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iJIM International Journal of Interactive Mobile Technologies

iJIM | eISSN: 1865-7923 | Vol. 19 No. 3 (2025) | OPEN ACCESS

https://doi.org/10.3991/ijim.v19i03.52091

PAPER

Designing Interactive Mobile Learning Applications for Visually Impaired Children: A User Experience Evaluation Based on Affective Design Principles Using Hypothetical Datasets and Heatmap Analysis

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ABSTRACT

This study explores the development and user experience testing of an interactive mobile learning application designed for children with visual impairments integrated with affective design principles. Despite the availability of various assistive technology (AT) solutions, existing mobile applications often fail to address the specific needs of visually impaired children, particularly regarding emotional engagement and usability. Affective design principles are essential in developing functional, emotionally resonant, and engaging products for users. Therefore, this study aims (i) to develop an interactive mobile learning application tailored for visually impaired children based on affective design principles and (ii) to validate the application through comprehensive user experience testing by utilizing a hypothetical dataset and heatmap overlay. Employing iterative triangulation methodology (ITM), the study demonstrates that integrating affective design principles significantly enhances the usability and engagement of mobile learning applications for visually impaired children. The findings highlight the critical role of affective design in promoting equitable and effective learning experiences for this demographic, contributing both theoretically and practically to the field of assistive technology.

KEYWORDS

mobile-human computer interaction (M-HCI), assistive technology (AT), affective design, user-centered design approach (UCD), user experience, visual impairment

1 INTRODUCTION

Mobile-human-computer interaction (M-HCI) devices, such as portable computers, mobile phones, and wearable technologies, have revolutionized how users communicate their psychological and cognitive states through digital systems [1].

Abdul Salam, S.N., Abdul Mutalib, N.A., Aziz, N. (2025). Designing Interactive Mobile Learning Applications for Visually Impaired Children: A User Experience Evaluation Based on Affective Design Principles Using Hypothetical Datasets and Heatmap Analysis. *International Journal of Interactive Mobile Technologies (iJIM)*, 19(3), pp. 87–114. https://doi.org/10.3991/ijim.v19i03.52091

Article submitted 2024-09-05. Revision uploaded 2024-11-06. Final acceptance 2024-11-06.

Despite advancements in educational technology, a significant gap remains in addressing the emotional and usability needs of visually impaired children [2, 27]. The initial investigation of this study found that existing assistive technologies (ATs) often overlook the emotional engagement necessary for affective learning [4, 11]. Most ATs for visually impaired users tend to focus primarily on functional needs, with limited attention to emotional engagement and usability [3, 11]. There is a clear gap in the development of emotionally meaningful learning applications that cater to the specific needs of visually impaired children, particularly in promoting a supportive and engaging learning environment [5, 11]. This is especially important in applications designed for children with visual impairments, where emotional interaction is critical to the user experience [6]. Research has demonstrated that integrating affective design principles, which focus on evoking positive emotions, into mobile applications can enhance usability and emotional engagement, thereby improving the overall learning experience [4, 7]. However, there is limited understanding of how these principles can be effectively implemented in mobile learning applications for visually impaired children [8]. Therefore, this study seeks to fill this gap by developing an interactive mobile learning application specifically designed for visually impaired children, integrated with affective design principles. In this context, two specific objectives have been formulated, which are (i) to develop an interactive mobile learning application for visually impaired children based on affective design principles and (ii) to validate the developed application through comprehensive user experience testing. These objectives align with existing literature, emphasizing the importance of incorporating emotional responsiveness into ATs to foster more inclusive and supportive learning environments for visually impaired children [9].

2 LITERATURE REVIEW

2.1 Affective design

Affective design focuses on developing interfaces that evoke positive emotions and satisfaction, not just functionality and usability [2, 5]. It aims to make interactions enjoyable and meaningful [3]. Table 1 outlines the components, elements, and principles of affective design as supported by previous studies.

Table 1. Affective design components, elements, and principles

Component	Element	Design Principle
Emotion	Memorable	Use consistent design elements like buttons and icons to help visually impaired children remember gestures [21].
	Motivational	Create strong color contrast between background and foreground to motivate continued use [12].
Feeling	Interest	Provide a clear, symmetrical layout for easy engagement. Use landscape orientation to increase the text size [15].
	Happiness	Imitate children's voice intonation in instructions to boost engagement [17].
Thought	Positive Perception	Include human characters to add humor and increase appeal [13].
	Positive Mind State	Label buttons clearly to match what visually impaired children hear with what they see [19].
Action	Navigation	Use large, sans-serif fonts to create a clear and readable interface [20].
	Interaction	Place buttons at the edges for easy access and provide feedback for a clear understanding of actions [10, 22].

When applied to ATs for visually impaired individuals, affective design is crucial as it enhances the emotional experience, making users feel empowered and supported [4, 18]. This approach goes beyond functionality by incorporating features such as soothing voice prompts, customizable feedback, and intuitive navigation to provide a stress-free experience [16]. Affective elements, such as encouraging sounds or vibrations, can reduce frustration and boost user satisfaction, leading to more effective use [14]. By focusing on both the practical and emotional needs of visually impaired users, affective design can facilitate the development of technology that fosters independence, inclusion, and well-being [15].

2.2 Reviews of existing mobile applications for visually impaired

Table 2 shows that most users of existing mobile applications are visually impaired, including those with blindness. However, many of these mobile applications are still partially or completely inaccessible to visually impaired users. This study compares the accessibility issues in 10 existing mobile applications, focusing on the challenges highlighted by [15], who studied user interface accessibility. The challenges identified in their research, listed in Table 3, are used in this study to evaluate and identify accessibility problems in the selected applications.

Table 2. Existing mobile applications with targeted users

Num.	Author	Application	Target Users
1.	[16]	Real-Time Mobile Application for Thai Banknote Recognition	visually impaired persons
2.	[17]	Mobile e-Learning Application for the Enhancement of Basic Mathematical Skills	visually impaired children
3.	[18]	BlindMuseumTourer: An indoor navigation smartphone application	blindness and visually impaired users
4.	[19]	Smart_Eye: A navigation and obstacle detection for visually impaired people through the smart app	blindness and visually impaired users
5.	[20]	DeepNAVI: A deep learning-based smartphone navigation assistant	visually impaired people
6.	[21]	Android Prototype Application for improving the orientation and mobility	people with visual impairments
7.	[22]	A Mobile Intelligent Guide System	visually impaired pedestrian
8.	[23]	Specialized Teleguidance-Based Navigation Assistance System	blind and the visually impaired
9.	[24]	WordMelodies: Literacy skills for primary school students	primary school visually impaired students
10.	[25]	Augmented Reality Audio Application	visually impaired persons

Table 3 highlights common accessibility issues in the existing mobile applications, including text size, text color, graphics, background color, icons, and buttons. Text size is the most frequent problem. Increasing text size can significantly improve readability for visually impaired users. These issues mean many visually impaired people struggle to use these applications, especially in digital learning tools for mathematics. Addressing these problems is crucial to helping visually impaired users engage effectively.

Table 3. Accessibility problems of existing mobile learning applications

Accessibility Problems of Existing Mobile Application	1	2	3	4	5	6	7	8	9	10
Text size	/	/	/	/	/	/	/	/		/
Text color										/
Background color					/					/
Icon	/					/			/	
Button	/	/	/				/	/	/	

The analysis of existing mobile applications for visually impaired users reveals ongoing accessibility issues that hinder usability [28]. Despite the advancement of ATs, these problems show that current designs often overlook the specific needs of visually impaired users, especially in educational contexts, particularly Mathematics. Affective design, which includes intuitive auditory cues, tactile feedback, and personalized interfaces, is essential for making these tools both functional and emotionally engaging. Addressing these needs can help developers build more inclusive and supportive digital environments that enhance independence and quality of life for visually impaired users.

3 MATERIALS AND METHODS

This study adapts iterative triangulation methodology (ITM), as depicted in Figure 1. ITM, commonly used in design science research, ensures comprehensive triangulation across all phases, helping to achieve research objectives [26]. It includes a crucial theoretical phase between development and testing, involving expert consultations and content analysis, to strengthen the study problem.

