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EMPOWERING BLIND STUDENTS WITH HIGH-QUALITY TACTILE GRAPHICS FOR STEM EDUCATION

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Abstract:

This study explores the essential features and design strategies required to produce high-quality graphics that effectively support blind students in Science, Technology, Engineering and Mathematics (STEM) education. This study involved individual semi-structured interviews with 19 blind students aged 14 to 17 years, enrolled at a secondary school for visually impaired students in Malaysia, in 2024. Each interview, lasting between 30 and 45 minutes, was meant to address the exact design flaws and cognitive obstacles that occurred during the exploration of STEM tactile graphics. Data were collected through audio recordings that were later transcribed verbatim. A systematic thematic analysis by Atlas.ti software allows identifications of key themes. Every student (100%) indicated an absence of access to assistive tools tailored for tactile graphic exploration, while also demonstrating the urgency for such resources. Furthermore, 84.2%

emphasized substantial obstacles in the exploration of tactile graphics, especially regarding gridlines. These challenges became worse when gridlines were excessively small, overlapping with other components, or appeared like braille dot labels, leading to increased confusion. These findings reveal the urgency for improved tactile design. The framework developed in this study is important for informing the development of high-quality tactile graphics so that a systematic approach can be developed to address design deficiencies and cognitive challenges faced by blind students. In addition, clear and identifiable textures and systematic guidance such as step-by-step navigation are of great importance in making it better understood and more accessible. This framework enhances STEM Mathematics accessibility and promotes independent learning among blind students.

Keyword:

Blind Student, Cognitive Load, Inclusive Education, Tactile Graphics, Visual Impairments

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Introduction

United Nations' Sustainable Development Goal 4 (SDG 4) aims to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all, including individuals with special needs (United Nation, 2015). However, most information is presented in graphical formats, making it difficult for blind students to access it (Melfi et al., 2020).

In the STEM disciplines, which are largely based on visual materials, take shape in mathematics or the anatomy of the heart in science, tactile graphics become very important, providing essential information and thus providing blind students with access to key information (Thévin et al., 2019; Bahrin et al., 2023; Melfi et al., 2020). They are created using various methods (Muhammad Ikmal Hakim et al., 2019) and include features like embossed lines, various textures, and different heights to help visually impaired students to read graphics through touch (Miller et al., 2010; Park, 2022; Rozniza & Lee, 2022). Instead, tactile graphics are carefully adapted, rather than simply being replicas of visual graphics, to ensure their clarity and accessibility for students who are blind (Miller et al., 2010).

However, tactile graphics do not always deliver the information as effectively as original visual graphics (Yang et al., 2020; Shoaib et al., 2023). Blind students often face increased cognitive loads and memory burdens when using complex tactile graphics, making it difficult for them to identify and imagine two-dimensional objects and understand complex information. As a result, they usually need help from sighted people, either teacher or peers, to fully understand STEM-related tactile graphics (Chase et al., 2020; Gong et al., 2020; Bahrin et al., 2023).

Although tactile graphics can be used to represent a graph, geometric problems, data presentation, and more, their effectiveness is limited by the density of information, which increases their complexity (Abrahamson et al., 2019). It's hard for them to identify whether a line is just a simple line or part of a bigger shape. They have to keep touching and tracing the whole line to determine it (Nguyen et al., 2018). Moreover, the blind respondents have problems when tracing graphs with sharp peaks because they usually misunderstand and think that the peak has no continuation (Fan et al., 2022). These challenges highlight the urgency for a structured approach toward improving STEM tactile graphic design and accessibility for students who are blind.

This research aims to overcome these critical gaps by developing a high-quality STEM tactile graphic framework that is designed to improve the ability of blind students to explore tactile graphics independently and easily, by reducing cognitive load and sustaining motivation and their well-being. Unless there is focused research on this topic, blind students will continue to be at a disadvantage in STEM education and face the barriers that come with low-quality tactile graphics.

