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Experimenting with Automatic Text-to-Diagram Conversion: A Novel Teaching Aid for the Blind People

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ABSTRACT

Diagram describing texts are integral part of science and engineering subjects including geometry, physics, engineering drawing, etc. In order to understand such text, one, at first, tries to draw or perceive the underlying diagram. For perception of the blind students such diagrams need to be drawn in some non-visual accessible form like tactile graphics. Technologies for producing tactile graphics are available but they are too expensive to be afforded by the blind students or schools in developing countries like India. As a result, science education for a large population of blind students is severely compromised. This paper proposes a novel solution to this problem. A method for digital to Braille mapping of geometry diagrams on the low-cost traditional Braille text printer is reported here. Later on, this is integrated with a previously developed text-to-diagram conversion system. Using the integrated system, a blind student can input a geometry word problem and perceive the underlying diagram on a Braille printout. The major part of the study involves rigorous evaluation of the system at a Blind school. The enthusiasm and the ability shown by the subjects in using the system strongly attest its viability as an effective teaching/learning tool for the blind students.

Keywords

Artificial intelligence, Geometry diagrams, Natural language problem, Tactile graphics, Blind people

Introduction

In many branches of study, we often encounter texts or problems that are visually represented by figures or diagrams. For example, in geometry, physics (mechanics) and in several engineering branches like mechanical, electrical, and electronics such texts appear very frequently. While solving a problem, usually, a problem statement (text) is first translated into a sketch (diagram) which visually articulates the essential problem parts; mechanical models, free-body diagrams, electrical/electronic circuits, geometry diagrams are instances of such transformation. From the point of view of understanding a problem, the representative diagrams are not only a mere convenience but also an inherent component in a person's cognitive representation of the text or problem. A blind person might rely on and need such diagrammatic representations just as much as a sighted user does and appropriate tactile representation may play that role.

For the sighted users, standard textbooks of science and engineering are widely available that contain numerous examples illustrated with diagrams. On the contrary, similar textbooks with embossed illustrations are not easily available to the blind students. This may be attributed to the fact that producing tactile versions of large number of figures for textbooks is a time consuming, labor intensive and costly process. In a classroom of sighted students, teachers can explain any topic or problem with free-hand sketch of suitable diagrams on blackboard. They can also use computer-based teaching (CBT) tools for better presentation of text and graphics. For the blind students, there are Braille image embossers and compatible graphics programs like *IVEO Viewer* (Viewplus, 2013), *PictureBraille* (PictureBraille, 2013), *TGD Pro* (Duxbury Systems Products, 2013), *Tiger Software* (ViewPlus Tiger Software Suite, 2013), *TACTICS* (Way & Barner, 1997), etc. using which a teacher can generate tactile diagrams from printed or digital diagrams. Also there exist sophisticated audio-tactile, audio-haptic, and multimodal interfaces, developed to produce diagrams in a form accessible to the blind students. Some of the examples are *IC2D* (Hesham & James, 1999), *TDraw* (Kurze, 1996), *NOMAD* (Parkes, 1991), *Talking Tactile Tablet* (Landau & Gourgey, 2003), *Touch Tiles* (Bussel, 2003), *IVEO* touchpad (Krufka & Barner, 2005), *DESENVOX* (Borges & Jansen, 1999), *AudioTact*(Barbieri et al., 2008) *Math Class* (Albert, 2006), and *SALOME* (Gouy-Pailler et al., 2007). Some interesting applications have been developed by Minagawa & Ohnishi (1996), Jayant et al. (2007), Watanabe et al. (2006), Guha & Anand (1992), Lahav & Mioduser (2008), and Toennies et al. (2011). But all such systems including Braille embossers are very expensive (cost of embossers ranging from US$ 5000 to 26,000) and hence not available in most of the blind schools in India. At best the schools can have access to traditional Braille text printers that cannot print tactile image.

Thus a large population of blind students in developing countries (Casely-Hayford & Lynch, 2003) like India grows up without any exposure to modern learning aids for diagram-based subjects like geometry. Historically, teaching geometry to these students is limited to giving basic theoretical definitions only and exercises requiring frequent diagram drawing are deliberately avoided. Though nail board or wooden pieces are sometimes used to perceive simple diagrams in lower grades, the lack of frequent access to tactile diagrams of wide varieties results in students memorizing facts as verbal assertions and this seriously limits the development of their scientific skill. In many parts of India, even today, blind students are forced to leave studying science subjects after 7th or 8th grade because of inconvenience of learning diagrams (Rahman et al., 2010). Herein lies the need for affordable and easy-to-use technology that could facilitate diagram drawing in tactile form upon reading a geometry text or problem. This paper is motivated by this need.

The paper reports a novel method by which digital diagrams can be converted to tactile diagrams using low-cost traditional Braille text printer. Keeping the primary focus on representing basic digital shapes (line and circle) in Braille, the paper further establishes how such shapes (and eventually, any geometric diagram) can be generated by the blind students themselves through text mode of input. In the process it integrates the Braille mapping module with our earlier developed system of automatic conversion of geometric text to digital diagrams (Mukherjee & Garain, 2009), the system comprising a geometry knowledgebase (Mukherjee et al., 2007), a NLP module (Mukherjee et al., 2013), and a graphics module.

Figure 1 shows a schematic diagram of the whole system that integrates the text-to-diagram conversion module with the Braille mapping module. This paper focuses on the part shown within the dotted lines. The main focus of the paper is, however, the user evaluation and impact analysis of the entire system of automatically generating geometry diagram on Braille.

