

PAPER

Development of Tactile Graph Generation Web Application Using R Statistics Software Environment

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SUMMARY We have developed software that uses the R statistics software environment to automatically generate tactile graphs—i.e. graphs that can be read by blind people using their sense of touch. We released this software as a Web application to make it available to anyone, from anywhere. This Web application can automatically generate images for tactile graphs from numerical data in a CSV file. It is currently able to generate four types of graph—scatter plots, line graphs, bar charts and pie charts. This paper describes the Web application’s functions, operating procedures and the results of evaluation experiments.

key words: blind people, tactile graphs, R statistical software, Web accessibility, tactile legibility

1. Introduction

Graphs are used to represent changes, trends and correlations in data. Since graphs are generally visual representations, it is difficult for blind people to use them. One way of supporting the use of graphs by blind people is to generate so-called “tactile graphs” that can be read by the sense of touch. The task of generating tactile graphs is usually performed manually by supporters such as Braille transcription volunteers and teachers at schools for the blind. Consequently, the preparation of tactile graphs can require considerable time and effort, making it impossible for blind people to obtain tactile graphs straight away. Another problem is that it is difficult for blind people to generate tactile graphs by themselves.

A number of R&D projects have tackled these issues. They are classified into two basic categories: (1) improving the efficiency of generating tactile graphs for supporters of blind people and (2) building up systems by which blind people can generate tactile graphs themselves. The former is further classified into two methods: (1-1) translating printed graphics into tactile graphs and (1-2) generating graphs from numerical data.

(1-1) Ladner et al. developed “Automated Tactile

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Graphs Translation”, which extracts pure graphic and text from an original scanned image that includes graphs [1], [2]. The text is then translated into Braille and put back in its original position in the graph. The result is embossed with an embosser (Braille printer). Chen and Takagi developed a method for extracting graph elements that includes not only solid lines but also broken lines for mathematical graphs [3]. (1-2) Goncu and Marriot developed a method of generating tactile bar graphs and pie charts from numerical data [4]. These tools are aimed at reducing the time it takes for sighted people to generate tactile graphs, and cannot be used independently by blind people.

At the same time, blind people have been working on creating environments in which they can generate tactile graphs themselves. (2) Fujiyoshi et al. developed a system called “Bplot” that enables blind people to generate tactile illustrations including graphs and schematic diagrams by writing a program [5]. However, this usage is considered difficult for people who have limited experience with programming. A new version of Bplot was developed that includes a graphical user interface for sighted people [6], but it still requires programming to make free-form curves such as graphs. Godfrey uses R Statistical Software from the terminal window of the Windows OS via a screen reader [7]. He also developed a package called “BrailleR” to provide blind users with a text interpretation of graph objects. Nakagawa et al. developed software that can be used independently by blind people to generate embossed tactile graphs [8]. This software reads in numerical data from a CSV (comma-separated values) file and automatically generates a tactile graph based on this data. However, it is only capable of generating line graphs and scatter plots, and as yet cannot generate various other types of tactile graph.

Against this background, the purpose of our study is to develop software 1) that is capable of being used easily by both blind and sighted people who do not have programming skill and 2) that can generate several different types of graph suitable for being read by touch. To achieve this goal, we used R statistical software and Shiny, a Web application framework for R, to turn the software into a Web application with a GUI.

This paper describes the software requirements (in which we elaborate upon tactile graph requirements), how to set graph parameters to meet the tactile graph requirements, our Web application’s functions and operating procedures, and the results of three evaluation experiments we

conducted to show the effectiveness of our Web application from three viewpoints: capability of tactile graph generation, usability of Web application, and legibility of tactile graphs created with the application.

2. Software Requirements

2.1 Operational and Functional Requirements

The software to be developed is subject to four main requirements:

- (1) Capability of producing diverse types of graph, such as scatter plots, line graphs, bar graphs and pie charts.
- (2) Capability of generating graphs with a layout that can be read easily by touch.
- (3) Accessibility to blind people, i.e. having keyboard access and speech feedback (speech is provided by a screen reader).
- (4) Easiness to use for ordinary computer users who have not experienced programming.