Semi-structured interviews were carried out with 19 blind students to identify the main factors that influence their exploration of STEM tactile graphics. This research is guided by the following questions: 1) How do poorly designed STEM tactile graphics increase cognitive load and make it difficult for blind students to understand and use them? 2) What are the high-quality specifications of tactile graphics that can enhance exploration, decrease cognitive load, and sustain motivation and well-being?.

Research Method

Research Design

This research involved 19 students who are blind, from a specialized secondary school. This study was conducted in 2024 at Kuala Lumpur, Malaysia. Each participant took part in one-on-one interviews lasting 30 to 40 minutes. The interview questions were developed as an initial draft to guide the semi-structured format, ensuring flexibility to explore participants' unique experiences.

Participants

The participants in this study were 19 students from a specialized secondary school for students with visual impairments, ranging in age from 14 to 17 years. They were distributed across Form 2 (14 years), Form 3 (15 years), and Form 4 (17 years). The group consisted of 7 females and 12 males, with demographic details summarized in Table 1. All participants were fully informed about the study and provided their consent. To maintain confidentiality, their names and personal information were anonymized and referred to using tags such as S1, S2, and so on.

Table 1: Demographic Information of Participants

Variable	Participants	
	Male	Female
Age	12	7
14	1 (8.33%)	3 (42.86%)
15	4 (33.33%)	2 (28.57%)
16	5 (41.67%)	2 (28.57%)
17	2 (16.67%)	0 (0.0%)
Form		
Form 2	2 (16.67%)	3 (42.86%)
Form 3	3 (25.00%)	2 (28.57%)
Form 4	7 (58.33%)	2 (28.57%)
Visual impairment categories		
Near vision loss	2 (16.67%)	5 (71.43%)
Profound vision loss	1 (8.33%)	0 (0.0%)
Total vision loss	9 (75.00%)	2 (28.57%)

The data shows that the highest participants were 16 years old (n = 7, 36.84%), then 15 years old (n = 6, 31. 58%), 14 (n = 4, 21.05%), and 17 (n = 2, 10.53%). Overall, the sample is mainly concentrated within the mid-adolescent age range, particularly between 15 and 16 years, which is an important stage for cognitive development and the understanding of mathematical concepts.

The participants were drawn from three forms: Form 2, Form 3, and Form 4. Most of them were from Form 4 (n = 9, 47.37%), while five students (n = 5, 26.32%) are from Form 2 and Form 3. This shows that the sample is more towards upper secondary students, who are generally expected to have more developed abstract thinking and problem-solving skills than others. This is relevant to the study, which focuses on the use of artificial intelligence algorithms to support the understanding of tactile graphical transformations

This researched included 12 male students (63. 16%) and 7 female students (36.84%). Most participants were classified as totally blind (n = 11, 57. 89%), followed by near vision loss (n = 7, 36.84%) and profound vision loss (n = 1, 5.26%). This indicates that many of the participants depend largely on non-visual ways of learning, highlighting the importance of assistive tools such as tactile graphics and AI-supported approaches in supporting independent learning.

Data Collection

First, interview questions were prepared by focusing on the problems encountered with respect to the quality and specifications of the tactile graphics and the suggested improvements by the student. The questions were validated by experts in special education for relevance and clarity. The interviews were one-on-one semi-structured format, with additional follow-up questions in order to bring out deeper insights. Table 2 outlines the key questions asked during the interviews. All sessions were audio-recorded for further detailed analysis.

Table 2: Core Interview Questions

No.	Core Interview Questions
1	What makes it difficult for you to explore STEM tactile graphics?
2	What specific elements in tactile graphics do you find challenging to identify, and why do you think they are difficult to recognize or interpret?
3	What are the characteristics of STEM tactile graphics that make them easy to explore?

Data Analysis

Ethical approval for this study was secured from the institutional ethics review board. This research followed the guidelines by Braun and Clarke (2006), emphasizing that each interview must be recorded and transcribed verbatim. Thematic analysis was employed to organize the data into appropriate themes and subthemes.

After the transcription process completed, all documents were repeatedly reviewed and systematically coded with relevant labels. Next, these codes were organized into subthemes and overarching themes using the network tools in ATLAS.ti software. This process resulted in 319 unique codes, identified from 944 quotes taken from the 19 interviews.