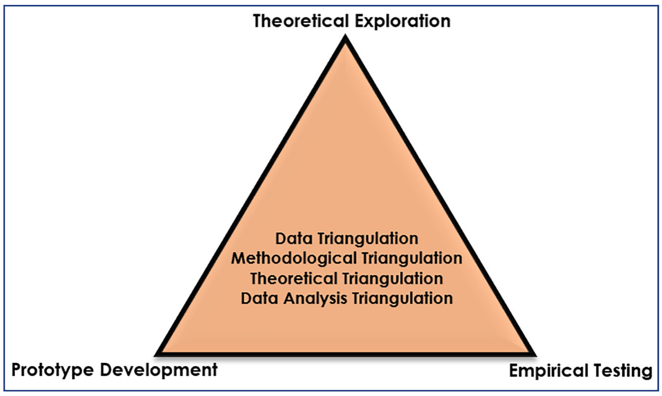

Fig. 1. Iterative triangulation methodology

Instead of starting with application development, this study began by thoroughly understanding the research context. Expert insights and reviews of existing theories, models, and technologies were gathered to build a strong foundation for prototype development and testing. ITM is designed to incorporate multiple forms of triangulation throughout the study, with each phase including specific activities aligned with the sub-objectives of the study. The phases are discussed as follows:

Phase 1: Theoretical exploration: The initial phase starts with a preliminary investigation using observations and interviews with target users. The research problem, objectives, and gaps are defined through an extensive literature review and content analysis of relevant theories and design principles. Each piece of input is critically evaluated to identify the main research gap. This phase results in a clear definition of the research problem, an understanding of user needs, and an analysis of existing concepts related to visually impaired interaction experience.

Phase 2: Prototype development: In the prototype development phase, the study identifies key components of affective design for visually impaired users through a literature review, expert consultations, and a user-centered design (UCD) approach. A UCD seminar refines these elements, fulfilling the first objective of the study. The development process includes three phases, which are pre-production, production, and post-production. Pre-production involves planning with expert input and user feedback to align with user needs. The production phase focuses on iterative prototype development, incorporating affective design principles and accessibility standards. In post-production, the prototype is evaluated and refined based on user feedback, resulting in a product ready for deployment to visually impaired users.

Phase 3: Empirical testing: In this phase, the study conducted user experience testing with seven visually impaired primary school children. This study used both observations and interviews to gather insights into participants' behaviors, experiences, and perspectives, enabling a comprehensive understanding of the subject matter. To reduce bias, triangulation was employed by using multiple methods to validate the findings, and neutral interview questions were carefully designed. Observations were systematically documented, while interviews were recorded and accurately transcribed. Initially, the data was analyzed using thematic analysis, a detailed and systematic approach to coding qualitative data and identifying recurring themes. Subsequently, the data was further analyzed using a hypothetical dataset and heatmap overlay to identify patterns from the users' interactions with the prototype. This comprehensive analysis provided a reliable evaluation of the prototype's effectiveness in meeting the needs of visually impaired children.

4 RESULT AND DISCUSSION

This section details the development of an interactive mobile learning application for visually impaired children, incorporating affective design principles. It also evaluates the application's development and effectiveness, emphasizing how these principles enhance emotional engagement and usability, ultimately making the application more accessible and user-friendly for visually impaired children.

4.1 The prototype of an interactive mobile learning application for visually impaired children based on affective design principles

The welcome segment. The welcome segment (see Figure 2) with Alisya uses affective design to engage visually impaired children. A friendly voice and captivating sounds create a personal connection, making users feel happy and welcomed. Alisya's cheerful look and playful "X" symbol make the interface familiar and reduce anxiety. Clear visuals and accessible audio ensure the design is inclusive, creating an enjoyable and supportive learning experience.

Fig. 2. The welcome scene

The content and activity segment. Figure 3 illustrates how affective design enhances a math learning application for visually impaired children by using accessible visual aids, simplified buttons, and engaging feedback to improve understanding and usability. The use of bright colors and bold fonts makes math problems easy to see. Pictorial representations link math concepts to real-world objects. Clearly labelled buttons like "MENU" and "NEXT" are easy to navigate. The consistent layout makes learning simple and enjoyable. Figure 4, provides clear feedback. A smiling face with a green checkmark signals a correct answer, boosting confidence. A sad face with a red "X" indicates an incorrect answer, but the gentle expression helps prevent discouragement. This feedback supports and encourages visually impaired children.

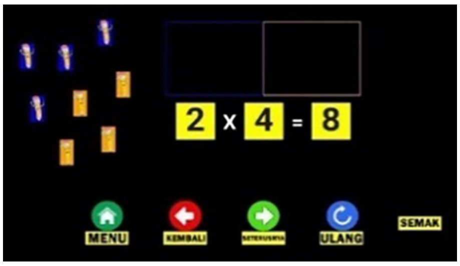

Fig. 3. Sample of content segment

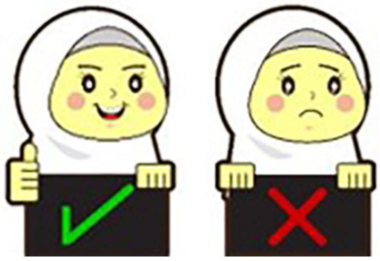

Fig. 4. Sample of character expression in activity segment

Implementation of affective design principles in the application. The interactive mobile learning application was developed by carefully integrating affective design principles to ensure that it not only served the functional needs of visually impaired children but also addressed their emotional and cognitive engagement. The affective design was implemented across four key components which are emotion, feeling, thought, and action.

Emotion component. The application aimed to evoke memorable and emotionally engaging experiences for the users. Consistent use of auditory cues and icons throughout the application helped visually impaired children remember gestures and navigation paths. For example, buttons were consistently labeled with both visual and auditory feedback, making it easier for users to memorize the layout. In addition, the color contrast between the background and the buttons was designed to create a visually stimulating environment that motivates children to continue interacting with the app. To further boost motivation, soothing sound effects were used when tasks were completed, while soft, encouraging audio feedback was provided for incorrect answers. These positive reinforcements were designed to keep users emotionally engaged and reduce frustration.

Feeling component. The application layout was designed to be visually simple and symmetrical to ensure ease of navigation with minimal cognitive load. A child-friendly character named Alisha was incorporated to serve as a virtual guide throughout the app. Alisha's cheerful voice and simple language made instructions easier to follow, fostering a sense of comfort and familiarity. Alisha's presence in the app also promoted emotional connection, as children could relate to a friendly, positive figure guiding them through the learning process. Additionally, the use of tactile feedback (e.g., vibrations when buttons are pressed) further contributed to user engagement, providing an additional layer of interaction that complemented the auditory cues.

Thought component. The application ensured that visually impaired children could easily associate audible labels with visual elements on the screen. For example, when a user navigated the app, the buttons were clearly labeled with a spoken word matching the corresponding action. This helped reinforce a positive perception of the interface and allowed users to develop a mental map of the app's structure, boosting confidence in their ability to navigate independently. To support a positive cognitive state, the app provided clear instructions with step-by-step guidance to reduce any confusion. The instructional videos and feedback were designed to be short and simple, ensuring that the cognitive load on the user was manageable while promoting a sense of accomplishment with every completed task.

Action component. Navigation within the application was designed with a user-centered approach, prioritizing ease of access. Large touchable areas for buttons were placed at the edges of the screen to avoid confusion and to ensure they were easy to locate. These buttons were distinctively separated from the content, allowing users to interact without interfering with the main learning content. Interaction feedback was a critical part of the action component. When users interacted with the app whether by answering questions or navigating through tasks, they received immediate feedback in the form of sounds and visual signals. A chime sound accompanied correct answers, while a soft buzzing sound was used for incorrect answers, gently guiding users to the correct solution without causing discouragement. This positive reinforcement mechanism kept children motivated to continue interacting with the app.

These design elements, rooted in affective design principles, were chosen to ensure that the application was not only accessible to visually impaired children but also emotionally engaging and cognitively stimulating. By focusing on the user's emotional and cognitive well-being alongside usability, the app fostered a positive learning environment where visually impaired children could learn comfortably and effectively.