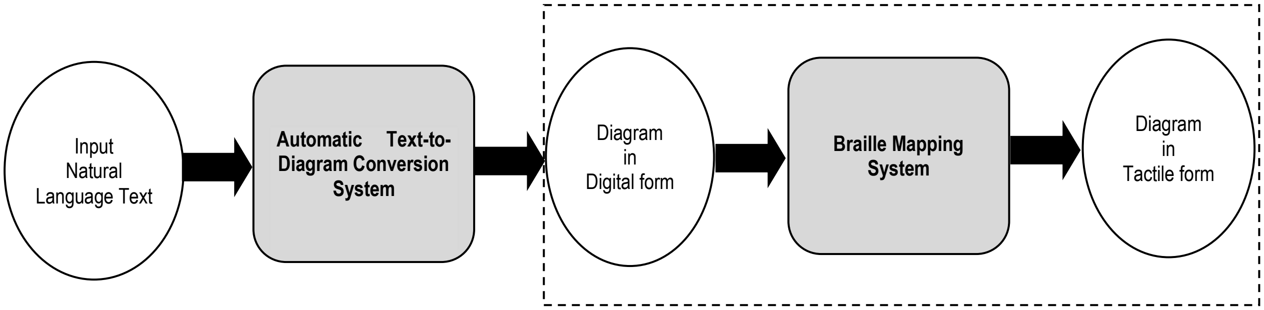


*Figure 1.*The connection between the system of automatic diagram drawing from text and the proposed Braille mapping system (within dotted boundary).

Drawing in Braille

Braille is a system commonly used by the blind people to read and write. In computer graphics, the smallest addressable picture elements are pixels. In Braille, the smallest physical unit is an embossed dot, while the smallest logical unit is a Braille cell –a 3 x 2 array of 6 dot-positions. While each pixel can display a color according to the bitmap value, each dot of a Braille cell may be in embossed state depending on the NUMBRL code (Krebs, 1977) of the character to be represented in that cell. A given NUMBRL code corresponds to a character of English alphabet or a punctuation symbol or a digit.

NUMBRL is basically a numeric code that represents the dot patterns in Braille cells. Each dot in a cell has a fixed position value (Figure 2b). The NUMBRL code of a cell is just the sum of the position values of the embossed dots of the cell. For example, consider a cell with embossed dot positions 4-2-6 (Figure 2a). The NUMBRL code for this cell is 1+20+4 = 25.

○ 1	● 4	**10**	**1**
● 2	o 5	**20**	**2**
○ 3	● 6	**40**	**4**
(a)		(b)	

Figure 2.(a) Dot positions (b) Position values

As there are 6 dots in a Braille cell the number of different patterns or characters (NUMBRL codes) that can be generated in a cell by embossing a subset of 6 dots at a time is 2^6 or 64.

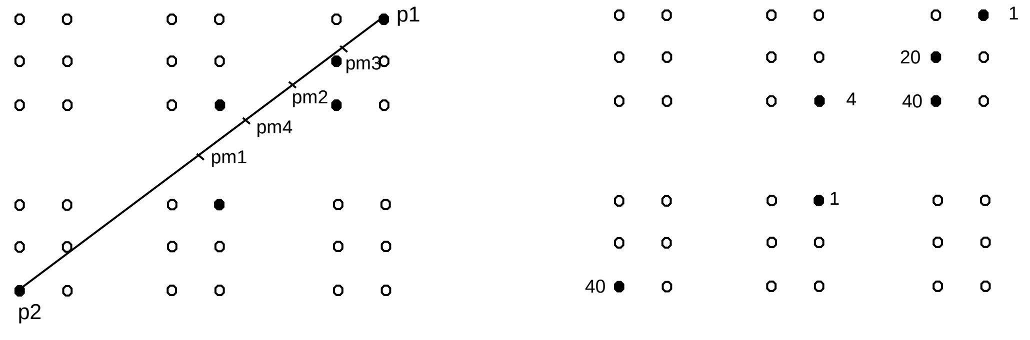
In digital graphics (Rogers, 1985), we can algorithmically select and illuminate a set of pixels to generate a line or circle. Similarly, in Braille, the first problem is to identify which dots in which cells are to be embossed for the best possible representation of a line or circle. Next cell-wise patterns of identified dots or the NUMBRL codes are passed on to a Braille text printer for producing the Braille-text version of a line or circle.

Digital to Braille mapping

To demonstrate the actual implementation of the Braille mapping system we have made a simulation of Braille character mapping of geometric entities. An array of 6-pixel groups displayed on the computer screen emulates the grid of 6-dot Braille cells printed by a Braille text printer on Braille sheet. One Braille dot having diameter of 1.5 mm is represented by a pixel. The distance between two adjacent dots in a cell is kept uniform (2.4 mm) while the horizontal and vertical distances between two corresponding dots in adjacent cells are set unequal (6.8 mm and 10.1 mm respectively) as usually found in the traditional Braille system. In our experiment, we have used an Automatic Braille Embosser (BPRT) developed by Webel Mediatronics Limited. This is basically a Perkins Brailler and costs about US $3000.