Figure 1 presents the critical aspects of High-Quality Tactile Graphics, focusing on five themes: Guidance, Cognitive Load, Gridlines, Label, and Texture. Each of these themes presents specific challenges that students who are blind face in their exploration of tactile graphics in STEM.

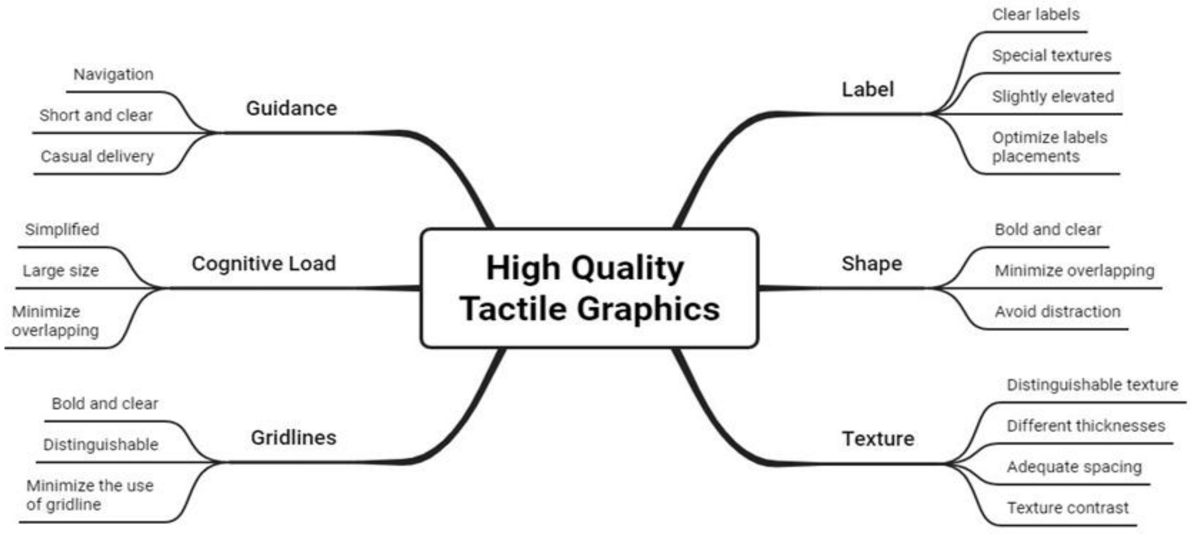

Figure 1: Network Diagram for High Quality Tactile Graphics

Validity and Reliability

To ensure data reliability, follow-up group interviews were conducted, allowing participants to validate their perspectives. These interviews also helped cross-check individual responses, deepening the analysis. Data triangulation compared results from individual and group interviews to maintain consistency. Peer debriefing was included, with experts in special education and tactile graphics, reviewing the coding framework and themes. This feedback ensured alignment with established research and improved accuracy. Together, these methods minimized bias and strengthened the study's credibility, ensuring the findings accurately represented participants' experiences.

Results and Discussion

The ability to fully understand the tactile graphics is highly depends on the quality of material by various aspects such as the cognitive load involved in the exploration, distinguishable textures, labels arrangement, the clarity of shapes, clear guidelines and necessary gridlines. All these aspects were the subthemes in this analysis that affected the struggles faced by blind students. Although most tactile graphic in Malaysia are not providing structured instruction, this research emphasizes the need for structured instruction to help blind students effectively explore the complex STEM tactile graphic as suggested in Expanded Core Curriculum (ECC) (Sapp & Hatlen, 2010). The urgency of producing high-quality STEM tactile graphics is essential to reduce learning barriers and ensure a more effective learning process for them.

These design issues significantly increase cognitive and emotional strain. As a result, the-low quality design of tactile graphics leads to an increase in extraneous cognitive load by adding unnecessary complexity, which simultaneously raised the demands on working memory and total cognitive load. Additionally, the intrinsic cognitive load is already high due to the complex nature of transformation graphics (Sweller et al., 1998).