4.2 The user experience testing

The study collected user experience data through observations and interviews. At first, this data was analyzed by using thematic analysis to assess the affective design elements in the prototype. Each interaction and feedback from the visually impaired children were reviewed to determine how well the design met their needs. The analysis compared their behaviors and responses with the intended outcomes, ensuring the prototype provided an engaging and supportive experience.

The demographic background of the subject. The user experiences testing for this study was conducted at a primary school in Malaysia with seven students, comprising four males and three females (Table 4 tabulated the demographic background of the subjects). Although the sample size is relatively small, the homogeneity of the participants, who share similar backgrounds and educational experiences, provides a basis for focused analysis. While homogeneous samples may limit the generalizability of findings to larger populations, they allow for a more detailed examination of interaction patterns and usability within a specific group. This approach offered valuable insights into the effectiveness of the developed mobile learning application for this particular demographic. However, the small and uniform sample may not capture the full diversity of experiences among visually impaired children in other contexts, thereby limiting the generalizability of the findings. To address this, future studies should aim to include a larger and more diverse sample to ensure that the results are applicable across different educational, cultural, and social settings.

Despite the small sample size and its limitations, the participants' prior familiarity with tablets provided an opportunity to gain deeper insights into their interactions with the prototype. Most had been using tablets since Standard One, which likely influenced their interaction with the prototype. This familiarity helped evaluate how effectively the affective design met the needs of visually impaired users, examining how students with different experience levels engaged with the application and how well it met their needs and preferences.

Table 4. The demographic background of the subjects

Subjects	Age	Gender	Race	School Level
Subject 1	9	Female	Malay	3 years
Subject 2	10	Male	Chinese	4 years
Subject 3	9	Male	Chinese	3 years
Subject 4	12	Male	Malay	6 years
Subject 5	10	Female	Malay	4 years
Subject 6	12	Male	Malay	6 years
Subject 7	8	Female	Chinese	2 years

Observation. The observation focused on four components of affective design, tracking participants' interactions with different scenes and their reactions. The aim was to see how affective design principles were applied.

Observation analysis of emotion. The emotion component explores how design elements foster memorable and motivational experiences, focusing on their impact on emotional engagement and encouraging continued use. It examined a mobile learning application for visually impaired children, using consistent buttons and icons to help them memorize gestures, reducing the need to relearn navigation. Initially, participants took longer to answer the first question, but response times decreased to under a minute as they became familiar with the interface. Subject 4, with the poorest eyesight, took the longest at 15.5 minutes but improved with practice. Most participants completed tasks in seven to nine minutes, showing better memorization over time. All subjects completed the application and were eager to repeat the activities independently, indicating that elements like color contrast encouraged continued use. Although Subject 4 was briefly distracted during the concept video, they remained motivated to complete all questions, showing that engaging activities kept them focused. Figure 5 illustrates an example scenario.

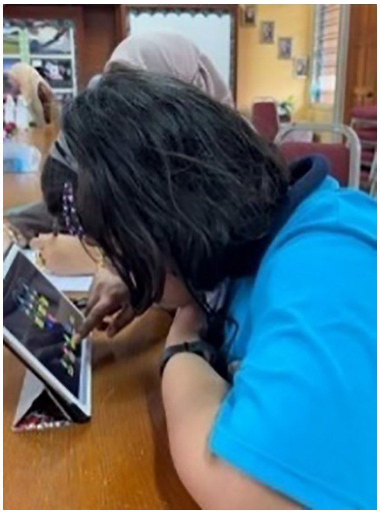

Fig. 5. Subject 5 clicking the next functional button without assistance

Observation analysis of feeling. The study evaluates how design elements cultivate attention and promote positive experiences by focusing on interest and happiness. It examines how well the design facilitates an engaging and satisfying user experience. To make the developed mobile learning application easier and more engaging for visually impaired children, a clear and symmetrical layout was used, requiring less cognitive effort for navigation and helping children easily find and use the buttons. However, placing the "Check" button next to the "Redo" button caused some confusion, leading to accidental clicks by Subjects 4, 6, and 7. Despite this, most subjects preferred the landscape orientation, with five out of seven finding it more comfortable and accessible. Figure 6 shows their seating positions, such as Subject 6 using the tablet in landscape mode. The character Alisha was included to promote happiness and engagement. Her clear voice was used for all commands, helping children follow instructions smoothly. All subjects completed the activities, with some, such as Subjects 1 and 4, repeating the explanations aloud, showing their connection with Alisha. Subject 3 even asked to replay her video, highlighting her positive impact. These interactions suggest that Alisha made the children feel happy and comfortable, enhancing their learning experience. Figure 7 shows a subject pointing to the tablet and speaking aloud, following Alisha's explanation.

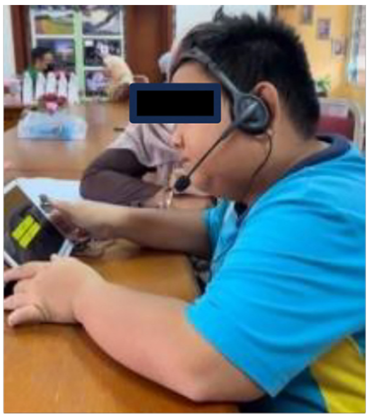

Fig. 6. Subject's sitting position while using the application

Fig. 7. Subject 1 points to the tablet and reads aloud the content

Observation analysis of thought. User experience examines cognitive aspects by focusing on positive perception and positive mind state. The study analyzes how the design influences users' thinking patterns, encouraging constructive and optimistic interactions. The objective is to determine how well the design promotes a positive cognitive response, enhancing the overall user experience. Regarding positive perception, when audible labels match the visual text on the screen, the user experience improves significantly for visually impaired children, making it easier for them to understand and navigate the content. For instance, Subject 2 was initially confused about which button to press to return home but identified the correct button after hearing the audible label. All subjects tended to mumble button labels aloud when they got lost during navigation, which helped them regain their orientation. This behavior indicates that audible labels boost their confidence and ability to use the application independently. This issue mostly occurred during the first interaction, especially when there were multiple buttons. To further support the users, the buttons also included sound, leading to a more positive and seamless experience for visually impaired children. Font size preferences varied between subjects with and without spectacles. Those with spectacles maintained an appropriate distance from the tablet, while those without moved closer. Of the seven subjects, three wore spectacles. Notably, Subject 4, with the poorest eyesight, sat very close to the tablet (see Figure 8). Despite these differences, all subjects could easily identify non-text elements like buttons and images, completing tasks that involved counting items on the screen (see Figure 9). This boosted their confidence and motivation, enhancing their overall experience with the application.

Fig. 8. The distance between subject 2 and the tablet

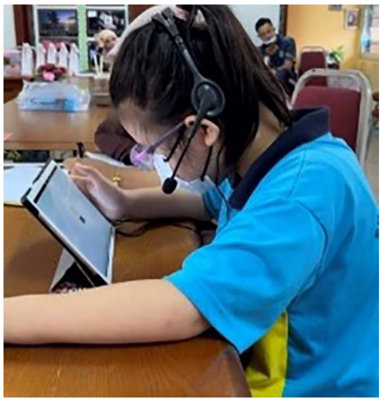

Fig. 9. The distance between subject 7 and the tablet

Observation analysis of action. This study also evaluates how efficiently users navigate and interact with the application, aiming to see how well the design supports intuitive use and a smooth experience. The navigation in this application is dynamic, allowing users to move freely between scenes. Buttons are strategically placed at the screen's edge, separated from the content to avoid confusion. All subjects quickly adapted to the button placement at the bottom of the screen, which kept the interface clear and organized, improving their navigation experience. On the other hand, to improve interaction, feedback is provided for each answer the subjects give. This feedback guides their actions, acknowledges their progress, and rewards correct answers with a chime sound, while incorrect answers trigger a buzzing sound. Figures 10 and 11 show Subject 3 smiling after positive feedback and Subject 6 raising their hand after a correct answer. Despite needing to tilt their head for better sight, leading to some mistakes in drag-and-drop activities, Subject 6 used the reset button to redo questions. This error-handling feature allows users to correct mistakes without closing the application, ensuring a smoother learning experience and a supportive environment.