2.2 Tactile Graph Requirements

The components of tactile graphics are surface, line, and point symbols. Of these, our present software development uses line and point symbols. Their requirements are summarized below (1) in accordance with the several guidelines for tactile illustrations [9]–[12]. As Braille is indispensable in tactile graphics, the requirements for this are described as well. The requirements for each type of tactile graph follow (2):

(1) Requirements for tactile illustrations made on capsule paper

- Line symbol

The main form of line symbols in tactile illustrations should be a solid line 1.0 mm wide ([9] pp.18–20). When other line symbols are used in addition to this solid line, they should be capable of being distinguished by touch, either by using solid lines of thickness 0.5 mm, or by using a different type of line symbol such as a dotted or dashed line [9]. Lines of less than 0.4 mm thick should not be used, as it can be difficult to obtain a sufficient bump on capsule paper [9].

- Point symbol

To prevent points from being confused with Braille, whose dot diameter is around 1.5 mm, when reading by touch, points should have a diameter of at least 2.5 mm, or no more than 0.5 mm [13].

- Braille

Text in tactile illustrations should be written in Braille oriented horizontally. A margin of at least 3.0 mm should be left around the Braille characters ([10] p.27).

(2) Requirements for each type of tactile graph

- Scatter plot and line graph

The graph should be able to include grid lines as guides for tactile reading ([11] pp.408–413).

- Bar chart

Horizontal bar charts should be used, as these are considered to be easier to scan with the fingers ([10] p.37).

- Pie chart

Segments should not be filled in, and only the circumference and radial dividing lines should be raised ([12] p.137). Data should be arranged clockwise in a descending order.

3. Development

3.1 Development Environment

We used R (version 3.1.2) as the development language, together with the RStudio (version 0.98.1091) integrated development environment (IDE). We also used the Shiny package (version 0.10.2.1) and Shiny Server to convert the R program into a Web application. They were run on Mac OS X (version 10.10.1).

3.2 R Statistics Software Environment

R is a statistics software environment with specialized statistical analysis and drawing functions. It also includes programming functions, which is why it is sometimes referred to as R programming language. It is free software, and can be obtained from the Comprehensive R Archive Network (CRAN) website [14], which also offers a wide variety of packages that extend R's functionality. Since R is compatible with various platforms (operating systems), it can be used by anyone.

There were four reasons why we chose R and Shiny for the development of tactile graph generation software:

(1) Availability of various graphs

R includes commands for drawing graphs of various different kinds. It is therefore possible to generate several different types of tactile graph. (Solution to requirement 2.1 (1))

(2) Changeability of graph parameters

In R language, graph parameters such as the line thickness, the format of the axes, and the text font can be customized by specifying the options via the “par()” function. It is therefore possible to generate tactile graph with layouts that are suitable for reading by touch. (Solution to requirement 2.1 (2))

(3) Creatability of Web applications

There is a package for R called Shiny that can convert R programs into Web applications (also called as Shiny apps). It is easier for non-computer experts to use Web applications with a GUI than a CUI, which requires sending commands from a terminal window or programming in an editor. (Solution to requirement 2.1 (4))

(4) Accessibility of Web applications

If the Web application is compatible with screen readers, it becomes automatically accessible to blind users. Shiny apps' control widgets are available through the Twitter Bootstrap project, a popular open source framework for building user-interfaces. Twitter, as one of the top IT companies, is deemed to be in accordance with accessibility. (Solution to requirement 2.1 (3))

There are also a couple of reasons we did not choose other languages and graph engines: one, visual effects in Gnuplot graphs are not suitable for tactile reading, and two, for future expansion, R surpasses Python in data analysis capability.

3.3 Settings of Lines and Plots

We set the “lwd” option to 2.5 for the graph lines and 0.8 for the grid lines so that the width of these lines becomes 1.0 mm and 0.5 mm, respectively. These settings make the lines of the graph discernable from the grid lines.

To make the plots conspicuous from the graph lines by touch, we set the “pch” option 19 for the plots on line graphs so that the plots become filled circles with a diameter of about 2.7 mm. For plots on scatter plots, we set the “pch” option to 20 so that the plots become filled circles with a diameter of about 2.2 mm. We selected a smaller diameter for scatter plots because scatter plots have many more plots than line graphs in general.

3.4 Braille

We set the “font” option to a Braille font and “ps” option to 18 point. We used a Braille font that is under development at our laboratory [15]. This Braille font uses dots of a diameter of about 1.2 mm in 18 point that can easily be read on capsule paper.

Our software automatically places the Braille number sign in front of numerical values such as in the axes.

3.5 3D Measurement

We used a one-shot 3D measuring microscope (VR-3000, Keyence) to measure the tactile lines, plots, and Braille that were generated by our software and confirmed that tactile lines and plots had the above-mentioned dimensions and that the Braille text had 3.0 mm of space around it.