Braille mapping of basic entities

Standard graphics algorithms for drawing digital lines or circles are modified using a Braille mapping function to search Braille dots that lie closest to the line or circle path. The function measures and compares the distance of a point (on line or circle) from each of the Braille dots that fall within a small square region around the point. The dot that gives the least distance is the nearest dot found in a search and its position is saved. Pixels at all such dot positions are marked with thick dots to emulate actual embossing of dots by a Braille text printer. Position values of the selected dots in a cell are then added up to find the NUMBRL code of that cell. If no dot is selected in a cell, the NUMBRL value of that cell is 0 which implies that the cell doesn't participate in Braille mapping of a line or circle. The NUMBRL codes of all the cells in the screen array are saved in a text file. As the printer prints the coded characters of the output file row-wise, the line or circle takes shape in Braille. This process is illustrated in Figure 3.



(a) (b)

Figure 3. (a) Corresponding to each digital point (pm1, pm2, etc.) on a line, a Braille dot (dark dot) is selected,(b) The NUMBRL position values shown for the selected dots in a Braille cell; The NUMBRL codes of the cells are (left to right, top to bottom): 0, 4, (20+40+1 =) 61, 40, 1, 0. The output list given by the braille function contains the following triplets: <1 1 0><1 2 4><1 3 61><2 1 40><2 2 1><2 3 0>

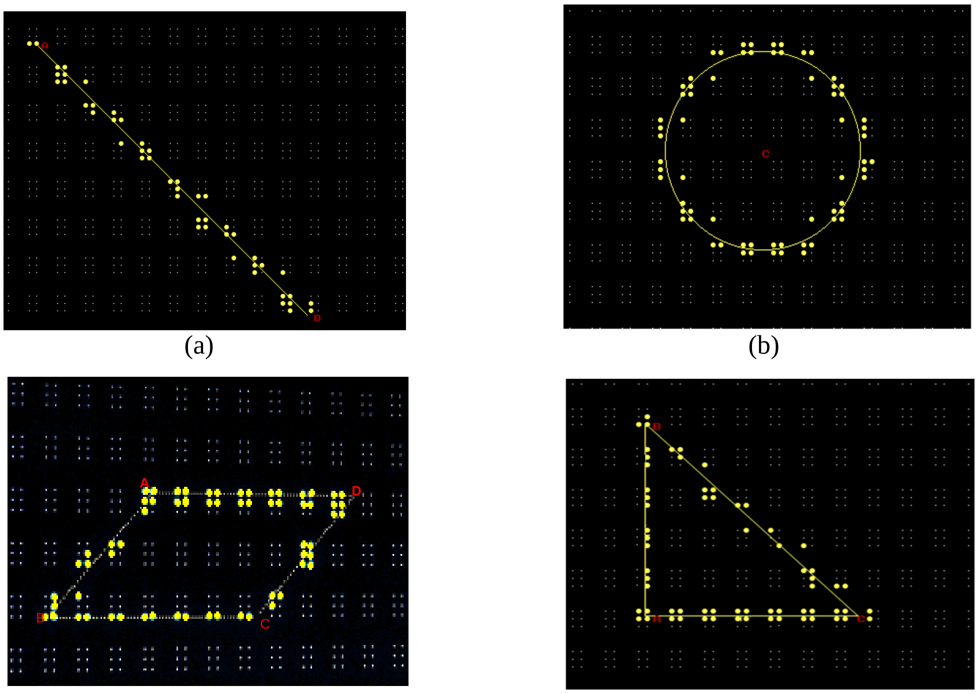
Braille mapping of problem diagrams

The earlier developed text to diagram conversion system (Mukherjee & Garain, 2009) generates numerical values of the parameters of all lines and circles (to be drawn) upon reading the corresponding geometric statements. For example, for a statement like ‘ABCD is a parallelogram’ the numerical values of the endpoint coordinates of the four component lines of the parallelogram ABCD are generated as:

AB: line (100,200),(50,100)
BC: line (50,100),(250,100)
CD: line (250,100),(300,200)
DA: line (300,200),(100,200)

Each of the above output is passed on as input to the Braille mapping module. The Braille line mapping function then creates four Braille lines to produce the Braille version of the parallelogram ABCD. A portion of the emulated Braille character grid and embossed dots approximating different geometric shapes are shown in Figure 4. After generating simple objects, the system is tested for diagrams comprising multiple objects. Given a geometric statement or word problem as input, the representative diagram is automatically generated in Braille. Out of a test set of 40 geometry problems, 32 were drawn correctly by the text-to-digital diagram conversion system. Again these 32 problems produced geometrically correct representations in Braille thereby yielding nearly 100% accuracy rate of text-to-Braille diagram conversion. In the present study we have only used these 32 problems corresponding to which the Braille diagrams are meaningful and useful for learning.

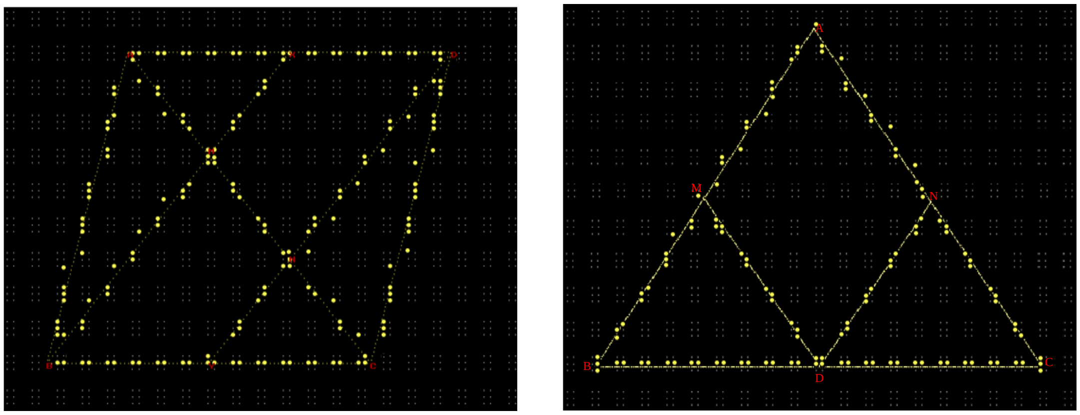
Still to improve the perception of a Braille figure by a blind user and also to improve drawing accuracy, some design optimization is done. Firstly, before Braille mapping, auto-generated digital diagrams are scaled up to fit to the full-screen which in-turn causes printing of enlarged diagrams on Braille paper. Secondly, selection of redundant Braille dots in representing a shape is eliminated using some heuristic functions – at the same time it is ensured that wide gap is not created between two adjacent dots. This is evident from the optimized output (from word problems) shown in Figure 5.