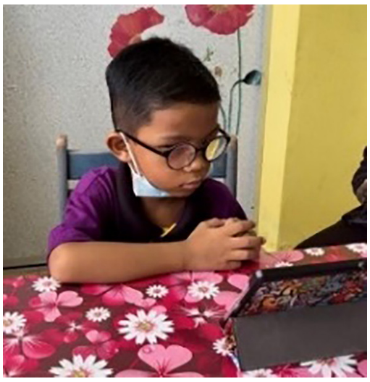

Fig. 10. Subject 3 smiled when interacting with the application

Fig. 11. Subject 6 raising his hand

Interview. Interviews were conducted to gather subjects' opinions regarding the effectiveness of the developed mobile application. The goal was to evaluate how well these principles were implemented. The interview questions were analyzed based on emotion, feeling, thought, and action to understand their impact on user experience. Table 5 organizes the questions to assess how the application meets users' emotional and functional needs, including emotion, feeling, thought, and action.

Table 5. Interview questions categorized by affective design elements

Component of Affective Design	Element	Interview Questions
Emotion	Memorable Experiences	Does it make it easy for you to remember?
	Motivational Aspects	Is the color okay for you?
Feeling	Interest	What was your feeling the first time you saw this mobile application?
		Do you like the orientation?
	Happiness	Do you understand the video?
		Do you like the character, Alisha?
Thought	Positive Perception	Do you think you understand the button function?
	Positive Mind State	Is the font large enough?
Action	Navigation	Do you think you can use this mobile application alone?
		Do you find it easy to navigate the mobile application?
	Interaction	Was it easy to interact with the application?

Interview analysis of emotion. The questions on emotions focused on two areas which are memorable experiences and motivation. The first set identified design elements that left a lasting impression, while the second explored how the application motivated users to stay engaged and complete tasks. This approach clarified how emotional triggers in the application contributed to a positive user experience. For memorability, participants were asked, "Does it make it easy for you to remember?" Most responded with "easy," and Subject 5 added, "It was easy to remember." These responses suggest the application was intuitive and user-friendly. All subjects completed tasks, replayed scenes, and improved their recall of button placements during the second interaction. This indicates the design effectively supported learning and retention, making the application easier to use and reducing cognitive load for visually impaired children. The next question on motivation asked, "Is the color okay for you?" Subject 4, with poor eyesight, responded "A little okay," and Subject 5 said, "A bit hard." These responses suggest that the color contrast in the application needs improvement. Proper contrast is essential for visually impaired children, as it affects their motivation and focus. The feedback from Subjects 4 and 5 highlights the difficulty in distinguishing screen elements due to poor contrast, indicating the need for adjustments to better support children with significant visual impairments.

Interview analysis of feeling. The interview questions related to the feeling component focused on two main areas which are interest and happiness. The questions about interest explored how well the application held the children's attention. Meanwhile, the questions about happiness assessed the level of satisfaction the children experienced while using the application. These questions aimed to understand the emotional engagement and overall enjoyment of the users as they interacted with the application. The interview asked about the mobile application's layout to assess initial reactions. Most subjects responded with "excited," showing strong interest. Subject 2 said, "I am proud to use this," and Subject 1 noted, "It is easy to use," indicating the layout was well-received. The symmetrical button arrangement was designed to engage visually impaired children. All subjects preferred the landscape orientation, with five out of seven favoring it for its larger size, making the application easier and more enjoyable to use. This feedback highlights the importance of layout and orientation in maintaining the interest and satisfaction of visually impaired users. To explore participants' feelings, questions focused on their happiness with the mobile application were also asked. All participants understood the video, with some, such as Subjects 5 and 7, noting they liked the voice, which was similar to a teacher and helped them enjoy the content. The consistent female voice explaining multiplication contributed to their satisfaction. When asked about the character Alisha, all participants expressed liking her and were happy with her explanations and visual presence. These responses show that both the voice and character design effectively enhanced the participants' happiness and engagement with the application.

Interview analysis of thought. The interview questions on thought focused on two areas which are positive perception and positive mind state. Positive perception examines how visually impaired children view experiences optimistically, influencing their behavior and decisions. A positive mind state looks at their overall mindset, focusing on resilience and hope. This approach helps understand how positive thinking shapes their outlook and emotional well-being, providing a complete view of thought's role in their well-being. Participants were asked, "Do you think you understand the button function?" All responded positively. The clear labels helped users easily identify the buttons' functions, reducing confusion and frustration. This boosted their confidence in navigating the application, making it user-friendly and supportive. For visually impaired children, the labels were crucial, enabling independent and effective interaction. This positive experience enhanced their engagement and trust in the application as a valuable learning tool. When asked about the font size, opinions varied. Four out of seven participants found it suitable, with

Subject 2 saying, "The font can be seen." However, Subjects 3, 4, and 5, who are visually impaired, found "small" or "a bit small," likely due to their impairments. When asked if they could use the application alone, all participants confidently said yes. During testing, they eagerly restarted and navigated the application independently, using buttons to move between scenes without help. This shows the interface is well-designed, with high contrast and clear visibility, empowering visually impaired children and fostering confidence and a positive approach to learning.

Interview analysis of action. Questions regarding actions were divided into navigation and interaction. This helps deliver a user-friendly and satisfying experience. By making navigation easy and interaction engaging, the developed mobile application becomes more accessible and enjoyable for visually impaired children. This approach boosts their confidence and encourages independent use. To assess navigation ease, participants were asked, "Do you find it easy to navigate the mobile application?" All responded positively, with comments such as "easy." Subject 1 said, "It is easy to learn," and Subjects 2 and 3 remarked, "Easy to use." These responses show that button placements are intuitive and accessible, allowing efficient interaction. The application design with buttons near the screen edges, aligns with natural hand positions, making navigation comfortable for visually impaired children. This thoughtful design reduces the effort needed to interact with the developed application, supporting a seamless user experience and encouraging confident exploration. By prioritizing accessibility and user comfort, the developed mobile application enhances usability and fosters a positive emotional response, making users feel more in control. Then, to assess the ease of interaction with the mobile application, participants were asked, "Was it easy to interact with the application?" All responded, "Easy to use." However, Subject 2 found the drag-and-drop feature difficult for visually impaired users. This suggests that the drag-and-drop feature should be reconsidered or removed. Subject 6 had trouble handling errors, particularly with the redo button, which resets all answers instead of just one action. Despite these challenges, all participants expressed a strong interest in continuing to use the application. These insights highlight the importance of affective design, which aims to build a positive emotional experience. Addressing challenges such as simplifying interactions and improving error handling can make the proposed mobile application more user-friendly and enjoyable. This approach ensures users feel comfortable, confident, and motivated, leading to a better learning experience.

Justification of findings from observation and interview. Based on both the observational and interview findings, the study demonstrates that the proposed interactive mobile learning application integrated with affective design principles effectively meets the needs of visually impaired children, fostering both engagement and usability. Observations revealed that key design elements including consistent button placement, clear auditory feedback, and engaging visuals helped the visually impaired children navigate the application with increasing ease over time, enhancing memorization and task completion. The emotional, cognitive, and interactive elements, as assessed through thematic analysis, showed that the children felt more confident, motivated, and supported in their learning experiences. Interviews further supported these findings, with participants expressing positive feedback on aspects including ease of navigation, enjoyment, and connection with the character Alisha, who significantly contributed to their emotional engagement. However, challenges like font size, button placement, and the drag-and-drop feature were identified as areas requiring refinement to enhance accessibility. Despite these issues, the overall positive response to the proposed application highlights its potential to provide an effective and emotionally supportive learning tool for visually impaired children, while also pointing to areas for future improvement to accommodate a broader range of user needs.

To ensure a more comprehensive evaluation of the user experience, the study also analyzed data gathered from observations and interviews using a hypothetical dataset and heatmap overlay. This approach provided a detailed visual representation of user interaction patterns, allowing for a clearer analysis of how different elements of the developed application were engaged with and quantifying the otherwise qualitative data from the observations and interviews.