Guidelines are important to support students navigating tactile graphics independently with step-by-step instructions. The guidelines will signal key elements that help reduce cognitive load and ensure the student can effectively understand the material as suggested by Mayer's Cognitive Theory of Multimedia Learning (CTML) (Mayer, 2002; Mayer & Moreno, 2003). If blind students exploring STEM tactile graphics without guidelines, they often felt lost and stressed, without knowing their direction and how to interpret it. They just try and error in the exploration and lead to high cognitive load and emotional distress. Without any direction and guidelines, it is nearly impossible for them to explore independently or fully understand the tactile graphic that affected the motivation to proceed. Hence, to enable blind students to independently explore STEM tactile graphics without high dependence to others, it is essential to provide proper guidelines with the tactile graphic.

Tactile graphics are still limited because of the producing process takes a lot of time, energy, expertise, and experience to ensure they are well understood by blind students (Fusco & Morash, 2015; González et al., 2019; Muhammad Ikmal Hakim et al., 2019; Marriott et al., 2021). Although they need to produce carefully, teachers often had limited time that leads to low quality tactile graphics because of rushing and workload. Unfortunately, the low-quality tactile graphics that are harder for blind students to understand, often leads them to ignoring tactile graphics altogether (Melfi et al., 2020). As one student (S8) noted,

> *"Sometimes the teachers were in a hurry, trying to create one set of tactile graphics for all students, which led to a rushed outcome with low quality tactile graphics".*

Other difficulties faced by them are to understand the intended content of the graphics (González et al., 2019). They need help from others to verify the information caused by confusing format, indistinguishable textures, elements placed too closely and poorly positioned braille labels (Fusco & Morash, 2015). Students frequently reported that the textures in tactile graphics were too similar, that make them difficult to distinguish between different elements. This situation increased the cognitive load because they need to spend more time and effort to understand the diagrams. S1 shared,

> *"If I don't know what the shape is, it becomes much more challenging. When the textures of different shapes are similar, it is even harder for me to tell them apart".*

Labels that were incorrectly placed or overlapped with other elements were difficult to read, causing confusion for students. The placement of labels is important because blind students will struggle to differentiate between elements and labels if the labels are misplaced or overlapping and increasing their cognitive load. As S18 stated,

> *"Some labels overlap with their lines, making them unclear and inconsistent."*

This overlap made it difficult for students to touch and feel the braille dots accurately because they became unclear when overlapping, leading to confusion and increased cognitive effort. S2 describe:

> *"The labels were not clear. There was label B, but around the label, there were small, dotted lines that were like braille dots. However, these are not braille dots, but part of the gridlines. Everything got mixed up and confusing".*

The overall design of many diagrams lack clarity. Shapes were often not clear enough, making it difficult for students to feel their boundaries. Some tactile graphics use varying texture densities, but it was proven that the variety of texture densities make the interpretation more complicated and harder to understand (Gupta et al., 2019). They also found that tactile graphics are easier to interpret if varying texture heights were used.

In this research, 63.2% of students reported that shapes were insufficiently distinct, making it challenging for them to identify or distinguish between various shapes, particularly when elements overlapped or not raised enough. These issues get worse when two shapes overlapped and used the same texture. It makes students unable to determine where one shape ended and the other begins. They are more confusing when the tactile graphics have distraction within the shape such as label in a shape. 68.4% of students in this research agreed with this situation and they feel the difficulty caused by overlapping elements, such as labels, shapes, textures, and gridlines. The overlapping makes textures not raised enough and it is hard to distinguish different shapes that affect their understanding.

