to move the text to an empty area of the tactile graphic and connect it with a line, if the text is short and the complexity of the graphic is low. The disadvantage is that the extra lines introduced can disturb and disorient blind students [2]. The second strategy (labeling) is to use a label with a key (e.g. a number) and to move it with the additional information to a digital document or printed document in Braille. Both methods mean that the people who explore a graphic have to detach their hands from the graphic and search for the corresponding index number, either in the digital or in the printed Braille document. If textual information is separated from the graphic in a digital or printed Braille document, some students use one hand to read the additional document (paper or digital) and the other to explore the graphic [24, 30] which however increases the risk to loose the overview. According to Rosenblum et al. [24], teachers identified the problem of losing track of the position of exploration in a tactile graphic. Thus, it is important that blind students use both hands when they work on a tactile graphic. The prerequisite of a good system for presenting graphics at schools is that tactile and textual information is available at the same time and place.

In this work, we introduce a new learning environment which facilitates the incorporation of tactile graphics at schools. It consists of a tablet (here an iPad Pro), various educational tactile graphics, a 3D printed frame to fix the tactile graphics on the iPad, an iPad-App that automates loading the visual and audio information and allows the interaction with the tactile graphics, as well as a Raspberry Pi to ensure a smooth spread of material to the students through a closed local Wi-Fi network. To evaluate the system, we compare three methods of interacting with a tactile graphic: a tactile graphic augmented by (1) an additional document with text in Braille, (2) textual information in a digital document and (3) the TPad system, an audio-tactile solution meeting the specific needs within the school context. In our study, we developed a procedure to incorporate real educational material to increase the usability of tactile graphics at school. We also investigate the preference of students on how to use the TPad. Moreover, we designed a questionnaire to retrieve the view of teachers' if they would be interested in using the developed system.

RELATED WORK

Many approaches developed interactive audio-tactile solutions to improve the access to graphics for visually impaired users. The majority of these studies focus on the specific case of infographics in the field of orientation and mobility, i.e. on maps for wayfinding when planning routes in advance [5, 6, 7, 12, 19, 28, 31] and not on educational topics. They rather concentrate on navigational aspects which improve the wayfinding skills. It is not clear, however, whether their findings can be easily transferred to the school situation without considering pedagogical aspects as well. To overcome this lack of knowledge, we conducted a within-subjects study where TPad was compared with other standard approaches used at schools making tactile graphics accessible and we collected feedback from both teachers and students. Moreover, most of the systems are in a prototype stage of development which cannot be directly introduced at school.

The previous approaches differ mostly in two ways: (1) how they produce tactile graphics, (2) the method of interaction for in- and output. In this section, one system per approach is described in more detail as an example.

Brock et al. [5, 6] developed an interactive map prototype composed of a raised-line map overlay on microcapsule paper placed over a multi-touch screen, a computer connected to the screen and loudspeakers for speech output. The authors showed that interactive audio-tactile maps are more usable than regular tactile maps with Braille text for blind users and confirmed that visually impaired people are able to memorize and mentally manipulate both route and survey spatial knowledge. TPad shares with this work the basic idea of mounting tactile graphics on a tablet touch screen. Our system goes beyond previous approaches as it is tailored to the needs of teachers and students regarding mobile mainstream hardware, support of interaction at school and evaluation in the educational context.

Other approaches use tactile graphics printed with a 3D printer for visually impaired people [10, 11]. Götzelmann et al. [11], e.g. produced the tactile maps with a maximum thickness to preserve the touch functionality of the electronic device below. The 3D printed tactile graphic allowed 4-5 different elevation levels for the relief printing of lines and textures, improving the representative capacity of the map. The user could explore the map as in the previous study and the prototype allowed also to interact with the map through voice input. The low production cost of a single map seems to be in favor of this solution compared to swell paper. The main disadvantages are, however, the long printing time for 3D graphics and the greater effort creating the 3D digital model which is an important disadvantage for teachers. Additionally, this technique provides no advantage for printing scientific graphics and printing Braille is challenging.

Instead of using touch displays, some approaches use finger tracking methods [8, 19, 22, 27]. The Tactile Graphics Helper (TGH) [8] for instance applies computer vision to recognize the tactile graphic and tracks the user's fingers to allow for a natural hands-free interface. Speech input and pointing gestures can be used to ask details about a tactile graphic. Compared to the other studies, they used educational material instead of maps. In their qualitative evaluation, the students felt that the TGH could help them with tactile graphics. However, the system is not ready for use in schools due to the complicated handling: a webcam with an adequate resolution which needs to be mounted, calibrated and connected to an additional laptop with the corresponding software. In general, these camera based solutions are not portable and some are sensitive to the ambient light condition whereas TPad is mobile and not perceived as an uncomfortable aid generating discomfort.