(a) (b)

(c) (d)

Figure 4. Simulation of Braille dot grid and Braille-converted geometric entities; the digital entities are shown in continuous lines while selected Braille dots are shown in thick dots. (a) line, (b) circle, (c) parallelogram, (d) triangle. Point labels are not auto-generated but put here for sake of clarity



(a) (b)

Figure 5. (a) Simulated diagram for the problem: ABCD is a parallelogram. X and Y are the midpoints of AD and BC. BX and DY cuts AC at M and N respectively. Prove that AM = MN = NC, (b) Simulated diagram for the problem: In triangle ABC, AB = AC. D is the midpoint of BC. From D, perpendiculars DM, DN are drawn to AB and AC respectively. Prove that DM = DN.

Comparison with other systems

Three software tools namely *BrlGraphEditor* (Batusic & Urban, 2002), *SparshaChitra* (Lahiri et al., 2005), and the one developed by Rahman et al. (2010) can be considered close (but not similar) to our system as they can convert existing printed images into tactile form using Braille text printer. As described by Rahman et al., each block of 3x2 pixels in a digital image is considered equivalent to a Braille cell (3x2 dots). The pattern of the marked pixels in each block is mapped to yield same pattern of raised dots in the corresponding cell of the Braille grid. All the mapped cells, when printed, reproduce the digital image in tactile format. So the basic approach taken by these systems is linear mapping from an evenly spaced pixel-grid to an unevenly spaced dot-grid which naturally causes some distortion in the geometric shapes. Moreover, the process does not attempt to optimize the number or position of dots to be embossed. It causes redundant dots being selected at positions other than the best possible positions with respect to the actual entity (line or circle) path. Our system, on the contrary, logically finds the dot nearest to the entity path at any sampling position and further optimizes the number of adjacent dots getting selected to make the best possible outline-representation of an entity. To draw a quantitative comparison of the accuracy of the system by Rahman et al. vis-à-vis our system, we have measured the approximation errors of the system outputs using the MSE method. It is found that the MSE of the Braille lines, circles and diagrams drawn in the other system is 2 to 3 times greater or even more than that in our system. Thus it can be stated that unlike other systems, our system produces tactile diagrams from textual description automatically and that too with greater accuracy.

User evaluation and impact analysis

Over a period of nearly seven months pre and post experiment study was conducted at *Blind Boy's School, Narendrapur*. Members of another professional organization for the blind people namely, *Blind Person's Association, Baruipur* also participated in the study. Both the institutions are situated in Kolkata, India. The study and analysis reported here follows the approach similar to that adopted by Chan et al. (2006) and Huang & Shiu (2012) in education technology survey.

Study of existing practice

Given the standard of average blind schools in India, the *Narendrapur* school is quite rich in resource. They have couple of desktop Braille printers or TED (text embossing device) and uses *DBT* (*Duxbury Braille Translator*) software to create Braille documents and print those in raised-dot form using TED. However, not many teachers and students have the skill of producing even simple line diagrams with DBT and TED. Still slate/stylus and nail-board system continues to be popular medium for teaching geometry in the class. The *Baruipur Association* has a costly Braille embosser or PED (plate embossing device) with compatible *TGD* (*Tactile Graphics Design*) software (Figure 6). But owing to the complicated process of producing tactile documents with images PED is rarely used.

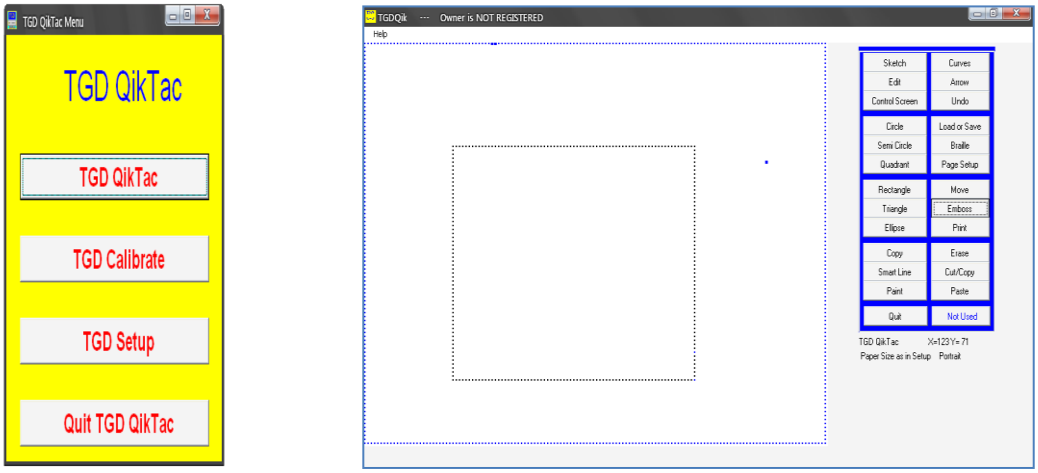


Figure 6. TGD QikTac drawing interface; simple geometric shapes can be drawn on screen and then embossed using costly image embossers

Figure 7. Simple geometric shapes printed in Braille using DBT software

Need analysis

To find out the limitations and problem areas for teaching and learning geometry in a classroom of the blind students, a questionnaire survey was conducted amongst the students of grade VIII to X and teachers of the blind school separately. Group discussions were also held involving all the science teachers and a group of working professionals who are blind. Following is the summary of the facts that came up after qualitative analysis of data collected through questionnaire survey and discussion.