Generation of the hypothetical dataset and its limitations. The hypothetical dataset used in this study was generated to simulate the interactions and responses of visually impaired children while using the developed mobile learning application. This dataset was based on observational and interview data collected during user experience testing, including metrics related to task completion time, error rates, and emotional engagement. By mapping these observations and interviews to predefined performance indicators, a hypothetical dataset was constructed to analyze user behavior patterns using heatmap overlay methods. The generation of this dataset relied on assumptions drawn from similar studies and expert consultations in the field of ATs. These assumptions enabled the study to approximate patterns of user engagement, even with a small sample size. One limitation of using a hypothetical dataset is that it may not fully capture the variability of real-world interactions, particularly across a larger and more diverse group of users. Additionally, the dataset is shaped by the subjective interpretation of observational data, which may introduce bias. To address this potential bias, several strategies were employed. First, multiple researchers participated in the observation and data analysis process, allowing cross-checking of interpretations and reducing individual bias. Triangulation was also applied by comparing and validating data from different sources (observations, interviews, and user feedback) to ensure consistency. Additionally, standardized criteria were used across all participants to maintain objectivity when coding behaviors and mapping them to the hypothetical dataset. These measures helped reduce bias and improve the reliability of the generated dataset.

Quantitative analysis of findings from observational data through hypothetical dataset and heatmap overlay. Table 6 presents the scores for each subject and highlights their engagement with affective design components.

Table 6. The hypothetical dataset of observational data according to affective design components

Subject/Affective Design Components	Emotion	Feeling	Thought	Action
Subject 1	4	5	4	4.50
Subject 2	5	4	5	6.00
Subject 3	3	3	3	4.50
Subject 4	3	2	2	10.25
Subject 5	4	4	4	4.50
Subject 6	4	3	3	6.50
Subject 7	4	5	4	4.00

In addition, to gain a clearer understanding of the overall user experience, the observational data from this study have also been analyzed through a heatmap overlay (see Figure 12), providing a detailed view of each participant's performance across the four key affective design components. Figure 12 presents a detailed description based on the specific results.

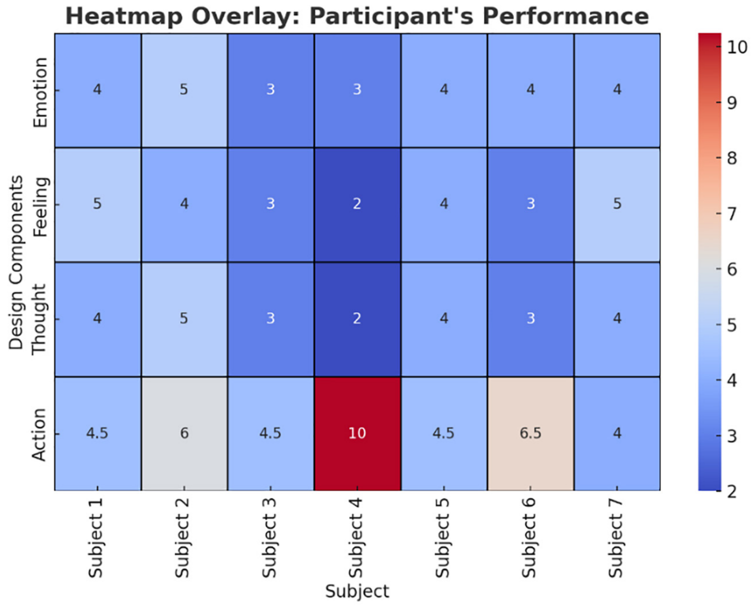

Fig. 12. The heatmap overlay of participants' performance

Emotion. The emotion scores, reflecting each participant's motivation and engagement with the application, reveal varying levels of success in maintaining user interest. Subject 2, who scored 5, was highly motivated, showing that the design and ease of use were effective in establishing a seamless and satisfying user experience. This high level of engagement demonstrates the importance of an intuitive interface and well-aligned content in reinforcing emotional connection and sustained focus, which is crucial for visually impaired users. In contrast, Subject 4 scored a 3, indicating lower engagement, attributed to difficulties in navigation or content that failed to capture interest. The lower score highlights critical weaknesses in the design, particularly for users with greater navigation challenges or those who require more engaging or accessible content. The difference between these scores reveals that the application is not equally effective across all users, potentially leading to frustration among some participants. This variation confirms the need for more adaptive design elements that accommodate a wider range of abilities, ensuring that the application remains engaging and motivating for all users, regardless of their specific needs or preferences.

Feeling. The feeling scores, which measure happiness and emotional satisfaction with the application, ranged from 2 to 5, indicating varying levels of user experience. Subject 1, who scored a 5, found the application highly enjoyable and rewarding, likely due to the smooth interaction and content that aligned well with their expectations. This suggests that when the interface is intuitive and the content is accessible, visually impaired children experience heightened emotional satisfaction, leading to increased engagement and positive reinforcement. In contrast, Subject 4 scored a 2, reflecting significant dissatisfaction, which appears to result from usability issues, a confusing interface, or content that did not meet their needs. This lower score highlights critical design flaws that disrupt the user experience for certain individuals, particularly those with more severe visual impairments or different cognitive preferences. The stark difference between Subject 1 and Subject 4's experiences indicates that the application lacks consistency in delivering a universally satisfying experience, emphasizing the need for greater flexibility in design. Features such as customizable interfaces, adjustable feedback mechanisms, or simplified navigation could help bridge the gap in emotional satisfaction among diverse users. The disparity in scores confirms that while the application is effective for some, it fails to accommodate the broader range of abilities and preferences within the visually impaired community, highlighting the importance of a more inclusive design approach.

Thought. The thought scores evaluate how effectively users understood and interacted with the application's content, revealing significant differences in user experiences. Subject 2, who scored a 5, demonstrated a strong understanding of the application, indicating that the design facilitated easy navigation and task completion. This high score shows that well-organized tasks, intuitive interfaces, and clear instructions were crucial in helping visually impaired users confidently interact with the application. The seamless interaction experienced by Subject 2 highlights the effectiveness of the design in promoting cognitive engagement and comprehension, contributing to a positive user experience. In contrast, Subject 4 scored a 2, reflecting significant difficulties in understanding and using the application. This low score suggests that unclear instructions, complex navigation, or poorly explained content led to confusion and diminished confidence. The stark contrast between Subject 2 and Subject 4's experiences points to inconsistencies in the application's ability to cater to different users, particularly those who require more simplified or adaptive features. This discrepancy emphasizes the need for enhanced clarity in instructions, more streamlined navigation, and flexible content delivery to ensure that users with varying cognitive needs can effectively engage with the application. Without addressing these issues, the application risks disengaging users who struggle with understanding its content, ultimately reducing its overall usability and effectiveness for a wider group of users.

Action. The action scores, which measure task completion time and error frequency, provide key insights into the application's usability and effectiveness across different users. Subject 4, who scored 10.25, faced considerable challenges, indicating that the application's interface was too complex, or the instructions were unclear. This high score reveals a significant usability issue, as difficulty in completing tasks and frequent errors indicate that the application did not sufficiently support this user's needs. This shows that elements of the design, such as navigation and task structure, were not user-friendly enough for individuals requiring more accessible interfaces. In contrast, Subjects 1, 3, and 5, who scored 4.5, demonstrated much smoother task completion with fewer errors, reflecting that the application was intuitive and allowed for easier navigation and interaction. These lower scores reflect a more positive user experience, where the design facilitated a more efficient workflow. The stark contrast between Subject 4's high score and the lower scores of other users highlights the inconsistency in the application's usability. While it performs well for some, it presents significant challenges for others, particularly those who need more straightforward interfaces or clearer guidance. This gap signals the need for more adaptable design features that cater to a broader range of users, ensuring that all individuals can navigate and complete tasks efficiently without unnecessary frustration. With improvements, the application has the potential to better meet the needs of diverse users, thereby enhancing its overall effectiveness and inclusivity.

The hypothetical dataset and heatmap overlay from the observation summarize each subject's performance across the four affective design components. The results from the emotion, feeling, thought, and action scores highlight both the strengths and critical weaknesses of the developed mobile learning application. While some users, including Subjects 1, 2, and 5, experienced smooth, intuitive interactions with high levels of engagement and satisfaction, others, particularly Subject 4, encountered significant challenges due to complex navigation, unclear instructions, and content that did not meet their needs. These disparities reveal a major flaw in the application's design, as its inconsistency in delivering a universally effective and inclusive user experience. The contrasting outcomes demonstrate that while the current design performs well for some, it fails to address the diverse abilities and preferences of visually impaired users. To fully optimize the application, it is essential to implement more adaptive features, including customizable interfaces, simplified navigation, and clearer instructions. These enhancements would not only reduce frustration for users struggling with the current design but also improve overall usability and emotional engagement across a broader range of visually impaired users. By adopting a more inclusive and flexible approach, the application can become a more powerful tool for all visually impaired children, strengthening both cognitive and emotional connections and ensuring that the learning experience is accessible, satisfying, and motivating for a wider group of visually impaired users.