Another interaction method, refreshable tactile displays are used in some studies, e.g. [12, 20]. Petit et al. [20] created a multi-modal device to adapt tactile graphics for children with visual impairment. The proposed solution is based on a STReSS (Stimulator of Tactile Receptors by Skin Stretch) and a Pantograph together with an audio feedback. They reproduced three tactile graphics of a history schoolbook (a building plan, a bar-chart, and a map) for their experiments. The results showed that the participants were able to answer the different questions correctly using the multimodal device. The drawback of the system is that only a small snippet of a graphic is shown which increases the cognitive load and prevents the user from exploring the tactile graphics with multiple fingers or both hands.

An alternative to using Braille labels in tactile graphics was developed by Baker et al. [4] using a QR code with embedded text. The user can access the information using TGV, a smartphone application specifically developed for blind users that scans a QR code but also helps the user to correctly angle the smartphone camera. The main disadvantage of this solution is that the user has to manage the smartphone with one hand and thus cannot explore the tactile graphic with two hands which easily leads to a loss of orientation on the graphic.

Within the commercial products, there are the Talking Tactile Tablet produced by Touch Graphics[1] and the IVEO by ViewPlus[2] which have been available for many years. These touchpads are peripheral devices for a computer designed to be used as a "viewer" for audio-tactile material. Both devices have been examined in several studies, including in the educational context [9, 16, 17]. However, both systems are somewhat unwieldy, not mobile and come with proprietary software for creating tactile graphics which limit the exchange of files between teachers, who cannot use the editors whom they like.

Zheshen et al. [28] proposed another approach for supporting instant access to maps for local navigation by people with visual impairment. They detect text and simplify graphics automatically but currently, the solution is suitable only for maps and not for educational material. Moreover, it shares the same disadvantages previously discussed for the IVEO.

Another commercial product is the Talking Tactile Pen [15] of Touch Graphics. It works by tapping the stylus point on any object on a map or diagram to hear its layered information. The drawback is that the user looses track of tactile information by using the stylus, and the graphic has to be printed on special proprietary paper.

Although many of the research conducted so far offers interesting and promising elements, in many cases the proposed solutions are still prototypes that does not meet the needs of teachers and students at school. In some cases, however, the solutions offer answers only to some of the current problems regarding the accessibility of graphics for people with visual impairment.

In our approach, we focus on educational material for schools instead of orientation and mobility maps. We take all aspects of school into account: easy handling for teachers and students, offline use, mainstream hardware and intuitive application software.

Problems with the access to graphics at school

Tactile graphics are an indispensable tool for students with visual disabilities to access information. However, some problems are still open and limit their employment. Based on a literature study and on our more than ten years of experience in creating tactile graphics for students at university level, we identified the following problems that limit the production and use of these media in school:

- Users are rarely trained in the efficient use of tactile graphics which often leads to the avoidance of graphics [24, 30].
- The quality of tactile graphics is often low because of lack of training, e.g. the labeling process significantly deteriorates the legibility of tactile graphics [1, 2].
- The time needed for the production of a tactile graphic and the corresponding description [30].
- The cost of devices and consumables for the production and use of tactile graphics.

Aldrich et al. [2] collected the user experience of visually impaired students with the use of tactile graphics. Labeling sometimes causes the user's confusion and the difficulty of confusable lines was mentioned frequently. More generally, tactile graphics must be as clear and essential as possible, avoiding unnecessary details and elements to be comprehensible. Sheppard et al. [25] confirmed this view in a survey with teachers of visually impaired children. They also mentioned the problem of information overload and clutter as well as the labor-intensiveness to create tactile graphics and the necessary description. Several participants admitted the fact that they try to actively avoid the use of tactile graphics.

From this point of view, it is therefore not surprising if in a survey on user experience in exploring graphics with 102 visually impaired [21], 44 reported having low or no experience with tactile graphics. But by interviewing participants with at least some experience with tactile graphics on how they would like to have access to images, more than half of them prefer tactile graphics with a supplemental description.

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[1] http://touchgraphics.com/portfolio/ttt/

[2] https://viewplus.com/product/iveo-3-hands-on-learning-system/

DESIGN OF THE TACTILE PAD SYSTEM

The system was conceptualized by imagining a typical teaching situtión in a mixed class with low vision, blind and sighted students: The teacher can provide the appropriate digital file with a few clicks via the back-end to all connected TPads. Blind students are able to download the file, explore the tactile graphic, and use it in class and for homework. We deploy inclusive tactile graphics printed on paper where the original graphic is augmented by tactile information to allow collaboration between sighted and blind students which is not possible on swell paper.

The system was developed together with persons with blindness using the co-design methods. Figure 1 shows the system and some examples of tactile graphics. It consists of three components: (i) a standard 12’’ touch pad (here an Apple iPad Pro) that holds an A4 tactile graphic thanks to a plastic frame printed with a 3D printer, (ii) a cross-platform mobile app which transforms standard tactile material to audio-tactile graphics and (iii) the teacher’s interface.

Figure 1. TPad system and some educational tactile graphics [14, 23] used during the experiment.