4. Web Application

4.1 Operating Environment

(1) Server

We are using R (version 3.2.0) and Shiny Server (version 1.2.3.368). Both are run on Ubuntu (version 12.04.5) and its kernel version is 3.2.0-23-generic.

(2) Client

We confirmed that our Web application works with Internet Explorer 10 and NetReader 2, which are popular browsers among blind people [16], along with a screen reader, PC-Talker, on Windows 7. However, as NetReader changes some of the standard key assignments, the use of Internet Explorer is recommended.

4.2 Function Overview

Our Web application software reads in numerical data from

a CSV file, accepts user input such as the title of the graph, and automatically generates images for tactile graphs based on this information.

4.3 Types of Graph

The application can currently produce four types of tactile graph—scatter plots, line graphs, bar graphs and pie charts.

4.4 CSV File

A CSV file is a text file that has two headings in the first line and a pair of data in each line in the second line and below. The first item in a data line is either an item for bar charts and pie charts or a number for line graphs and scatter plots. The second is a number for all types of graph. CSV files can be generated by either spreadsheet applications or text editors.

4.5 Operating Method

A screenshot of the Web application is shown in Fig. 1. At the top left of the screen is a file selection button for selecting a CSV file. Below that is a set of radio buttons for changing the type and the layout of the graph to be generated. These are followed by a set of text boxes for setting the graph title and the units and ranges of each axis. The graph image is displayed on the right side of the screen. This graph image immediately reflects any changes the user makes to the graph parameters. Below the graph image, there is a download button.

Users operate the Web application as follows:

(1) Select CSV file

A CSV file is selected, and the numerical data is read in by the software. At this point, a graph image of the selected data is displayed at the right side of the screen.

(2) Select graph type

The type of tactile graph is selected from the following: scatter plot, line graph, bar graph and pie chart.

(3) Select font

The style of text displayed in the graph can be selected from inked characters and Braille characters. Using inked characters, it is possible for a sighted person to operate the software while checking that there are no errors in the graph’s text annotations.

(4) Select whether or not to include grid lines

The user can choose whether or not grid lines should be included in the graph.

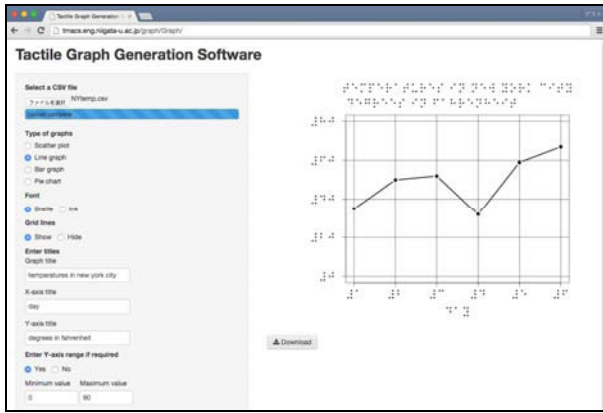
(5) Input titles

The user enters titles for the graph and for the horizontal and vertical axes.

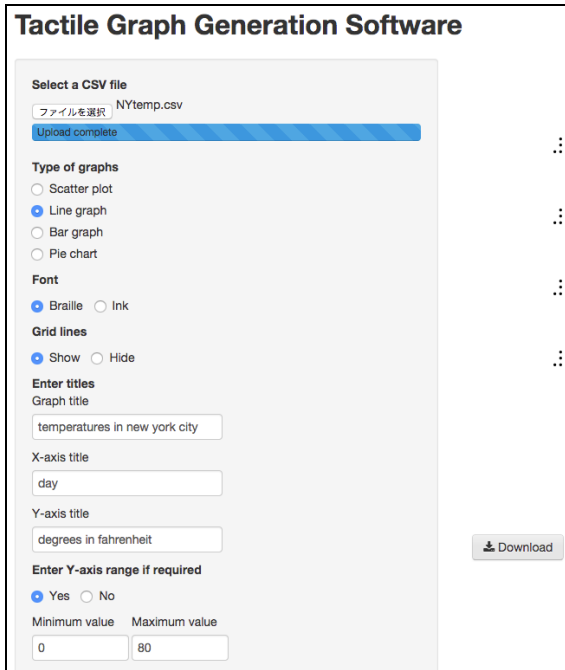
(6) Set y-axis range

The display range of the graph can be set by entering minimum and maximum values for the y axis. If not set, the y-axis range of the graph is automatically set from the minimum and maximum values of the numerical data.

(7) Save the results



(a) Entire page



(b) Left part enlarged

Fig. 1 Screenshot of the Web application.