The school does not have enough funding to afford an image embosser which would have been an ideal solution for generating tactile diagrams to help teaching geometry. Drawing diagrams using DBT-TED is a tedious process. One has to type 6-dot characters at suitable positions such that the character chain represents a geometric shape (Figure 7). The majority's opinion was that the nail-board or slate-stylus system is more effective than TGD or DBT though only simple diagrams can be tried with those. Overall, the inconvenience of sharing and accessing diagrams has practically limited teaching geometry to dictating facts and procedures only, deliberately omitting any reference to diagrams. The students also have option to avoid geometry questions in mathematics examinations. Some blind teachers revealed that they themselves were deprived of geometry education owing to lack of learning aids. The exercise revealed the need for a low-cost utility requiring minimal manual operation to serve as a self-learning tool for the blind students as well as a useful teaching aid for diagram-based subjects.

Selecting test subjects

To get a subjective assessment of how different categories of users react to our prototype, seven groups of test subjects as detailed in Table 3 were selected.

Table 3. User profile

Groups	Composition	Average age	Visual Impairment
Group I	4 students of grade VIII (2 male, 2 female)	13 years	Completely blind
Group II	4 students of grade IX (2 male, 2 female)	14 years	Completely blind
Group III	4 students of grade X (2 male, 2 female)	15 years	Completely blind
Group IV	2 senior teachers (1 male, 1 female)	55 years	Sighted
Group V	2 young teachers (1 male, 1 female)	30 years	Sighted
Group VI	2 technical professional (1 male, 1 female)	40 years	Completely blind
Group VII	2 non-technical persons (1 male, 1 female)	30 years	One person completely blind, the other person almost completely blind with deteriorating vision

The sample size in each group was kept small to impart effective training with limited number of trainers and also to ensure that each subject's reaction or performance is observed closely. In the student groups, students from high, low and medium rank category were chosen to test whether the system is equally useful irrespective of the academic merit of the subject. In each group 50% female members were included because female literacy/education is a national issue in India; how the blind female subjects perform with a new learning tool may be significant for further study.

Training and test of recognition of simple geometric objects and relations

Firstly, the working mechanism of our integrated system, its input, and output were verbally explained to all the 7 test groups. Then practical demonstration of the system was given by presenting automatic generation of simple shapes like line, circle, rectangle, triangle (using Braille text printer) corresponding to input statements like "*AB is a line*", "*A circle is centered at O*", "*ABCD is a rectangle*", etc. Next, figures representing relations between two geometric entities e.g., "*AB is perpendicular to CD*", "*Lines AB and CD intersect at E*"etc. were generated and explained. Initially we found most students having difficulty in understanding the output as diagram – they rather read the diagram as Braille text, attempting to pronounce the individual characters that formed the diagram. The teachers were asked to perceive objects through touch only (without seeing) and their performance was similar. At this stage their responses with some tactile shapes printed on Braille sheet using our system was recorded and shown in Figure 8.

Each group was given 2-weeks initial training @ 1.5 hours each day until they were able to perceive Braille character chains as geometric shapes rather than text. In the beginning, concept of tracing the outline of a shape was given. We guided the students' fingers over a figure-outline with verbal commentary and pointed out the key elements of the figure (e.g., sides and vertices of rectangle). Then we trained them to differentiate the shapes by emphasizing the attributes like orientation, length etc. Some students struggled to identify shapes as they did not carefully trace the entire outline. But most subjects could successfully retrace a shape without our help if they were prompted about the object and its starting/ending position. Gradually this support was withdrawn and after a week of practice @ 1 hour each day, the performance of each group in recognizing 10 different geometric objects were recorded (Figure 9a). The 10 objects are – point, line, square, rectangle, parallelogram, pentagon, trapezium, arc, circle and angle. Next, 10 geometric relations each involving two entities (namely, perpendicular lines, parallel lines, intersecting lines, diagonal of a rectangle, bisecting lines, bisector of an angle, tangent to a circle, diameter of a circle, two concentric circles, two intersecting circles) were given to recognize after another 10 days of training-cum-practice @ 1 hour each day. Figure 9b shows the performance of each group.