The aim of this system is to allow visually impaired users to interactively explore a tactile graphic with a multi-modal exploration strategy (tactile and audio). The elements of the tactile graphic are underlain with audio descriptions containing information about the element. The user can explore the tactile material by regular two-hands exploration and request the additional audio information by touch input.

Development of the app

The TPad app was developed with Apache Cordova, which is an open source framework for cross-platform development.

In the app, the user can request information about a specific element by a double tap. Initially, a single tap was implemented. However, during the first preliminary test with blind users, while exploring the tactile graphic with two hands, elements were sometimes accidentally activated due to the sensitivity of the touch monitor. For this reason, double tapping was introduced. It is implemented with the following parameters: 300 ms allowed delay between two taps, 300 ms allowed press time, maximum 90 px position difference between two taps and maximum 90 px movement while doing the tap. When testing the application with sighted users, smaller values of the parameters were sufficient. However, incrementing the parameters, especially the maximum position difference between two taps, made it more comfortable for visually impaired users. The double tap triggers an audio output through the default text-to-speech synthesis (TTS) of the operating system of the device. So the speech can be customized to the preferred needs (speed, voice, etc.).

In the early stages of application development, we noticed that various standard tablet gestures were detected during graphic exploration. Gestures are widely used by iOS, Android, and screen readers (VoiceOver, TalkBack) as a shortcut for specific actions, e.g. a four-finger tap near the top of the screen to select the first item on the screen. According to our blind accessibility expert, this often leads to a loss of orientation and severely impedes the exploration of the graphic

To prevent that touch gestures interfere with the TPad app while exploring the graphic, the standard multi-touch gestures of the iPad were disabled in the settings. The screen reader is also switched off automatically when the app is opened and the basic speech and touch interactions are internally replicated. A right or left swipe moves the focus to the next or previous item in the menu and a double tap on the screen activates the selected item. In this way, we avoid changing settings which is challenging for persons with visual impairment according to Szpiro et al. [26].

Preparation of the input files

The TPad app accepts standard SVG files as input. There are no restrictions on the software to use creating the Scalable Vector Graphics file (SVG) (e.g. Inkscape, CorelDRAW). The only technical requirement is that the description is inserted within the <desc></desc> tags of the SVG, e.g. the insertion of a title on top of a graphic:

```
<g class = "com.sun.star.drawing.TextShape">
  <desc>
    Title: Schema of substrate and effect
    specificity. It shows how...
  </desc>
  <g id = "id3">
    ... graphic object ...
  </g>
</g>
```

A convenient open-source editor to create a digital version of the tactile graphic is LibreOffice Draw (ODG file), used as a standard editor for our print service for tactile learning materials. With this software, it is sufficient to select the element and open the description interface from the main menu (from the menu bar select: Format -> Description) to insert a description for an element which will be read on demand by the TPad. LibreOffice offers the possibility to export the file in SVG format, ready to be used by the TPad app.

If a vectorized version of a graphic is available, entering the audio information can take as little as two minutes to produce an audio-tactile graphic for TPad. Transforming a scan (raster image) can take up to ten minutes, which is still a reasonable time. In this case, the teacher will first trace the main elements of the graphic with vector shapes using the raster image as orientation and will then enter the appropriate description.

The system can deal with polygons that overlap each other. The TTS will prioritize the polygon in the foreground over the element in the background.

Teachers' Interface

When used in a classroom, the TPad system consists not only of the app installed on the student's tablets but also of a repository for tactile graphics on a Raspberry Pi[3]. It works as an access point for a small local network as many schools often do not have Wi-Fi access in all classrooms or students may not be allowed to access them. However, it is possible to install the repository on any web server and to access it via internet. In this case, the Raspberry Pi is no longer necessary.

The repository is equipped with a web interface reserved for teachers which allows them to upload new graphics to specific categories, and to send a graphic to all connected TPads. In this way, it is possible to respond to the specific requests of the teachers, i.e. that the system works offline and that easy sharing of new graphics with the students is facilitated.

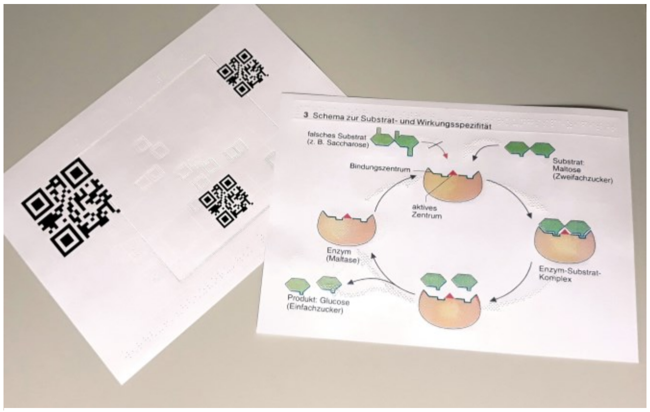

Figure 2. Tactile graphic example [23] used during the study, front-side on the right, back-side with three QR codes printed on the left.