Gridlines were either not raised enough or too small, blending with other overlapping elements. Gridlines in transformation graphics can be confusing and slow down the time required for blind students to interpret the diagram (Round Table on Information Access for People with Print Disabilities, Inc., 2022). 84.2% of students in this study express the difficulty of tactile graphic exploration with the existence of gridline. It gets worse when the size of gridlines is too small, overlapping with other elements and similar with braille dots label. When all gridlines are raised in tactile graphics, students had to touch every single raised gridline in the graphic and it takes time to understand all the information. Although the complete gridline was tidy and neat in the eyes, it was difficult using a touch. As S12 stated:

> *“The neat and tidy tactile graphic might look nice to those who can see it, but for us, it’s unnecessary... Because we can’t see it, so the appearance doesn't matter for us”.*

The texture of the gridlines, often use braille dots, is further added to the confusion, especially for students dealing with letters like ‘A’, E’, and ‘I’, which have only one or two braille dots. S4 noted:

> *“I was confused... I looked at the label, and when the label was in the middle of the diagram, sometimes I thought it was part of the pattern”.*

Improper label placement can lead students to mistake labels for graphic elements, causing misunderstandings. ‘Ghost dots’ was unintended braille dots that appear out of nowhere when using a malfunction brailler and often make student more confuse. The same situation when traces of labels that are manually erased are left behind and create unnecessary elements in the diagram. Unnecessary elements like this will increase the cognitive load and affect attention to the essential learning process as highlighted in CTML (Mayer, 2002; Mayer & Moreno, 2003). Moreover, excess glue from labels or other elements often formed unintended raised lines on tactile graphics. To overcome this, they need simplified and high-quality tactile graphics.

They also need a clear guideline that includes step-by-step instructions, consistent starting points, and directional cues. By reducing unnecessary complexity and improving design elements, tactile graphics can be made more accessible as suggested in ECC (Sapp & Hatlen, 2010). Including clear navigation guidelines would facilitate independent exploration, reduce cognitive load and enhancing student engagement with STEM content.

The major findings of this study, by highlighting the fundamental need for clear guidelines and indicating the challenges faced by students with overlapping labels, have led to the creation of a framework for STEM tactile graphic design that will encourage exploration, ease cognitive load, and enhance accessibility for blind students. This framework not only overcome the technical shortcomings of existing STEM tactile graphics but also underscores the independence of the blind students and their holistic educational experience.

The quality tactile graphic design framework is built upon the key elements as in Figure 2. This framework aims to provide specific guidelines for enhancing the quality and usability of tactile graphics. With this framework, tactile graphics are easier, more comfortable, and engaging for blind students, aligning with SDG to provide inclusive and quality education for all. The improvements of tactile graphics are critical to preventing a wider gap in STEM education within blind students with their sighted peers. The most urgent factor that highlights in this framework compared to current tactile graphics was sufficient instructions and proper testing that are important to ensure independence in tactile graphic exploration. The framework is structured around several essential components, including cognitive load management, texture differentiation, label clarity, shape definition, instruction quality, gridline simplification, testing and precision, 3d model support and guidance and scaffolding