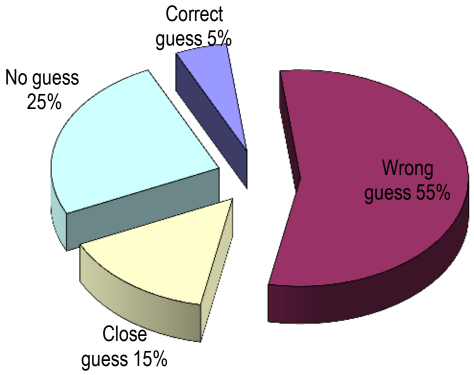


Figure 8. Only 5% guesses were correct, the rest were incorrect; some guesses were very close like identifying a parallelogram as a rectangle

From Figure 9a we find the mean is 6.29 and standard deviation (SD) is 1.50 for the male subjects, while for the female subjects the mean and SD are 6.71 and 1.38 respectively. The t-value is 1 and p=0.3559 (>0.1). In Figure 9b, mean and SD for male and female performances are 5.57, 1.72 and 5.86, 2.19 respectively. Here also the t-value is 1 and p=0.3559 (>0.1). Therefore, the difference in performance of male and female in recognizing both object and object relation is not statistically significant. However, upon calculating the overall means (6.5 and 5.71) from both the charts we find the recognition accuracy diminishes by 12% when more than one entity features in the diagram.

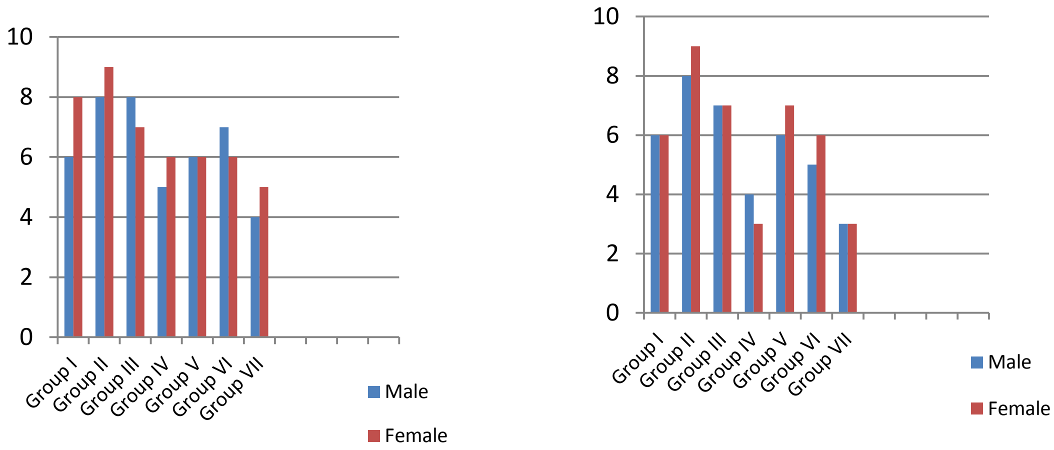


Figure 9. (a) Recognition accuracy for objects generated in Braille, (b) Recognition accuracy for object relations generated in Braille

Students (particularly those belonging to Group II) were quite receptive and they learnt very fast. Out of 10 single objects and 10 configurations (with two objects) given for testing, 7.6 objects and 7.1 relations respectively were recognized correctly by the three student groups on an average. The average students' performance over the two tests was therefore 7.41 or 74.1%. The average performance of the senior teachers was 45% while that of the young teachers was 62.5%. The performance of Group VI and VII were 37.5% and 60% respectively. It was noted that maximum failure occurred for circle, pentagon and parallelogram amongst objects while for tangents, bisector and concentric circles amongst the relations. Similar tests with different object-relation set were conducted at every one week interval and the performance recorded. After one month the average performance of the student groups (Group I, II & III), teacher groups (Group IV & V) and the remaining groups (Group VI & VIII) were 92.5%, 74% and 67% respectively which shows improvement with practice.

Test of classroom teaching-learning

6 experiments, spanning a duration of 3 months, were carried out in classroom environment. A teacher from Group IV or V was assigned to each of Group I, II, III and VI. Each of these four groups was given a desktop Braille text printer and the teachers were given desktop PCs with our system installed in it. Each time the teacher typed a geometry problem in his machine, the problem-diagram was drawn by the system simultaneously in the simulated form in the teachers' machine and in the tactile form through the Braille printer accessed by the students. The test set contained 10 geometry word problems of varying hardness. It was observed that when a diagram was presented as a whole, the students at first could not follow most of the objects and their relations. It seemed difficult for the students to determine whether the elements within a bigger entity (e.g., two smaller lines within a triangle as in Figure 5b) were part of the outer outline or a detail inside the diagram. Then the teacher was asked to verbally dictate a problem one statement at a time to see whether the student could recognize those Braille objects mentioned in the statement. More help was then provided to the students who were still faltering by orientating them to a starting position (like the vertex "X"of a triangle "XYZ") and along a tracing direction (like along a side XY from point "X"). The result was much better this time.

After this initial support, the recognition accuracy was measured in terms of number of diagrams perfectly identified and traced. If they misinterpreted any one object or relation of a diagram we considered it a failure. It was commonly found that as the number of geometric entities/relations increased the problem-diagrams became more complicated and therefore the subjects misinterpreted one or more objects/relations. With repeat tests conducted every 15 days (same problems given in random order), the performance of the subjects gradually improved (Figure 10). To minimize the chance that the students could memorize the patterns and therefore recognize correctly, they were not told about what they did was correct or not in each test. But in-between two tests usual practice (on an average 1hour each day) was given on other simple shapes and diagrams drawn on Braille. In the last test (Test 6), Groups II and III emerged most successful (7 diagrams recognized correctly out of 10 i.e., 70% success). The score of other two Groups were 6 (60%) and 4 (40%) and the average final score of all the groups was 6 (60%). If we look at the respective minimum scores of 3 (30%), 2 (20%) and 1(10%) in the beginning of the test series then the improvement achieved in 3 months is statistically significant (t-value 9.79, $p=0.0023 < 0.01$) and quite encouraging as far as trainability of the technology is concerned. This result also indicates the potential of our system as an effective classroom tool for the blind pupil.