Quantitative analysis of findings from interview data through a hypothetical dataset. Based on the interview results, the dataset in Table 7 is organized into four main affective design components which are emotion, feeling, thought, and action. Each component is divided into elements reflecting different aspects of the user experience with the mobile application. The dataset provides scores for each subject, allowing for an evaluation of how well the application meets users' emotional, cognitive, and practical needs.

Table 7. The hypothetical dataset of interview data according to affective design components

Subject	Emotion (1)	Emotion (2)	Feeling (1)	Feeling (2)	Thought (1)	Thought (2)	Action (1)	Action (2)
Subject 1	4	4	5	4	5	5	4	5
Subject 2	5	4	5	5	5	5	4	5
Subject 3	3	3	4	3	3	4	3	3
Subject 4	3	2	3	2	2	3	3	2
Subject 5	4	4	4	5	4	4	4	4
Subject 6	4	3	4	4	4	4	3	4
Subject 7	4	4	4	5	4	5	4	4

Notes: **Indicator:** Emotion (1) – Memorable, Emotion (2) – Motivation; Feeling (1) – Interest, Feeling (2) – Happiness; Thought (1) – Perception, Thought (2) – Positive Mind State; Action (1) – Navigation, Action (2) – Interaction.

Emotion. The emotion scores, which assess both memorability and motivation, reveal varying levels of the developed application's success in engaging users and encouraging continued use. Subjects 2 and 5, who scored a 5 for memorability, demonstrate that the developed application effectively used design elements to help them retain key features and content, indicating strong engagement with the interface. In contrast, the lower memorability scores of other subjects, such as Subject 4, suggest that certain aspects of the application were less impactful or failed to leave a lasting impression. The motivation scores similarly reflect this variation in engagement. While Subjects 1, 2, 5, and 7 scored a 4, indicating that the developed application successfully maintained their interest and encouraged further interaction, Subject 4's score of 2 highlights a significant design flaw, where the application struggled to sustain engagement. The lower motivation score suggests that the design did not resonate with this user's needs, possibly due to unclear navigation or content that did not align with their preferences. These findings emphasize the importance of tailoring the application to accommodate a wider range of users, ensuring that design elements are adaptable to different needs and preferences. By addressing these variations, the application has the potential to maintain interest and engagement for all users, ultimately enhancing its effectiveness as a learning tool.

Feeling. The feeling scores, which measure both interest and happiness, show that the developed application successfully engaged the majority of users and delivered a positive emotional experience to most, indicating that the design elements effectively aligned with their preferences and needs. Subjects 1, 2, 5, 6, and 7, who scored between 4 and 5 in terms of interest, demonstrated that the application was highly engaging, capturing their attention and sustaining their emotional involvement. This indicates that the design and content connected well with these users, contributing to a compelling user experience. Additionally, the happiness scores, particularly for Subjects 2, 5, and 7, who scored a 5, reflect a strong sense of satisfaction and enjoyment, suggesting that the application delivered a rewarding and emotionally fulfilling experience. Although Subject 4 scored lower in both interest and happiness, with scores of 3 and 2, respectively, this feedback provides valuable insight into areas for improvement. By refining certain aspects of the design, such as making the interface more intuitive and ensuring that the content better aligns with individual user preferences, the application has the potential to increase emotional satisfaction and engagement for all users. Overall, these results highlight the application's ability to connect with its users on an emotional level, pointing to opportunities for further enhancing its inclusivity and user experience.

Thought. The thought scores, assessing both perception and positive mind state, highlight the application's ability to encourage clear understanding and maintain cognitive engagement for most users. The majority of participants, particularly Subjects 1, 2, and 7, scored 5 in perception, indicating that the application's interactive elements, such as buttons and navigation, were well-designed and easy to understand. This reflects a high level of user-friendliness, suggesting that the application's layout and functionality were intuitive, promoting a smooth and accessible user experience. Additionally, these same subjects scored 5 in maintaining a positive mind state, demonstrating strong cognitive engagement and mental resilience while using the application. This indicates that the design not only facilitated understanding but also sustained a positive and engaged mental state, which is crucial for promoting ongoing use and learning. Although Subject 4 scored slightly lower, with a 3 in both perception and positive mind state, this feedback offers valuable insights into areas for improvement. By refining certain aspects of the interface, such as making the navigation even clearer and reducing potential frustrations, the application can further enhance cognitive engagement and satisfaction for all users. Overall, these results highlight the application's strengths in promoting clarity and positive mental engagement while also identifying opportunities to make the experience even more inclusive and supportive for a broader range of users.

Action. The action scores, evaluating both navigation and interaction, provide valuable insights into how user-friendly and accessible the application is for visually impaired users. Most subjects, including 1, 5, and 7, scored 4 in navigation, indicating that the application's design allowed for smooth and intuitive movement through the interface. This suggests that the navigation elements were well-organized and clear, promoting a seamless user experience for the majority of participants.

However, Subject 4's score of 3 highlights some challenges in navigating the application, pointing to opportunities for further refinement in making the navigation even more accessible for users with different needs. In terms of interaction, most subjects scored 4, demonstrating that they were able to engage easily with the application's features, such as buttons and task completion, reflecting the overall effectiveness of the interface. Subject 2's score of 3, however, signals minor challenges with specific elements, potentially linked to more complex tasks like drag-and-drop functionality. This feedback offers constructive insight into areas that can be improved to make interactions even smoother and more intuitive for all users. By addressing these minor obstacles, the application can enhance its usability and ensure a more consistent experience for every user. Overall, the results confirm the application's strengths in providing effective navigation and interaction while also identifying areas for improvement that could make the experience more inclusive and seamless for all participants.

The heatmap overlay of affective design components scores with mean values. The heatmap (see Figure 13) visualizes the scores for each subject across different affective design components, alongside the mean values for each component. This visual representation enables a clear understanding of how each component performed and where improvements are necessary.