When a teacher uploads a new file, the following automatic workflow is initiated: (1) conversion of the document into the required format (SVG), (2) generation of a unique identification number for the document with the graphic (3) insertion of a blank page with a QR code containing the graphic ID.

In the next step, the teacher is able to download the document from the repository and emboss it. It contains a QR code on the back to access the tactile graphics using the TPad app. The student can then download the SVG files to use the tactile graphics at home for further exercises without requiring the repository.

Interaction with the TPad

To explore a tactile graphic with TPad, the first step is to load the SVG file of the tactile graphic. There are four different possibilities to do this: (1) selecting an SVG file already present in the device, (2) loading it from the repository using the menu, (3) loading it from the repository by scanning the QR code, or (4) receiving the file from the teacher via remote control as mentioned in the previous section.

When connected to the repository, the TPad app downloads the list of available graphics arranged according to the category/lesson associated with each file. In this case, the user can navigate the category menu to select the desired graphic and open it (method 2).

However, as shown in our experiment, the most effective and satisfying way to load the graphic is by scanning the QR code that each graphic has on its backside (see Figure 2). When the student selects the "Scan QR Code" item from the main menu, the front camera of the tablet starts to search for the QR code, and when it finds it, the application downloads the corresponding SVG file from the repository. A short sound notifies the user when the file is successfully opened.

To facilitate scanning of the QR code for a blind user, it is printed three times on the backside of the tactile graphic in different sizes and in different positions (see Figure 2).

After having loaded the SVG file with the audio information, the user fixes a 3D printed frame on the tablet holding the tactile graphic in the correct position. The tactile graphics can be replaced easily and no calibration is required. The graphic covers the display of the tablet without interfering with the touch functionality. This means that the TPad will be able to detect the finger's position of the user while he/she explores the tactile graphic. Double tapping on an element while exploring the tactile graphic initiates the audio feedback.

We did not find a substantial reduction in touch screen efficiency using standard paper (160gr) to emboss the tactile graphics. From our preliminary tests, the TPad system is also compatible with other materials such as swell paper and thin 3D prints.

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[3] https://www.raspberrypi.org/

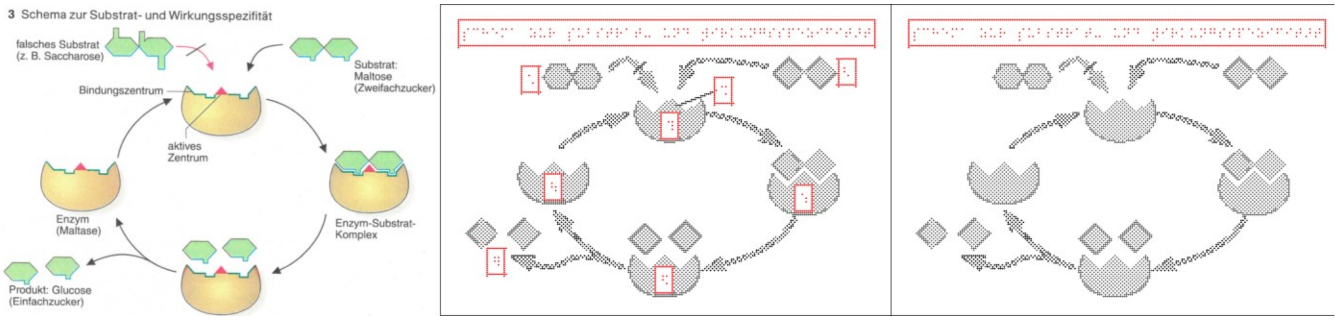

Figure 3. On the left, the sighted version of a biology process [23]. In the middle the corresponding tactile version with title and labels in Braille highlighted in red, on the right the TPad version (without Braille labels).

DESIGN OF THE TEST MATERIAL

The aim of our study is to use real educational material from school. Thus, we contacted a school for visually impaired students. A biology teacher provided a selection of appropriate graphics from his subject such as the transport of water in the body, the cycle of a virus infection, the mode of action of an enzyme, and a scheme of an immune response. We also received material from computer sciences from the area of unified modeling language i.e. class diagrams. In a next step, we created the tactile graphics and three questions to monitor the learning success for each graphic. The example in Figure 3 shows the mode of action of an enzyme as the original graphic (image on the left), the tactile version of the graphic with Braille labels (image in the middle), and the tactile version for TPad (image on the right).

In this case, we asked the students the following three questions:

(1) Which statement is correct? a) Sucrose combines with the binding center of the enzyme. b) Maltose combines with the binding center of the enzyme.

(2) What happens after enzyme and substrate have combined?

(3) What does it mean: Enzymes are substrate specific?

It has proved successful to meet the teachers in person and to discuss the created graphics and the questions with regard to the learning target of the graphics. They were involved to monitor the difficulty of the questions and the complexity of the tactile graphics.