Figure 10. Gradual improvement of performance of each group; performance measured in terms of number of problems (along vertical axis) recognized correctly

Test of self-learning

Finally the students' self-learning ability upon using the system was tested with four groups for more than 1 month. A total of 10 problems were tested @ 2 tests every week. In between tests, the participants practiced themselves and training/help was seldom provided during this period. They were asked to type the text of a word problem as input to the system after reading the same already printed in Braille. Then they were asked to auto-generate the diagram in

Braille and explain the problem with reference to the diagram. All the subjects operated the system comfortably without any significant help and could correlate the problem texts with parts of the diagrams. The average time taken by each group from typing to tracing the auto-generated diagram for each problem is shown in Figure 11. Though initially the time consumed was quite high for all the test groups, later on it came down to 45 minutes for a 3 or 4 line problem. If we can pre-feed the problems in the system (as maximum time was taken for typing a problem) then time required by the subjects to generate and trace the diagrams would come down to around 15 minutes per problem.

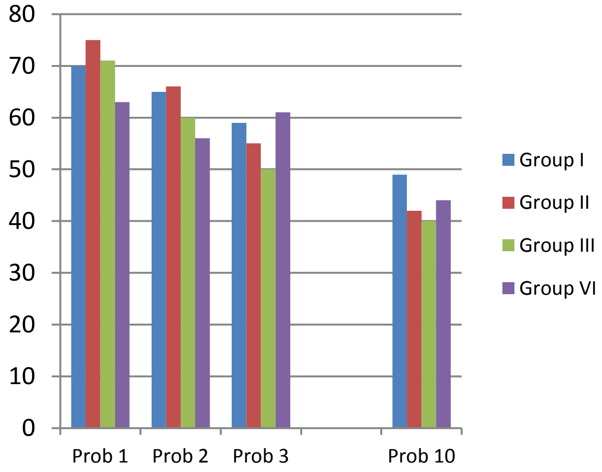


Figure 11. Time taken (in minutes) to draw and trace a problem using the new system

Results and analysis

After a series of trainings followed by tests conducted for around 4.5 months, another questionnaire survey was conducted to get quantitative data on user perception about the new system. Beside the test groups (including 12 students and 8 seniors), 14 more students (i.e., a total of 26 students) participated in this survey as those students (who did not take part in the training) by this time learnt and used the system knowing from their peers of Group I, II and III. Questions were framed to bring out the average value of the evaluation indexes like satisfaction, ease of use, impact and effectiveness. The different indicators under each index and user response against those are illustrated in Tables 4 to 7. Each indicator is assessed on a five-point Likert scale that ranged from 1 (strongly disagree - SDA) to 5 (strongly agree - SA). The values in the columns SA to SDA are the percentage of number of users responded in respective category. Considering the response percentage against each category (SA to SDA) as frequency (f) of occurrence of respective scale values (x), we calculate the mean as $\bar{x} = (\sum \mathrm{xf})/100$ and standard deviation as $\sigma = \sqrt{\sum(\mathrm{x}^2\mathrm{f})/100 - \bar{x}^2}$ against each indicator.

Table 4.Satisfaction

Indicators	SA (5)	A (4)	N (3)	DA (2)	SDA (1)	Mean ($\bar{x}$)	SD (σ)
Satisfied with the tool and willing to use it in class now; could not use the existing tools so effectively	22	64	8	3	3	3.99	0.83
Perceived as a useful tool as any and many geometry problem can be discussed during a class	14	56	22	8	0	3.76	0.79
Perceived as an effective tool as there will be more time for teacher-student interaction	17	66	11	6	0	3.94	0.72
Perceived as a helpful tool as a student can practice geometry problems by his own thus enhancing self-efficacy and confidence level	33	56	11	0	0	4.22	0.63
Average						3.98	0.74

Table 5. Ease of use

Indicators	SA (5)	A (4)	N (3)	DA (2)	SDA (1)	Mean ($\bar{x}$)	SD (σ)
The interface is user-friendly	11	45	28	8	8	3.43	1.85
The operations are simple	22	61	11	3	3	3.96	0.85
It requires no external help	22	56	11	8	3	3.86	0.95
Tracing geometric objects is easy	11	44	6	22	17	3.10	1.33
Flexibility of storing and reusing a diagram once produced	28	61	11	0	0	4.17	0.60
Average						3.70	1.12

Table 6.Impact

Indicators	SA (5)	A (4)	N (3)	DA (2)	SDA (1)	Mean ($\bar{x}$)	SD (σ)
Interesting	39	61	0	0	0	4.39	0.49
Enjoyable	19	58	17	6	0	3.90	0.77
Like	28	56	13	3	0	4.09	0.72
Average						4.13	0.66

Table 7. Effectiveness

Indicators	SA (5)	A (4)	N (3)	DA (2)	SDA (1)	Mean ($\bar{x}$)	SD (σ)
Accurately represents a problem	6	41	28	17	8	3.20	1.05
Minimizes user operation	28	72	0	0	0	4.28	0.45
Minimizes cognitive load of students	19	69	6	6	0	4.01	0.70
Minimizes effort of teacher	30	56	6	0	8	4.00	1.04
Increases learning outcome	33	64	3	0	0	4.30	0.52
Average						3.96	0.75