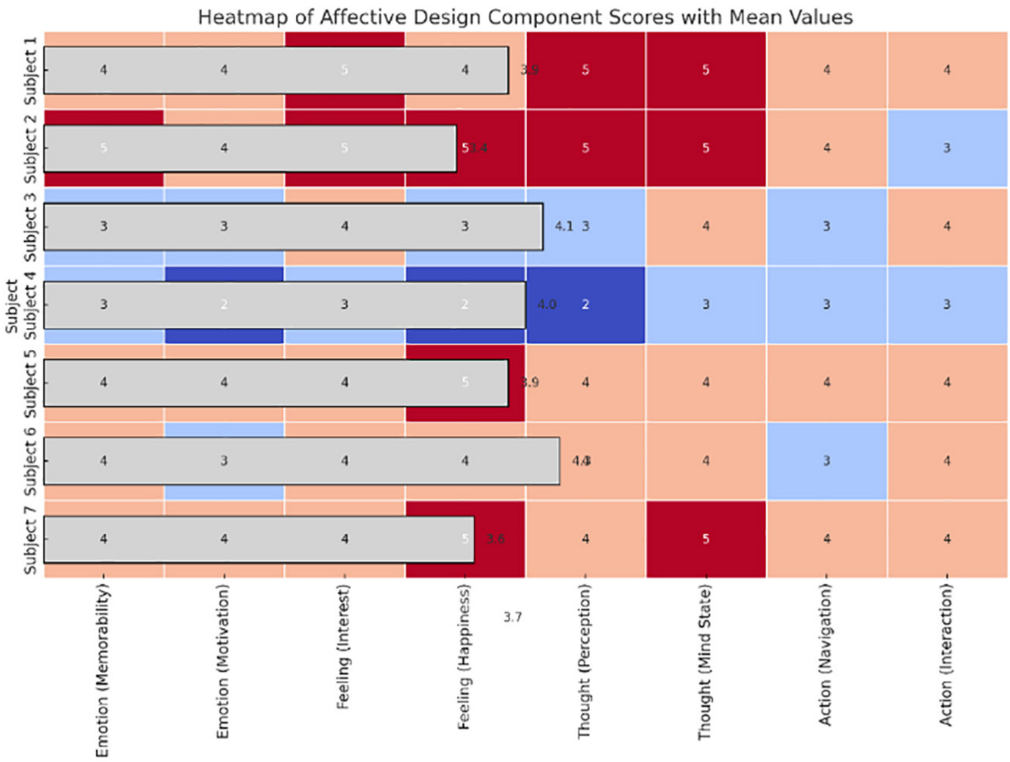

Fig. 13. The heatmap of affective design components scores with mean values

Emotion. The emotion scores reveal that the application was generally effective in promoting memorability and motivation, with a mean score of 4 for memorability and 3.9 for motivation. Subjects 2 and 5's high scores indicate that the application's design successfully connected with them, making key features easy to remember and keeping them emotionally engaged. These results highlight the strengths of the design in delivering an engaging experience for certain users. However, the lower scores from Subjects 3 and 4 suggest that specific design elements were less impactful for all users. Subject 4's consistently lower scores across both memorability and motivation highlight the opportunity to refine the application, ensuring that it provides an equally engaging experience for all users. By making targeted improvements to better engage users such as Subject 4, such as by enhancing the motivational elements and simplifying key features, the application can become more inclusive and emotionally impactful across a wider range of users. Overall, the results show that the application has a strong foundation in emotional engagement, but further refinement is necessary to ensure it consistently meets the needs of all users.

Feeling. The feeling scores indicate that the application was largely successful in capturing user's interest and delivering emotional satisfaction, with a mean interest score of 4.3 and a happiness score of 3.9. Most users, particularly Subjects 2, 5, and 7, rated their experience highly, reflecting the application's ability to provide an engaging and emotionally fulfilling interaction. These results demonstrate that the design elements strongly connected with the majority of users, effectively meeting their expectations. However, Subject 4's lower scores, particularly a 3 in interest and a 2 in happiness, highlight areas where the application can be further optimized. These lower scores suggest that adjustments in the design, such as improving usability or offering more tailored content, could significantly enhance emotional satisfaction and engagement for users who did not fully connect with the current version. By addressing these challenges, the application can better meet the diverse needs of all users, ensuring it consistently delivers a satisfying and engaging experience. Overall, while the results are promising, they also reveal opportunities to strengthen the inclusivity and emotional appeal of the application.

Thought. The thought scores reflect that the application was generally effective in delivering a clear and understandable interface, with a mean perception score of 4.1 and a positive mind state score of 4.2, indicating strong cognitive engagement among most users. Subjects 1, 2, and 7, who scored a 5 in both areas, demonstrated a deep understanding of the application's features and maintained a high level of cognitive engagement, suggesting that the design successfully aligned with their expectations and needs. These high scores highlight the effectiveness of the interface in fostering a positive user experience for the majority of participants. However, the lower scores from Subject 4, particularly a 2 in perception and a 3 in positive mind state, suggest that the application's usability requires enhancements to ensure it is fully accessible and intuitive for all users. The difficulties faced by Subject 4 point to the need for more inclusive design adjustments, such as clearer instructions or more simplified navigation, to support users who struggle with complex interfaces. Overall, while the high mean scores demonstrate that the application was well-received in terms of cognitive engagement, addressing the lower scores will ensure a more universally accessible and satisfying experience for all users.

Action. The action scores reflect that the application was generally effective in terms of navigation and interaction, with mean scores of 3.7 and 3.9, respectively. The majority of users, particularly Subjects 1, 5, and 7, found navigation smooth and straightforward, as indicated by their scores of 4. This suggests that the application's layout and navigation were well-organized for these users. Similarly, most subjects scored 4 in interaction, demonstrating that the interface allowed for seamless and efficient engagement with the application's features. However, the slightly lower scores from Subjects 4 and 2, with scores of 3 in navigation and interaction, indicate opportunities for further improvement. These users clearly encountered challenges with more complex design elements, such as drag-and-drop functionality, which suggests the need for simplifying certain tasks to enhance usability. Overall, the high mean scores highlight the application's strong foundation in usability, but targeted refinements could ensure that the interface is more intuitive and accessible to all users, leading to an even more streamlined experience across the board.

Comparison with similar studies in other educational contexts. The findings of this study both align with and challenge existing research on using affective design in educational tools for students with disabilities. A few comparisons and distinctions emerge when considering similar studies. The discussions are as follows:

User engagement through affective design. Like prior research, this study highlights how integrating affective elements such as auditory feedback and friendly character interactions improves user engagement among visually impaired children. Studies by [3] and [7] showed that incorporating emotional feedback in educational tools can boost motivation for students with autism or cognitive challenges. This study similarly finds that positive auditory cues and consistent feedback keep children engaged. However, this study uniquely focuses on visually impaired children and emphasizes multisensory engagement combining sound, touch, and intuitive design. While other research often emphasizes visual aids, this study underscores the importance of designing for non-visual senses, filling a critical gap in assistive technology for visually impaired learners.

Data collection methods and analysis. Unlike many studies that rely on real-time interaction data for user testing [10], this study used hypothetical datasets and heatmaps due to the small sample size. This method allowed a visual understanding of potential user interactions without extensive testing. While hypothetical data can provide preliminary insights, it lacks the depth and accuracy of real-world interaction logs. This makes the study's findings less generalizable compared to those using larger datasets. However, it demonstrates a practical method for early-stage analysis when access to larger participant groups is limited.

Focus on emotional comfort and cognitive support. Both this study and research by [8] emphasize that cognitive support, like clear instructions and auditory labels, can build confidence among visually impaired learners. But while [8] work is more concerned with older students in higher education, this study highlights the importance of emotional comfort for younger children. This focus on emotional connection through a character such as Alisha and engaging voice prompts is particularly relevant for primary school children, who may need more encouragement and positive reinforcement to maintain focus and confidence. This contrast suggests that age-specific design strategies are crucial for effective educational tools.

User-centered design and co-creation. The importance of iterative, user-centered design aligns with studies such as [15], which found that co-creating technology with end-users enhances usability and satisfaction. Both studies show that direct feedback from users leads to tools that better meet their needs. However, this study's emphasis on playful and interactive elements for children differs from the more formal approaches used in tools for adults. It suggests that developing for younger users requires a shift in design priorities to emphasize engagement and emotional connection rather than purely functional improvements.

This study encourages the conversation on affective design by focusing on non-visual, emotionally engaging features that address the specific needs of visually impaired children. It presents a practical approach to early-stage testing using hypothetical data but acknowledges the limitations in terms of generalizability. By emphasizing the need for age-appropriate, emotionally supportive design, it fills an important gap in the development of assistive learning tools and provides a basis for refining similar technologies in diverse educational settings.

Practical implications of the findings for educators and developers. The findings of this study, particularly the successful integration of affective design principles in an interactive mobile learning application for visually impaired children, provide important practical implications for both educators and developers.

For Educators

Enhancing engagement and inclusivity. The study demonstrates that applications designed with emotional engagement in mind can significantly enhance the learning experience of visually impaired children. Educators should consider integrating digital tools that emphasize emotional responsiveness and personalization in their teaching practices. By using applications that evoke positive emotions, educators can foster a more inclusive and engaging learning environment that meets the needs of children with varying levels of visual impairment.

Supporting independent learning. One of the key findings is that affective design elements—such as auditory feedback, character interaction, and positive reinforcement—promote a sense of independence among visually impaired children. Educators can leverage these types of applications to support independent learning, allowing students to explore educational content at their own pace. This can reduce the reliance on constant teacher intervention, empowering visually impaired children to take ownership of their learning. The study also highlights the importance of customization in educational tools. By adjusting settings such as font size, color contrast, and audio feedback, educators can create personalized learning experiences that align with individual student preferences and needs, ensuring that no child is left behind due to accessibility barriers.