All tactile graphics used for this study were designed in A4 format with a landscape orientation. At the top left corner of the page, there is a title in Braille giving the student a first hint about the content of the graphic. The graphics are created with LibreOffice Draw and embossed with an EmFuse printer from ViewPlus[4]. They are designed based on the sighted version of the graphics by a tactile graphics specialist, using only lines, arrows and shapes (no icons or images) using two different colors as the embosser used is capable of representing colors in different dot heights. The final design of the tactile graphic was further improved by the supervision of a blind accessibility expert.

USER STUDY AND PROTOTYPE EVALUATION

Thanks to the support of two teachers of a school for students with visual impairment, we performed a user study with students enrolled in the last classes of secondary school. Our goal was to investigate the efficiency, effectiveness, and satisfaction of three different methods to explore tactile graphics. We assume that the tactile graphic exploration reflects the efficiency, the correct answers' rate correlates with the effectiveness and the method preference expresses the user satisfaction. Our study hypotheses were:

Hypothesis 1: Audio-tactile graphics (TPad) have higher efficiency, effectiveness, and satisfaction than the other methods.

Hypothesis 2: The student memorizes more information after having explored a tactile graphic using TPad than with the traditional methods as the learning process is not interrupted by the consultation of a key index.

In general, we evaluate if the TPad could be a useful educational aid for visually impaired students and their teachers.

Participants

We conducted the study with 2 sighted teachers and 5 participants (3 males, 2 females), with age ranging from 19 to 39 years, and an average age of 25.8 (SD = 8.3). All the participants were blind, 2 became blind later in their life. They use a laptop, a screen reader and a touch device on a daily basis. Their experience in reading of long texts in Braille ranged between no experience to a weekly frequency. Except for one participant with weekly experience with tactile graphics, the experience with this type of graphics was limited. No one had previous experience with audio-tactile graphics.

Methods for exploring tactile graphics

We investigated three methods to explore tactile graphics: Braille key method (BKM), digital key method (DKM) and audio-tactile graphic (TPad)

1) BKM is the traditional method for presenting tactile graphics. It consists of a tactile graphic with a key index.

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[4] https://viewplus.com/product/vp-emfuse/

The index and additional educational information are printed on a separate page in Braille. In our study, the index is printed on an A3 page with a short general introduction to the graphic. In all graphics, there is no text in Braille except for the key index and the title of the graphic.

2) DKM is a very common method used at schools. The tactile graphic is the same as in BKM but instead of a key index in Braille, the key index is provided digitally in a Word file. In our study, the participants used a laptop with Windows 10, a screen reader (JAWS) and a refreshable Braille display (Freedom Scientific Focus 40 Blue) to consult the key index.

3) The TPad system doesn't need a tactile graphic with Braille labels and key index. For the experiment, the only text in Braille occurs in the title which is associated with an introductory description. All descriptions can be recalled with a double-tap on an element.

Experiment

The experiment was conducted at the school of the participants, in a comfortable and quiet room. One of the two teachers involved attended the experiment to better assess the potential and the disadvantages of the new method proposed (audio-tactile graphics). Feedback from the teachers was collected in the days immediately after the experiment through an open-ended questionnaire sent by email.

Each participant was first briefly introduced to the experimental design and to our motivation: "To compare three different methods to learn tactile graphics". We did not inform them that the TPad was developed by our team to avoid a bias for the system. In a next step, the participant was interviewed about personal characteristics.

The experiment itself was divided into two parts: Initially, the participant used the three different methods to explore three tactile graphics (one for each method). Second, the participant tested two different modalities to load an audio-tactile graphic in the TPad. At the end of the experiment, the participant was interviewed with five open-ended questions to collect some general feedback on TPad.

*** Part one**. Before we started the real test for each method, the participant acquainted oneself with the method in a short familiarization phase. We used the same tactile graphic for the exploration of the different methods. After familiarization, the experimenter started with the real test. The participant received a tactile graphic and could explore it autonomously without time limit. However, we asked the participants to be "as quickly and accurately as possible" and informed him/her that the time would be recorded. Then, the user was asked two questions about the graphic. The difficulty increased from the first question (multiple-choice question) to the second (open-ended question). To answer each question the student could explore the graphic while the time and the answers were recorded. The last question had to be answered without the tactile graphic. The methods and the order of the tactile graphics were permuted across the participants. When the test of a method was finished, the student was asked to answer the SUS and NASA Raw TLX questionnaires.

*** Part two**. In the second part, we focused exclusively on the use of TPad. In particular, we wanted to evaluate the efficiency and satisfaction of using the QR code strategy compared to a menu navigation based strategy to load the right SVG file into the TPad. The student received three tactile graphics and loaded the graphics into TPad scanning the QR code printed on the backside of the tactile graphic. The total time required was recorded. Then, the student was asked to load three tactile graphics, whose category and filename were written in Braille on the top left corner of the tactile graphic by selecting the correct file from the file list in the menu of the TPad.