The tactile graph image can be saved by clicking the download button. The image is then saved as a PNG file in the user's download folder.

(8) Print and raise the image

The saved image can be printed on capsule paper by an ordinary printer. When passed through a special heater (PIAF, Quantum Technology), the black printed parts form raised bumps to produce the final tactile graph.

4.6 Content of Tactile Graphs

Figure 2 shows an example of a tactile line graph generated using this software. Its graphical elements are the graph line, grid lines, and the border line. The text and numbers in the graph are displayed in Braille. The graph title is positioned at the very top of the tactile graph and the y-axis (and its unit) appears below this title. Then the x-axis title (and its

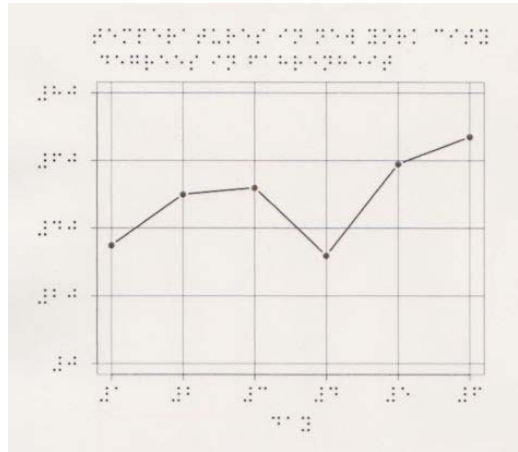


Fig. 2 Example of a tactile line graph created by our software. The graph corresponds to Fig. 1.

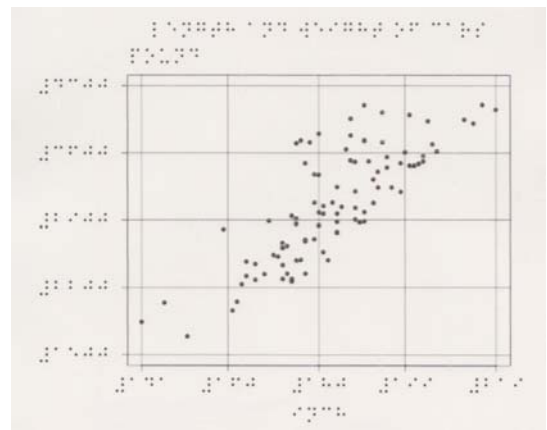


Fig. 3 Example of a tactile scatter plot created by our software.

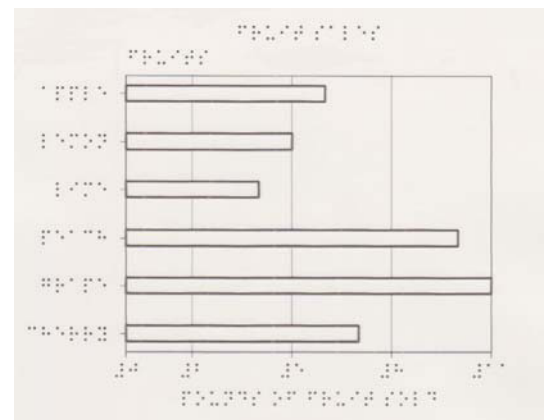


Fig. 4 Example of a tactile bar chart created by our software.

unit) are positioned at the very bottom of the graph. The axis numbers appear at the left and bottom end of each grid line.

Figures 3, 4, and 5 respectively show examples of a tactile scatter plot, bar chart, and pie chart generated by our

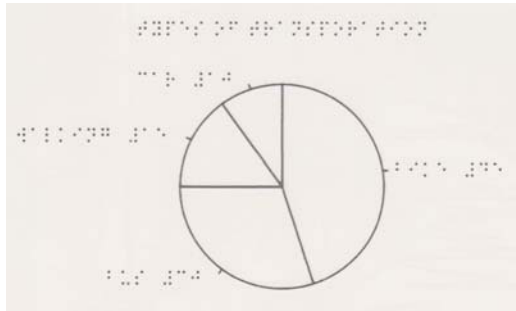


Fig. 5 Example of a tactile pie chart created by our software.

software.

5. Evaluation 1: Capability of Tactile Graph Generation

In Evaluation 1, we explored whether our Web application can generate tactile graphs of general numerical data. We also checked whether the graph labels including axis numbers were properly displayed.

5.1 Materials

We used 10 sets of data for line graphs, another 10 for scatter plots, 16 for bar charts, and 12 for pie charts. All sets were taken from six commercially available books dealing with data analysis using R and/or Excel because these were thought to be typical examples of graph usage. [17]–[22]. In these books, bar and pie charts are more prevalent than line graphs and scatter plots, and thus the numbers of data sets utilized in the experiment varied by graph type.