The average mean of the satisfaction index (Table 4) is 3.98, which implies user's comfort and positive attitude towards using the system. Only 5% (average) users disagreed that the tool is useful, helpful and can be effectively used in the classroom. The Technology Acceptance Model theory (Davis, 1989) states that acceptance and use of a technology is determined by two factors: perceived usefulness and perceived ease of use. From the above statistics, the perceived usefulness is given by $\bar{x}$= 3.76, σ = 0.79 (Table 4) and the average mean for ease of use is 3.70 (Table 5). Simple operation ($\bar{x}$ = 3.96, σ = 0.85) (Table 5) and flexibility of storing the diagrams for future reuse ($\bar{x}$= 4.17, σ = 0.60) (Table 5) are the two aspects accepted by majority. However, there are several reasons behind low scoring against 'Tracing geometric objects is easy' ($\bar{x}$= 3.10, σ = 1.33) (Table 5). Firstly, the subjects were habituated in recognizing the 6-dot Braille characters as text only. With lot of practice and training they were gradually successful in recognizing the Braille character chains as part of diagrams - it was definitely not so easy that they could trace the diagrams correctly at first attempt. If the students are exposed to Braille text based diagrams from lower classes, then tracing complex diagrams will be much easier in higher classes. Secondly, there were some senior teachers and non-technical participants who had a mindset of not welcoming the new technology - they rather felt comfortable with the traditional methods even after accepting limitations of those methods. The young teachers are more receptive and can always be trained easily on this new technology.

Impact gives a general evaluation of the user's reaction to the new system, especially when they used it for the first time. The average mean of 4.13 (Table 6) implies that the users liked it in-spite of possible impeding factors like typing a problem or tracing a diagram which may be time-consuming and training-dependent. Effectiveness measure as shown in Table 7 estimates whether the new system fulfills its specific educational and pedagogical objectives for the target users for whom it has been designed. The low score ($\bar{x}$= 3.20, σ = 1.05) against 'Accurately represents a problem' (Table 7), may be attributed to the inherent poor resolution and non-uniform spacing of the Braille dots which causes unevenness in shapes. It obviously does not mean that the Braille diagrams are geometrically incorrect, rather implies that the smoothness of the Braille lines or circles is not as good as those created using nail-board-elastic band/slate-stylus/PED which produce better perception of tactile geometric objects. Few participants had some previous exposure to figures drawn using those tools/devices. But as a teaching-learning tool our system is quite effective due to certain user-perceived advantages – firstly, diagram drawing is totally automated and it minimizes manual operations which in turn helps to reduce the cognitive load of the student and effort of the teacher in a class. Secondly and more importantly, the students can self-operate the system and learn without assistance. That's why the average mean (3.96) of effectiveness (Table 7) and user's perceived learning outcome ($\bar{x}$= 4.30, σ = 0.52) (Table 7) are quite high.

Conclusions

In the backdrop of limited facility and exposure of the blind students to tactile diagrams in many developing countries, one distinct contribution of our research is that we introduce tactile diagram drawing method based on traditional Braille printer (text-only) because such printer is the cheapest of its kind and commonly available in blind schools in India. The proposed method does not make use of any sophisticated interface rather relies on Braille character cells with uneven spacing of dots to map elements of a diagram already defined for digital display. The system evaluated in this study is capable of representing digital point, straight line, and circle, using Braille code; therefore, any simple geometric shape (like triangle, rectangle, angle etc.) and diagrams comprising many shapes and configurations can be produced using Braille text printer. The existing Braille graphics programs cannot produce shapes on Braille text printer and very limited research can be found on this mode of drawing.

Simply producing tactile diagram from digital diagram at low cost cannot resolve the actual difficulty of learning mathematics by the blind students. It could have certainly given them significant accessibility benefit, but it could not be used as a self-operated learning tool had it not been integrated with our earlier developed text-to-diagram conversion system (that produces digital diagrams from textual description in natural language (English)). As a result of this integration, a blind student can create and access diagrams without any human assistance. The system is also tested to be helpful for the teacher as it significantly eases his effort in creating and presenting accessible graphics for the blind students in a geometry class. In the review of NLP-based systems (Mukherjee & Garain, 2008) we hardly find any automated approach for producing diagrams (for blind learners) directly from word description of mathematical problems.

The core contribution of this study is the series of field tests conducted with blind students studying at different grades, teachers and blind persons in profession. To evaluate the actual utility of the low-cost Braille version of geometry diagrams we have tested the integrated system as a whole. The acceptance of our system is reflected in the interest generated in our subjects; most of them could recognize the Braille shapes with reasonable accuracy and could relate the Braille diagrams to the problem statements within a short learning time. The results of the usability tests, pre and post-test questionnaire survey underline the need and impact of such an affordable teaching-learning aid for the blind community.

The experiments with the system hint that there is enough scope for improvement in the Braille conversion algorithms. In future, we hope to make even better Braille approximation of graphic entities so that users do not confuse inner details with outlines of a diagram. Future measures like systematic training from lower classes, addition of voice guidance utility and step-by-step diagram drawing facility would definitely help in enhancing the recognition accuracy. Some other issues are to be addressed in future. One of them is addition of editing and scaling capability. Labeling of points on a diagram has been deliberately ignored in the present study (to avoid confusion of the subjects) and hence it is taken up in the 2nd phase of our research. We plan to integrate our text-to-diagram conversion module with other existing Braille graphics software tools (like QikTac, IVEO Viewer, etc.) so as to generate tactile graphics using high-end image embossers. Infrastructural constraints restricted our experiments with limited number of users. In future, experiment with larger sets of test subjects and word problems will bring out more general observations. Moreover, we can make further survey with a control group of users to compare the learning outcome in two systems.

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