RESULTS

In this section, we report our results regarding efficiency, effectiveness, user satisfaction and the different methods how to load a graphic.

Efficiency

Figure 4 shows the average time required by the students to explore the content of the tactile graphics before answering the questions. The TPad method performed an average exploration time of 111 seconds (SD = 7), the Digital Key Method (DKM) an average of 277 seconds (SD = 92) and the Braille Key Method (BKM) 359 seconds (SD = 147).

After verification that each set of data was normally distributed with the Shapiro-Wilk test, we performed a within-subjects one-way ANOVA. The test supports the hypothesis that the method used to explore the tactile

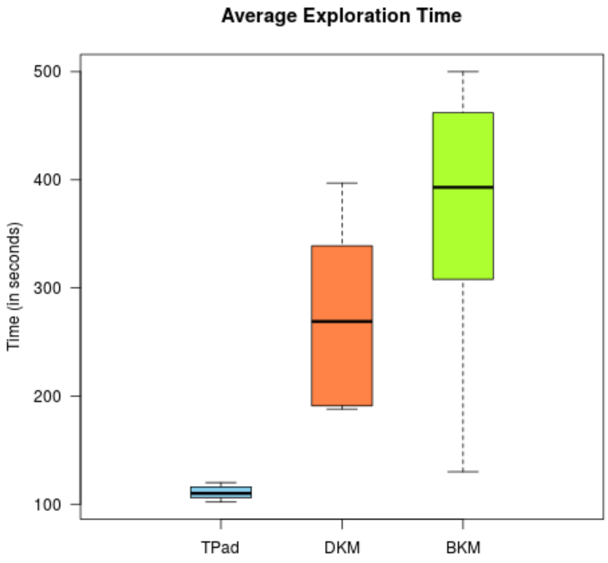

Figure 4. Boxplot of exploration time of the tactile graphic before answering the questions. TPad 111 seconds (SD = 7), DKM 277 seconds (SD = 92), BKM 359 seconds (SD = 147).

graphic had a statistically significant effect on the exploration time [F(2, 8) = 8.93, p = 0.01].

Performing a post hoc analysis with paired t-test corrected with Holm method ($\alpha_1 = 0.05$, $\alpha_2 = 0.025$, $\alpha_3 = 0.017$), the TPad shows a better performance in exploration time compared to DKM [t(4) = 4.01, $p = 0.016 < \alpha_3$] and BKM [t(4) = 3.87, $p = 0.018 < \alpha_2$]. The difference between DKM and BKM is not statistically significant [t(4) = 1.17, $p = 0.30 > \alpha_1$]. To answer the questions 1 and 2, participants had the opportunity to consult the tactile graphic. There are no differences between the three methods in answer time. The maximum time to answer the first question was 22 seconds (average 5’’) and many students did not consult the graphic to answer. Each participant was informed, before starting the test session, that he was not allowed to use the graphic to answer the third question. The aim was that the student explores the entire graphic more carefully and comprehensively. This is probably why many students responded correctly to the first question (the easiest one) without consulting the graphic further. For the second question, the average response time was 19 seconds and only two students answered without consulting the graphic.

Effectiveness

Students answered correctly to more questions using the TPad (11 total right answers) and BKM (11) than the DKM (5). However, the average correct answer rates are not significantly different using a Friedman test [$\chi^2(2) = 2.92$, p = 0.23]. The number of correct answers is shown in Table 1.

	TPad	**DKM**	**BKM**
Tot. right answers	11 (73%)	5 (33%)	11 (73%)
Tot. right answers memory question	4 (80%)	1 (20%)	3 (60%)

Table 1. The total amount of correct answers received from the students, in total (first row) and only for the memory question (second row).

To investigate the possible correlation between the short-term memory for information and the method used to read the tactile graphic, we asked the students to answer the last question without using BKM, DKM or TPad.

Four students (80%) answered correctly the last question after the TPad session; three students (60%) after the BKM session and only one student (20%) after the DKM.

It is an important result that 80% of the participants answered correctly using TPad for the last question (only 20% using DKM); in particular, if we take into account that the probability of answering correctly an open question is extremely low (the question was not a multiple choice). These data are in line with our second hypothesis: "The student retains more information after having explored a tactile graphic using TPad". Analyzing the data with the Cochran's Q test for dependent samples, we cannot refuse the null hypothesis (the proportion of “successes” is equal for all groups) [$\chi^2(2) = 3.5$, p = 0.17]. However, the lack of significance of the last two tests is probably due to the number of participants involved in the study and a larger sample size could formally support the hypothesis.

The cognitive load of the different methods, in exploring a tactile graphic, was evaluated through the raw NASA TLX. All the methods have a similar index, as supported by the ANOVA test that doesn't stress any significant differences [F(2,8) = 3.44, p = 0.08]. The results are shown in Figure 5a.