Most of the bar chart and line graph data dealt with sales or the number of customers per day, month, shop, and so on. The amount of data in the bar charts varied from 4 to 14 items with an average of 6.9 while that in the line graphs varied from 4 to 36 with an average of 6.9. Most of the pie chart data dealt with market shares, with the amount ranging from 3 to 6 with an average of 4.8. Scatter plot data showed some kind of relationship between x and y. The amount of data in the scatter plots varied from 5 to 93. Five of these data sets came from one book and their numbers of data items, 93, were identical.

5.2 Results and Discussion

Evaluation results are shown in Table 1. Out of 48 data sets, 45 graphs were successfully generated, and for 39 out of 45 graphs, labels were produced properly. These results demonstrate our software’s capability of generating tactile graphs.

The failures are classified into three categories: wrong data type, overflowed labels, and overlapped labels (Fig. 6). The reasons for the failure and the possible solutions to them are discussed below.

Failure to generate tactile graphs occurred in only three

Table 1 Evaluation results of tactile graph generation capability.

Graph type	Number of data sets	Generation of tactile graphs		Label display	
		Success	Failure	Success	Failure
Scatter plot	10	10	0	10	0
Line graph	10	7	3	6	1
Bar chart	16	16	0	13	3
Pie chart	12	12	0	10	2
Total	48	45	3	39	6

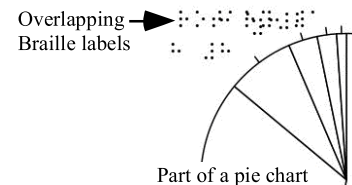


Fig. 6 Failure in displaying Braille in a tactile pie chart. Labels were overlapped at the upper left of the chart.

data sets out of a total 48. These three data sets included date data such as “2002/1/1.” For line graphs and scatter plots, all data except the headings should be numbers. To avoid this kind of graph generating failure, the software should check the data type when they are read in and if it is date data when the line graph is selected, it should give a warning to the user or change the date data into numerical data automatically.

Four y-axis labels overflowed in a line graph and three bar charts. As Braille requires some space, the length of the y-axis label is limited to seven letters. The y-axis labels of the line graphs and scatter plots are numbers. To display numbers in Braille, the number sign should be placed before numbers. Therefore, numbers of up to six digits can be properly displayed. To avoid overflow problems, the software should count the lengths of the labels beforehand and give a warning to the user when they exceed the upper limit. Then, the user can either abbreviate the names of the items or change the unit and data so that the labels have seven letters or less.

In the pie chart with a descending order, the proportions of the last few items are small and their labels are inevitably located close to each other. As Braille text occupies wider space than ordinary fonts, the labels in Braille are inclined to overlap with each other. This issue is discussed further in Sect. 7.3.

6. Evaluation 2: Usability of Web Application

As Evaluation 2, we conducted a usability experiment to confirm that blind people could create tactile graphs using our Web application.

6.1 Participants

Because operations of the Web application using a screen reader were the main focus of the experiment, one of the requirements for participation was the daily use of screen readers to access the Web. Participants of this experiment

were also engaged in an evaluation of the legibility of the tactile graphs. The second requirement for participation was therefore experience in using tactile graphs at schools for the blind.

Seven totally blind persons who met both requirements participated in the two experiments. All of them were 21 to 26 years of age. Four were men and three were women. Each had 10 to 16 years of experience in using screen readers and 12 to 20 years of experience in using Braille. Four participants used Braille every day, one nearly every day, and one two to three days a week; one participant did not read Braille every day (because he met his needs with a screen reader.)

6.2 Apparatus

Apparatus used were a notebook PC (Dynabook RX3MT, Toshiba [CPU: Intel Core i5-M560, memory: 2 GB, OS: Windows 7]), a laser printer (LP-S120, Epson), and a capsule paper heater (PIAF, Quantum Technology). Screen reader software (PC-Talker, Kochi System Development) was installed in the PC. Internet Explorer 10 was used as the browser. Zy-Tech 2 paper in A4 size (Zychem) was used as capsule paper.

6.3 Method

The experiment was conducted in a quiet room. It was composed of the following steps: an explanation of the overall goals of the experiment, practice in using the Web application, and the experiment on using it.

As practice in using the Web application, each participant created a tactile bar chart in accordance with the instructions. After practicing, the actual experiment was carried out, with participants creating sheets containing one graph each—pie chart, line graph, and scatter plot—using various data.