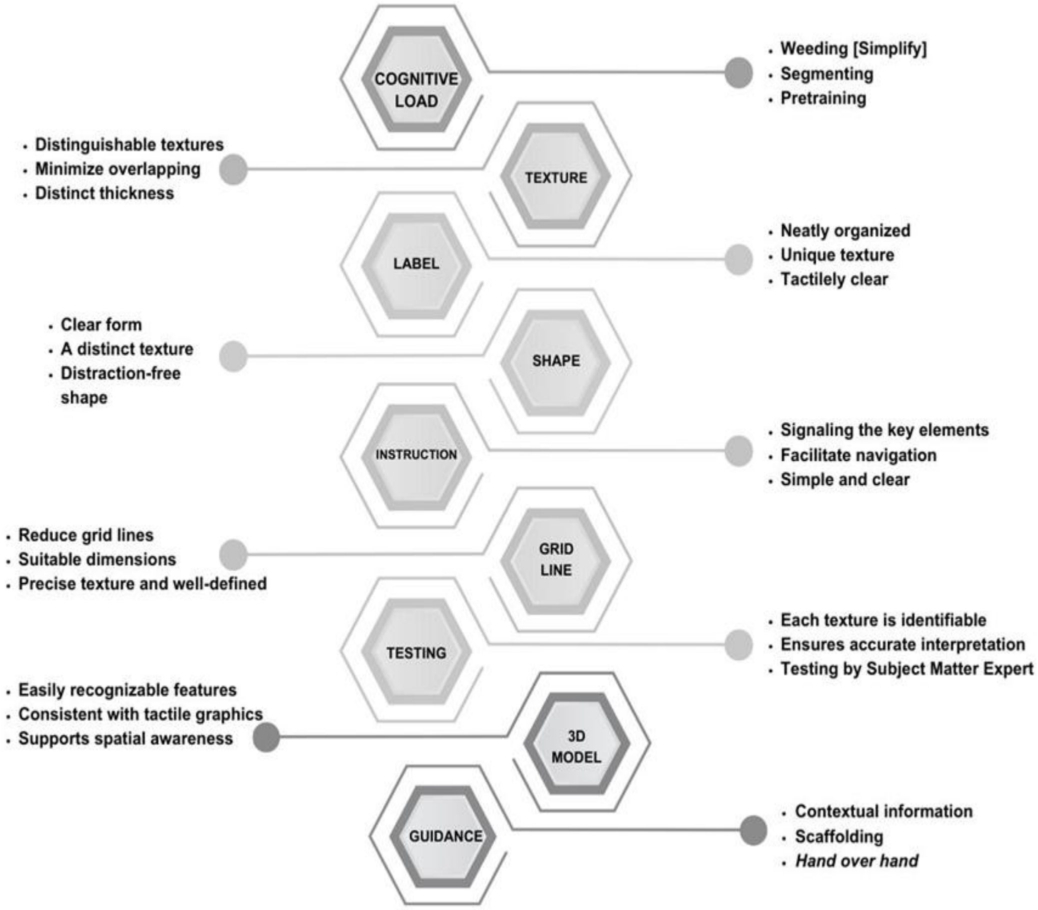

Figure 2: Quality Tactile Graphic Design Framework

Cognitive Load Management

Blind students could explore tactile graphics with more comfort and high motivation if the cognitive load was well-managed. The cognitive load can be reduced by several strategies such as weeding, segmenting, and pretraining to simplify the content (Mayer, 2002; Mayer & Moreno, 2003). Weeding involves removing unnecessary elements to reduce complexity. The unrelated elements will be omitted, and the complex graphics will be simplified as much as possible. Segmenting breaks down information into smaller, more manageable sections. For complicated graphics, it will be divided into several simpler images that focus on a specific part for easier understanding. Pretraining is important to familiarize students with key concepts before full content is delivered, which helps to reduce the cognitive load. This concept could overcome the critical challenges in transformation graph, where the overlapping shapes with gridlines keep confusing the students. With the pretraining concept, students will explore the shape without any gridlines at first, so they can fully understand the shape before adding the gridlines. Blind students will be able to understand the tactile graphic faster and easier with this step-by-step approach. The tactile graphics also will become more accessible by reducing overlapping, using distinguishable texture and various thickness.

Texture Differentiation

The framework highlights the importance of choosing the right textures for effective interpretation. Textures must be unique, easily identifiable, and distinctly tactile to help students differentiate between various graphic elements. It is crucial to ensure that the textures used are suitable for thermoforming, as some textures may not be raised or may sink during the process, making them difficult to feel. Additionally, textures that are not raised enough may be hard for students to perceive by touch. For example, sandpaper can be used, but it is important to choose carefully, ensuring that only rough sandpaper is used, as finer sandpaper may not provide enough tactile distinctions for students to identify effectively.

Reducing overlapping and ensuring distinct thickness in textures can make the exploration of tactile graphics easier to understand, thus reducing cognitive burden and increasing engagement. Wherever possible, overlapping should be avoided. This overlap can lead to confusion for students between lines such as gridlines or specific textures used to represent points, axes, objects, and images (Fusco & Morash, 2015). If overlapping is necessary, it is important to ensure that overlapping textures remain distinguishable, as some overlaps may make the textures difficult to identify.

Distinguishable features help reduce confusion, enabling students to identify shapes and boundaries more effectively. The texture must be chosen carefully because some visually appealing textures are difficult to sense by touch. Overlapping shapes must use different thickness or distinguishable textures to ensure students can easily differentiate and identify each shape without confusion.