Considering that the maximum possible value of the index is 120, all the methods performed a good result in the range from the average minimum value of 26.4 (SD = 12.7) for TPad, to the value of 38.2 (SD = 5.4) for DKM.

Satisfaction

After having tested the three methods, we asked the participants to point out their favorite one and to motivate the answer. All the participants were in favor of the TPad, while only one expressed two options (TPad and BKM). Three students reported that they prefer TPad because they consider it faster than the other methods. Two students reported: "I hate to read Braille; with TPad this is not necessary"; "I like that all the information was in one place". In particular, two participants showed strong enthusiasm for the use of the device and would like to actively participate in the future development.

TPad and DKM received a good SUS score, the BKM score is under the average (68) [TPad 75.0 (SD = 14.9); DKM 76.8 (SD = 10); BKM 65.25 (SD = 9.8)] and a graphical comparison is presented in Figure 5b.

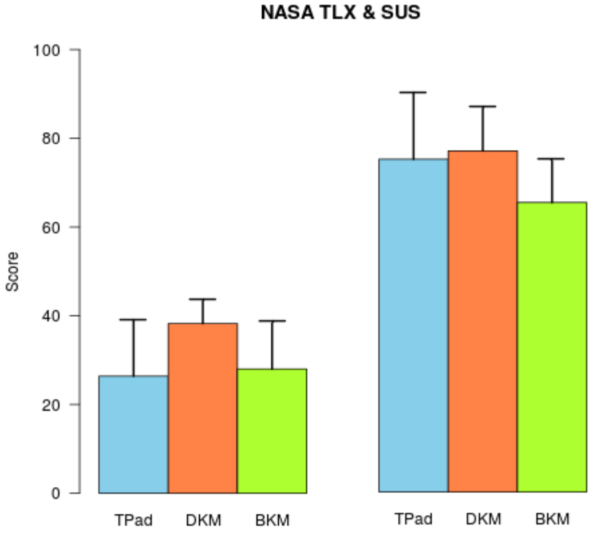

Figure 5. The average score for the raw NASA TLX in fig. a [TPad 26.4 (SD = 12.7); DKM 38.2 (SD = 5.4); BKM 28.0 (SD = 10.8)] and for the SUS in fig. b [TPad 75.0 (SD = 14.9); DKM 76.8 (SD = 10); BKM 65.2 (SD = 9.8)].

However, the three scores are not significantly different analyzing the data with a Friedman test for data not normally distributed [$\chi^2(2) = 2.84$, $p = 0.24$].

Loading tactile graphics methods with TPad

Loading tactile graphics into the device via QR code was an unexpectedly quick method. After a brief familiarization phase with the method, almost all the participants developed an effective methodology for scanning the QR code printed on the backside of the graphic: first placing the graphic on the tablet and then lifting upwards until the QR code was scanned.

One participant was able to load a graphic in less than two seconds. Figure 6 shows that the average time to scan a QR code was faster (4.6 seconds (SD = 3.2)) compared to the average time for searching for the file in the app menu (11.4 seconds (SD = 7.2)).

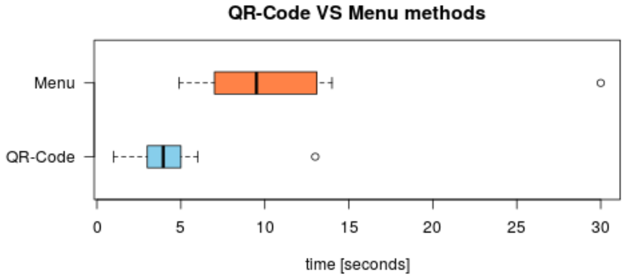

Figure 6. Boxplot with time (in seconds) to load the tactile graphic into the TPad app either with the QR code or with the menu. [TPad 4.6 seconds (SD = 3.2); Menu 11.4 (SD = 7.2)].

The timekeeping does not include the time needed to read the category and the name of the file, printed in Braille as the title of the tactile graphic. For the evaluation of the paired results, we used the non-parametric Wilcoxon Signed Rank Test ($z = -2.7$, $p = 0.004$). The difference found in loading time is statistically significant.

Assuming that the preference expressed for the loading method reflects user satisfaction, the QR-Code method showed a better performance as all the participants expressed their preference to load the tactile graphic through the QR code instead of the application's menu.

TEACHERS' FEEDBACK

We met with the teachers to discuss the TPad system before the study and presented the workflow for using it in the classroom: (i) Creating a tactile version of a sample graphic from a school book with LibreOffice Draw (ii) Uploading a file to the repository (iii) Demonstrating the functionalities of the repository web interface (iv) Simulating the use of the system in classroom.

At the end of the meeting, we gave a questionnaire to the teachers with eight open-ended questions regarding their opinion (i) if they would use the TPad system, (ii) the reason, (iii) the subjects where it could be useful, (iv) for which tasks, (v) possible difficulties, (vi) the workflow, (vii) further improvements, (viii) additional applicability. We request to complete the questionnaire during the following days and deliver it by the end of the study.