The CSV files used to create the graphs were selected from the data used in Evaluation 1. The selected file name, type of graph, font, use or non-use of grid lines, graph title, x-axis title, and y-axis title of each graph were conveyed to the participants verbally at appropriate times.

The use of the Web application consisted of using push buttons (and ensuing file selection in a dialog box), using radio buttons, and text inputting. The experimenters observed the operability of each operation.

6.4 Results and Discussion

Six participants could operate push buttons, radio buttons, and text boxes via the screen reader's voice feedback to create three tactile graphs per person and put them through the capsule paper heater to make them tangible. One participant, however, was only able to make one tactile graph and gave up on the other two due to frequent program hang-ups.

Two issues during the operations were observed. The

first issue occurred when participants were not able to operate the "Select File" push button with the Enter key. The problem was circumvented by pressing the Space key. Another issue was that the application sometimes hanged when another CSV file was read in after a graph was created. This problem was circumvented by pressing the F5 key to re-read the Web page, or by restarting Internet Explorer.

Because using buttons by pressing the Enter key is a general operation, it needs to be possible for the application's usability. Therefore, instead of the file input combobox currently being used, a push button that works with the Enter key should be used.

Concerning the program hanging, there was no consistency (type of data, immediate previous operation) to this occurrence, so its cause is not clear. Because the hanging occurred when re-reading the Web page and the Web application kept on working without modifying the program, it seems that poor wireless Internet connection might be the cause. Still, we need to keep on exploring the reason by accumulating cases in which this hanging occurs.

7. Evaluation 3: Legibility of Tactile Graphs

As Evaluation 3, we conducted a legibility experiment to confirm that blind people could understand the tactile graphs produced by this Web application.

7.1 Method

The participants in Evaluation 3 were the same as those in Evaluation 2.

We used a total of 12 tactile graphs that were created by our Web application: three sheets each of four types of graph. The graph data were selected from those used in Evaluation 1.

The experiment was carried out in a quiet room with each participant one by one. The participant sat on a chair and touched the tactile graphs on the table. The experimenter handed the participant one tactile graph per trial in the order of bar chart, pie chart, line graph, and scatter plot. After handing over the graph, the experimenter verbally asked the participant one or four questions (elaborated upon in the next paragraph). Participants were allowed to take as much time as they needed to find an answer. After examining three graphs of the same type, participants were asked to evaluate the legibility of the tactile symbols (elaborated upon two paragraphs later). Finally, the participants responded to a question on the legibility of Braille by choosing a response from three choices.

The participants were required to answer questions related to the contents of each graph. For the bar chart, pie chart, and line graph, questions were asked about the maximum and minimum data items and their values. These questions were selected on the basis of a paper on tactile graphs [23] and several quiz Web sites on graphs [24]–[26]. Because the purpose of the scatter plot was to present a data trend [27], participants were asked to choose the data trend

from three choices: positive correlation, negative correlation, or no correlation.

To subjectively evaluate the legibility of the tactile graph, participants were given two or three choices as responses to questions on whether graph lines and plots could be easily distinguished from grid lines and the border. In addition, we solicited their comments on each graph type.

7.2 Results

7.2.1 Bar Chart

The rate of correctly identifying the item with the maximum value was 86% (Fig. 7, Bar Chart, Q1). The rate of correctly identifying the item with the minimum value was 86% (Q3). Both rates were high. For wrong answers, the item with either the second highest value or the second lowest value was chosen.

The correct answer rate for reading the maximum value was high, at 86% (Q2). In the bar charts used in this experiment, the maximum of the x-axis was automatically set to the maximum values of the data by R. Therefore, it was easy for the participants to obtain the correct answer to the maximum value questions. This is the reason for the high correct answer rate.

In contrast, the correct answer rate for reading the minimal value was low, at 19% (Q4). The minimal value of the x-axis, 0, did not coincide with the minimum values of the data. The participants therefore had to guess the minimum value from nearby tick mark values. This led to incorrect answers.

To the subjective legibility evaluation questions, all seven participants responded that they could easily distinguish between the bars and the grid lines (Fig. 8, Bar Chart, Q1). Six of the seven participants responded that they could easily distinguish between the bars and the border. One person responded that distinguishing the difference was not

easy (Q2).

The participants' comments about the bar charts were as follows. Three participants preferred bars filled with a texture to blank bars. One participant wished the grid lines were dotted lines and one preferred no grid lines. One participant said that the x-axis numbers should be round.