It has been demonstrated that varying texture heights make tactile graphics easier for blind students to interpret, as different heights help distinguish elements more clearly. However, using varied texture densities can complicate the interpretation process, suggesting that consistent and straightforward texture usage is key for effective comprehension (Gupta et al., 2019).

Label Clarity

Neatly organized labels will reduce uncertainty, confusion and improve understanding. Improper labeling such as too far apart or too crowded will lead to unnecessary confusion. The use of unique textures for labels such as distinct shapes or bold enough textures could enable blind students to easily locate the labels. It’s easier for them if the labels are placed in the most suitable location, without overlapping with other elements that makes it difficult to sense the braille dot. Consistent labeling helps students quickly understand that these elements are indeed labels, contributing to better navigation and understanding.

Shape Definition

Shapes were the main element in the tactile graphics that need to identify by the students. Hence, it must be bold enough, easy to recognize to prevent wasting time touching each corner seeking for main elements. The shapes must be clear enough without unnecessary distractions within the shape, such as gridlines or labels. Carefully producing processes are essential to avoid glue marks that can form unnecessary distraction lines around the shape. The standout shape was a process of signaling key elements that can reduce the cognitive load.

Instruction Quality

Instructions should clearly signal key elements, facilitate navigation, and be kept simple. Quality instructions act as scaffolding, supporting students until they can independently explore and understand tactile graphics. Before presenting a tactile graphic, a sufficient textual explanation should be given to provide blind students with an overall understanding (Round Table on Information Access for People with Print Disabilities, Inc., 2022). Most tactile graphics in Malaysian Braille textbooks have insufficient instruction, which leaves students confused and unsure where to start or what the graphic represents. As a result, it often takes them a long time to identify and understand the content effectively.

Clear instructions, presented in bullet points and using signaling techniques, can provide students with clear directions on where to start, what to find, and what the graphic includes. For example, an instruction could indicate: "At the top right, there is a trapezium labeled ABCD. At the bottom left, there are two overlapping triangles." Another example might say: "JKLMN is a shaded pentagon overlapping with triangle STU." Such clear guidance helps students navigate tactile graphics efficiently, minimizing confusion and exploration time. Clear instructions are also crucial to reducing cognitive load, maintaining emotional stability, engaging motivation, improving understanding, and minimizing exploration time. During examinations, although blinds students are given extra time, it is often still insufficient for them to fully explore tactile graphics. Providing precise and well-structured instructions can significantly improve their ability to interpret and understand graphics efficiently, even within time constraints.

Gridline Simplification

Blind students often be confusing and take a long time to interpret the diagram with gridline (Round Table on Information Access for People with Print Disabilities, Inc., 2022). The framework suggests reducing gridlines to only what is necessary, ensuring suitable dimensions, and making textures precise and well-defined. The texture of gridlines must be consistent and should not be confusing compared to other elements. Using braille dots for gridlines can be especially confusing, as they may resemble braille labels. Therefore, it is important to use a distinguishable texture for gridlines to avoid confusion and facilitate easier navigation.

Gridlines should also not be too small or placed too close together, as this can make them difficult to feel and cause confusion for students. Gridlines must be not less than one centimeter and were omitted if unnecessary (Pather et al., 2022). When gridlines are complete as in sighted textbooks, students often take a long time to touch each line thoroughly to understand the entire graphic. It's because they depend only on touch and had to gather and organize small piece of gridline that their finger touch to understand the whole graphic (Perkins Schools for The Blind, 2010). However, if only the necessary gridlines are retained, the graphics become simplified, easier to understand, and reduce exploration time. This simplification helps minimize unnecessary distractions, making tactile exploration more focused and efficient.

Testing and Precision

Each texture used in tactile graphics should be tested for its identifiability. Ensures accurate interpretation by verifying that the textures and elements are easily distinguishable and not confusing for the students. Testing is crucial because some diagrams that may seem sufficient at first can turn out to have issues during practical use. These issues may include textures not being raised enough to be felt clearly, elements being indistinguishable, creating uncertainty, or feeling crowded and confusing for the students.