Analyzing the feedback from the teachers shows that the most worry is the workload for the creation of tactile graphics. Only a few teachers know how to create tactile graphics using an embosser. Thus, we created training material and we plan to organize a training course to improve the technical knowledge of the teaching staff. Although several research projects are dedicated to the development of automatic or semi-automatic tools for the production of tactile graphics [13, 18] they are far from being applicable in school environment.

A second important point is related to the purchase of useable tablets. In addition to the cost issue, the administration of the tablets also plays a role: where to keep the devices when not in use, manage lending and software updates. The best solution would be for each student to have her/his own device. As the tablet is useful in different situations, a purchase is a reasonable option unlike a special device.

According to the teachers' opinion, the application of TPad is numerous and ranges from mathematics to social studies, from handicraft training to computer science and physics. In particular, it is deemed useful in all those tasks that involve the study of flowcharts, organization charts, process flows (biology, economics), chronological graphics (history), function charts, maps. Among the extracurricular activities, educational trips were mentioned, supporting the orientation during a visit of a city or within buildings, and tactile presentation of the main works of an art exhibition or in a museum.

CONCLUSIONS

Access to visual content using tactile graphics is essential for students with visual impairment at school. Many approaches focus on orientation and navigation skills, i.e. tactile maps. In our paper, we describe the audio-tactile TPad system designed for an educational environment which incorporates a touchpad, a tactile graphic, an accessible app that automates loading the visual and audio information as well as an offline method to ensure a smooth spread of material to the students. We created a questionnaire to learn from the experiences of the teachers how a system should be implemented in school. Moreover, we compare the exploration method of tactile graphics using TPad with two traditional interaction methods for tactile graphics. The results of our study shows that audio-tactile graphics are an effective teaching tool for visually impaired students at school. Using TPad, the participants acquire the knowledge about a tactile graphic faster than with the other methods and answer correctly more than 70% of the questions.

A very interesting result of our study is that generally the students had more difficulties and achieved worse results when interacting with the digital key method than with the other two methods. We assume that this is due to the change of interaction method, PC/screen-reader/keyboard on the one hand and graphic-tactile/Braille-labels on the other resulting in a loss of orientation.

In the Braille key method, the interaction method (reading on embossed paper) is the same for the graphic and the key index, which is probably an advantage in respect to the digital key method. However, the Braille method requires that the user is able to read long texts in Braille which is rarely the case.

With TPad, the multimodal interaction provides two advantages: first, the user is focused only on one device; second, the student can access the information in less time. We hypothesize that this is the reason why 80% of the participants were able to answer correctly to an open-ended question at the end of the TPad test without using the device.

It is important to emphasize that while all the participants had experience with the other technologies (screen readers, tactile graphics and Braille documents), TPad was a totally new interaction method for exploring audio-tactile graphics for all of our participants. We expect that the positive effects on using the TPad will even increase with more experience.

For the purpose of the study to keep the methods comparable as much as possible, the potentials of TPad has not yet been fully exploited. With TPad it is possible to insert information even for very small and close graphic elements reaching a granularity unthinkable with other methods that require to label each element with bulky labels in Braille. Moreover, the association between audio description and the graphic element is always certain and immediate when using TPad and does not involve an additional cognitive load for the student. We have also limited the length of the descriptions of the elements for the study to be able to provide the student with a printed document that did not exceed one A3 page of Braille text for the Braille key method. It is also possible to store cascaded information on the TPad which can be obtained by other gestures than double tap.

During the preparation of the educational material a teacher pointed out that TPad offers the opportunity to add more verbose explanations compared to graphics with Braille legend where abbreviations are extensively used to limit reading time.

TPad also speeds up the production of tactile graphics as it is not necessary to insert labels in Braille or extra lines for space reasons and to create a key index. Moreover, another advantage compared to commercial products is that there is no need for special software. The developed application is cross-platform so it is sufficient to install it on a normal tablet already in the possession of the school or the student. It can be used for other purposes as well and there is no need for additional hardware. Besides, TPad is to the best of our knowledge the most portable solution among those available. Moreover, the repository installed on the Raspberry Pi supports the teachers in their work. They can archive their graphics required for the lecture, automatically convert their documents to the TPad compatible format, load the correct tactile graphic on all the connected tablets using the remote control. Hence, they can focus their work exclusively on teaching without having to worry about logistical aspects, as the students can follow the lesson independently with the help of the tactile graphic on the TPad.

The possibility of using this solution also for those who are not fluent in Braille offers potential applications also outside the school context. Given the strong interest of the students involved in the study, as well as the productive collaboration with the teachers, we plan to test the feasibility of introducing TPad in some courses at the collaborating school. This allows us to further improve the system with our co-design method in a real-life context during the school year, using the feedback of teachers and students.

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