7.2.2 Pie Chart

In the pie charts used in this experiment, items were arranged clockwise in a descending order and their proportions were written in Braille. Thus, the correct answer rates for both identifying the item with the maximum value and reading the maximum value were 100% (Fig. 7, Pie Chart, Q1 and Q2). However, one participant overlooked the last item, which lowered the correct rates for identifying the item with the minimum value and reading the minimum value to 86% and 90%, respectively (Q3 and Q4).

To the subjective legibility evaluation questions, five out of seven participants responded that reading the proportions from the shape of the pie (or from the labels) was easy (Fig. 8, Pie Chart, Q1).

The participants' comments about the pie charts were as follows. Two participants wished the labels were located in the pie for quick understanding. One participant raised two issues related to the labels: the labels were too close to each other and the space between a label and the value was too narrow. Two participants said it was difficult to grasp the shape of the pie charts. Two participant said the values following the labels helped in understanding the charts.

7.2.3 Line Graph

The rate of correctly identifying the item with the maximum value was 81%, a high rate (Fig. 7, Line Graph, Q1). The rate of correctly identifying the item with the minimum value was 71% (Q3), lower by 10% than that for the max-

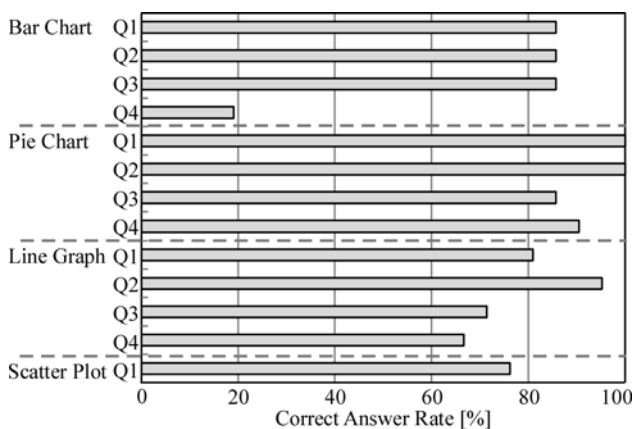


Fig. 7 Correct answer rates for graph contents questions. For bar charts, pie charts, and line graphs, Q1: Item with maximum value, Q2: Maximum value, Q3: Item with minimum value, Q4: Minimum value. For scatter plots, Q1: Data trend.

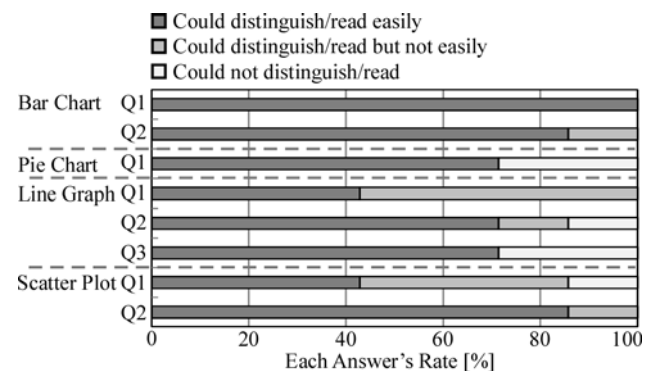


Fig. 8 Subjective evaluation of tactile legibility. For bar charts, Q1: Distinguish between bars and grid lines, Q2: Distinguish between bars and border. For pie charts, Q1: Read the proportions. For line graphs, Q1: Distinguish between graph lines and grid lines, Q2: Distinguish between graph lines and border, Q3: Distinguish between graph lines and plots. For scatter plots, Q1: Distinguish between plots and grid lines, Q2: Distinguish between plots and border.

imum value. For wrong answers, either the item with the second highest or the second lowest value was chosen. One participant seemed to misunderstand how to read the line graph: the value was bigger to the right.

The correct answer rate for reading the maximum value was also high, at 95% (Q2). This is because, like the bar charts, the maximum value of the data in a line graph corresponded with the maximum of the y-axis. Unlike in the bar charts, in the line graphs the minimum value of the data also corresponded with the minimum of the y-axis. Thus, the correct answer rate for reading the minimum value was 67% (Q4), higher than that for the bar charts. Four out of seven incorrect answers stem from incorrect answers to Q3: one incorrect answer read the wrong grid number and two answer provided a round figure near the minimum value.