Testing must also be conducted by subject matter experts. For example, science experts would test science graphics only, while mathematics experts would test the mathematics graphics only. It is important to ensure that testing is accurate, as only subject matter experts can thoroughly evaluate whether a graphic meets quality standards. Unfortunately, this crucial step is often overlooked by just simply letting one person test all subjects. This risky approach can lead to mistakenly approving graphics that are insufficient or incorrectly considered as high quality.

3D Model Support

The inclusion of 3D models is an essential component of the quality tactile graphic design framework. 3D models provide features, such as clear, raised, and distinguishable textures, that are consistent with the tactile graphics, making them easier for blind students to touch, identify, and understand. Physical representations in 3D models support spatial awareness that enable blind students to better understand abstract concepts that are difficult to understand through 2D tactile graphics alone (Smith et al., 2020). They often struggle to imagine the concept using only 2D tactile graphics, especially for spatial diagrams such as a heart diagram and pyramid. They only will fully understand if they could feel the 3D model. The use of 3D models helps students visualize the layout, structure, and relationships between different parts of these shapes, improving their overall understanding.

The use of 3D models complements tactile graphics by providing context, making abstract or complex STEM concept more tangible and easier to understand for blind students. Therefore, using 3D models together with tactile graphics ensure students fully understand the concept, making tactile graphics easier to understand and creating a more engaging and effective learning experience.

Guidance and Scaffolding

Blind students need appropriate guidance and scaffolding strategies that specifically for them, as teaching them like sighted students will not be effective. The guidance for the blind student should be step-by-step, detailed, and provide clear directions. Scaffolding approach with direct and detailed guidance and gradual reduction as students become more skilled, is effective to building independent in tactile graphic exploration (Wood et al., 1976; Spadafora & Downes, 2019). For example, when introducing a tactile graphic, a teacher can first use hand over hand to guide a student's fingers to key elements, explaining what they are touching. As the student becomes more comfortable, the teacher can reduce this level of guidance, allowing the student to locate elements independently.

In the early stages, it is important to use hand over hand guidance to ensure students get a clear picture of the tactile graphics. Contextual information, such as the meaning of specific elements must be explained altogether. For example, when guiding a student through a transformation graph, the teacher could explain that ‘this line represents the axis of reflection,’ or ‘this point marks the intersection of two shapes.’ This contextual information will help blind students to understand the intended information behind the tactile graphic (Chase et al., 2020; Mikulowski

& Brzostek-Pawlowska, 2020; Bahrin et al., 2023; González et al., 2019). Although with guidance, it is important to ensure students can find specific elements themselves and give them extra time to find the elements. Clear explanations are also essential, not just unclear pointing, so that students fully understand.

In conclusion, the quality tactile graphic design framework addresses the specific needs of blind students by focusing on reducing cognitive and emotional barriers. By ensuring tactile graphics are designed according to the framework, students can more easily explore and understand STEM content. These findings confirm the urgency to redesign tactile graphics based on cognitive accessibility principles, supporting more inclusive and independent STEM learning for blind students.

Conclusion

This study highlights the challenges that blind students faced while exploring STEM tactile graphics by identifying the significant design flaws that leads to cognitive overload, misinterpretation, and learning frustration. A framework was established through thematic analysis of interviews with 19 blind students, highlighting nine essential factors that enhance accessibility, clarity, and independence in STEM tactile graphic exploration. These findings answered the research questions regarding the impact of poor design and specifications of high-quality STEM tactile graphics. The study contributes not only to the field of inclusive STEM education, but also to the practical redesign of learning tools for blind learners. The implications of this framework are far-reaching, offering structured guidance to special education teachers, tactile designers, and policymakers. This research shows the urgent need to transform current practices and calls for future innovations to ensure blind students receive equal learning opportunities in accordance with Sustainable Development Goal 4.

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Ethics Statement:	This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.
Author Contribution Statement:	[Author 1,2 and 3] was responsible for conceptualization, data gathering, and writing. [Author 2] handled the conceptualization, supervision, writing and editing. [Author 1 and 2] managed data analysis and validation. [Author 4 and 5] checked the writing, review and editing.

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