To the subjective legibility evaluation questions, three participants responded that it was easy to distinguish between the graph lines and the grid lines. Four other participants responded that distinguishing them was not easy (Fig. 8, Line Graph, Q1). Five of the four participants said that distinguishing between the graph lines and the border was easy. One participant could distinguish between the two but said that it was not easy, and one participant could not distinguish the difference (Q2). As for distinguishing between the graph lines and the plot points, five participants responded that it was easy. Two participant responded that she could not distinguish the difference (Q3).

The participants' comments about the line graphs were as follows. Two participants said that some vertical grid lines were missing, which made reading the graphs hard. One participant said that when the graph line was steep, it was difficult to distinguish it from the grid lines. Similarly, two participants wished that grid lines were expressed as dots embossed on the back of the paper or as dotted lines for distinguishability. One participant said that the grid values should be round.

7.2.4 Scatter Plot

The rate of correctly identifying the scatter plots' data trend was 76% (Fig. 7, Scatter Plot, Q1). Four incorrect answer considered the scattering of the plots as "no relationship." One other incorrect answer mistook "positive correction" for "negative correlation." These "errors" suggest the difficulty in grasping the trend out of many scattered plots by touch.

To the subjective legibility evaluation questions, three participants answered that it was easy to distinguish between the plots and the grid lines. Three participant responded that distinguishing between them was not easy, and one participant responded that he or she could not do it (Fig. 8, Scatter Plot, Q1). Six participants said it was easy to distinguish between the plots and the border (Q2).

One participant said that more height for plots would have improved the legibility of the graphs.

7.2.5 Braille

All seven participants responded that Braille was easy to read.

A Braille translation error was found by the participants. According to the Braille Authority of Japan, negative numbers must be written in the order of the minus sign, the number sign, and numbers [28]. However, our software output the number sign, hyphen, and then numbers. This error occurred because our software put the number sign before the numbers automatically regardless of whether a number was positive or negative. This bug must be corrected.

7.3 Discussion

Because the correct answer rates for questions on graph contents were mostly high (Fig. 7), it is safe to conclude that blind people can grasp summaries of data from the tactile graphs produced by our Web application.

However, several issues were observed concerning the legibility of individual tactile symbols of the graphs and R's plotting capability. We discuss here solutions to those issues raised by two or more participants.

7.3.1 Improvements on Tactile Symbols

We had designed the graph elements so that the graph lines and grid lines could be distinguished by the width of the lines. However, both lines were difficult to distinguish from each other when their angles became close to each other. Participants therefore suggested changing the type of grid lines for not only line graphs but also bar charts.

In the case of Braille embossing, a method called "reversed dot" is available [12], where the embossing is done on the side of the sheet opposite from the usual embossing. Lines and surface patterns created by this method have a unique texture and can be clearly distinguished from raised lines. Tactile graphs made by an embosser include grid lines with this method. However, because capsule paper raises only in one direction, this method is not possible. Thus, we are exploring methods of using dotted lines, as suggested by participants. We must pursue further experiments to create dotted lines that allow grid lines to be clearly distinguishable when graph lines are made solid lines.

For bar charts, three participants desired the bars to be filled. Filling bars with a texture is a general method in embossed tactile graphs [12], and the participants are accustomed to this practice. R has a function to fill the inside of bars with a texture and we are going to use it. The appropriate texture for legibility must be chosen through a further experiment.

Concerning the position of labels in the pie charts, a suggestion was made to place the label inside the pie, and issues of the labels being too close together and even overlapping were raised. To follow this suggestion and address these issues, labels must be located at the desired positions

precisely. However, R's graphic functions do not always allow for this. Therefore, we believe a practical solution is to create only the pie chart image with R and then have sighted users place the Braille labels at the appropriate locations on top of the image.

7.3.2 R's Graphic Issues

Users and developers of R recognize that the software has issues of non-round numbers at the axes and missing grid lines. Fortunately, solutions to these problems are currently being developed (for example, [29]). We will resolve these issues by tracking such information and using the appropriate version of R.

8. Conclusion

We have developed software that uses R statistics software to automatically generate tactile graphs. We have released this software as a Web application to make it available to anyone, from anywhere. This software allows the user to generate a tactile graph immediately by selecting a CSV file and providing other information such as the graph title.

Aside from modifying the software as described in the discussion, we will work on the following two issues:

(1) Enabling the generation of other types of graph

We will make it possible to generate other forms of tactile graphs, such as histograms and graphs of mathematical functions.

(2) Improvement of text input method

The current software requires the user to translate ordinary text into Braille when inputting Japanese text from textboxes. This can be a burden for the user who is not necessarily familiar with Braille. To resolve this issue, we are planning to use the Japanese-into-Braille Translating Server [30].

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