For Developers

Incorporating affective design in educational technologies. The findings underline the necessity of considering emotional and cognitive aspects in the development of educational applications for visually impaired users. Developers should prioritize the integration of affective design principles, including elements that address user emotions, memory, and interaction, in future assistive technologies. Features such as customizable interfaces, intuitive navigation, and multisensory feedback (auditory, tactile, and visual) should be standard components in applications designed for visually impaired children.

Designing for a wider range of users. Developers should also consider the diversity of visual impairments when designing educational applications. The study's findings suggest that applications must be adaptable to accommodate users with different levels of impairment, from partial vision loss to complete blindness. For instance, providing options to adjust the contrast, brightness, or size of on-screen elements can enhance the accessibility of applications for users with varying needs. Incorporating features such as screen reader compatibility and gesture-based controls can further enhance usability for children with severe visual impairments.

Improving usability through real-world testing. The study emphasizes the importance of user-centered design and iterative testing. Developers should engage with educators and visually impaired students early in the design process, conducting real-world testing to gather feedback on usability, emotional engagement, and accessibility. Incorporating feedback from these testing phases could ensure that the final product meets the needs of its users. Continuous refinement based on user interactions could also enhance the application's effectiveness, ensuring it remains aligned with the evolving needs of visually impaired children.

The practical implications of this study emphasize the importance of integrating affective design principles into educational tools for visually impaired children. By addressing both the emotional and functional needs of students, educators and developers can create more inclusive, engaging, and effective learning environments. This study provides a framework for future collaborations between educators and developers, encouraging the co-creation of tools that meet the diverse needs of visually impaired learners and ensuring that they have access to educational experiences that foster both independence and emotional well-being.

Consideration of cultural and regional differences. The effectiveness of the interactive mobile learning application for visually impaired children may vary significantly across different cultural and regional contexts. Several factors related to cultural norms, language, and regional educational practices can influence how children engage with and benefit from the application. They are discussed as follows:

Impact on auditory guidance. The application relies heavily on auditory feedback, including instructions and interactions guided by a character with a friendly voice. While the initial version uses a specific language or dialect suited to Malaysian users, linguistic variations can impact how well users from other regions understand and engage with the content. For example, the pronunciation, tone, and word choices used by the virtual guide Alisha may need to be adapted to align with local dialects and speech patterns in different regions.

Localization needs. To ensure the application is effective in various cultural contexts, localization is necessary. This involves not only translating the content into different languages but also adjusting idiomatic expressions, cultural references, and the tone of the voice prompts to resonate with children from different backgrounds. Localization can help create a sense of familiarity and comfort for users, making the application more engaging and reducing potential language barriers.

Alignment with regional curricula. Educational practices and learning standards can differ widely between regions. For example, the mathematical content and problem-solving approaches in the application may align well with the Malaysian curriculum but may require adjustments to fit the educational frameworks of other countries. Developers must collaborate with local educators to ensure that the content is relevant and matches the learning objectives and styles of different regions.

Perceptions of assistive technology. Cultural attitudes towards technology and assistive devices can vary, influencing how receptive parents, educators, and children are to using the application. In some regions, there may be a strong cultural acceptance of technology as a tool for education, while in others, traditional learning methods might be preferred. Understanding these attitudes is important for designing strategies to encourage adoption and use of the application. For instance, providing evidence of the application's benefits through local pilot studies could help increase acceptance in regions where there is skepticism about digital learning tools.

Design aesthetics and character representation. Cultural preferences can also affect how users perceive visual and auditory elements of the application. For example, the character Alisha, designed with a specific appearance and voice, may resonate differently with children from various cultural backgrounds. Adjusting character design, attire, and even background music or sounds to match regional tastes can help create a more culturally inclusive experience.

Visual sensitivity and symbolism. The choice of colors, symbols, and visual cues within the application can carry different meanings across cultures. For example, certain colors may have positive associations in one culture but negative connotations in another. Developers must consider these cultural nuances when designing user interfaces and ensure that the visual elements are appropriate and welcoming to users from different backgrounds.

By considering and addressing these cultural and regional variations, the application can be better positioned to serve visually impaired children globally, ensuring that it provides a meaningful, engaging, and accessible learning experience for all.

Long-term implications and potential for scaling up the application. The interactive mobile learning application developed in this study offers significant potential to impact the education of visually impaired children and advance assistive technology. The discussion covers the following aspects:

Integration into educational systems: The application's ability to engage visually impaired children suggests it could play a role in inclusive education programs, supporting these students alongside their sighted peers. This aligns with global goals for equitable access to education. In addition, expanding the app to cover more subjects such as literacy, science, and social studies could allow for broader integration into school curricula. However, such expansion must ensure the content remains accessible and tailored to the needs of visually impaired learners, avoiding a one-size-fits-all approach.

Integration with emerging technologies: Leveraging artificial intelligence (AI) and machine learning (ML) could make the application more responsive to individual learning needs, offering personalized feedback. AI-driven features such as speech recognition could improve user interactions, making the app more intuitive for those who rely on voice commands. However, incorporating advanced technologies requires a balance between innovation and usability, ensuring that AI-driven features do not overwhelm users or create new accessibility challenges.

Long-term educational and social impact: The application could have a lasting impact by helping visually impaired children develop critical skills, preparing them for higher education and future employment. It could also promote social inclusion by enabling these students to participate more fully in mainstream classrooms. As the app is used more widely, it could become a model for inclusive educational technology, encouraging other developers to focus on emotional engagement and accessibility. However, maintaining its role as a template requires ongoing updates and evidence of its effectiveness.

Scaling this application could significantly improve access to education for visually impaired children worldwide. Localization and technology integration are key to making it a globally adopted tool. With its adaptability and focus on accessibility, the app has the potential to promote educational equity and empower visually impaired learners to reach their full potential, provided its development remains aligned with diverse user needs.

5 LIMITATIONS OF THE STUDY

Despite the success in developing and testing an interactive mobile learning application for visually impaired children based on affective design principles, this study faces several limitations that must be addressed.

One key limitation is the small and homogeneous sample size. The study involved only seven participants, all from the same primary school in Malaysia, with similar educational and cultural backgrounds. While this provided valuable insights into the effectiveness of the application within a specific context, the limited sample size restricts the generalizability of the findings. A small, homogeneous sample may not capture the diversity of experiences and interaction patterns among visually impaired children in different regions or with varying educational needs. Future studies should expand the sample size to include a more diverse group of participants, such as children from different cultural, socioeconomic, and educational backgrounds, to ensure the findings are more representative of the broader population of visually impaired learners. Additionally, including participants with varying levels of visual impairments (e.g., partial vs. complete vision loss) could provide a more detailed understanding of the application's usability.

Another significant limitation is the reliance on a hypothetical dataset for part of the user experience analysis. The hypothetical dataset was generated based on observational and interview data from a small group of participants, simulating their interaction patterns with the application. While this approach allowed for the visualization of potential user behaviors and engagement through heatmap overlays, it does not fully capture the complexity and variability of real-world interactions. Hypothetical data inherently lacks the richness of actual, longitudinal user interaction data, which would offer a more comprehensive evaluation of how children interact with the application over time. Moreover, relying on a hypothetical dataset introduces the risk of bias in interpreting user behavior, as it is shaped by assumptions and subjective interpretations of the observational data.

Overall, while the current study provides important insights into the role of affective design principles in developing mobile learning applications for visually impaired children, the small sample size and the use of hypothetical data limit the generalizability and depth of the findings. Future research should address these limitations by incorporating larger, more diverse samples and real-time data collection to ensure that the application meets the needs of a wider range of visually impaired users and provides a truly inclusive learning experience.

6 CONCLUSION AND FUTURE WORKS

This study successfully developed and evaluated an interactive mobile learning application for visually impaired children, emphasizing the integration of affective design principles to enhance user engagement and accessibility. Through user experience testing and the use of hypothetical datasets, the study demonstrated how multisensory design elements, such as auditory feedback and engaging character interactions, can significantly improve both the emotional and cognitive experiences of visually impaired learners. This focus on emotional engagement sets the study apart, as it addresses a critical gap in the current landscape of assistive educational technologies, where many existing tools prioritize functionality over user experience. The primary contribution of this study lies in its demonstration of how affective design principles can be applied to create a learning environment that is not only accessible but also emotionally supportive. By focusing on the needs of visually impaired children in early education, this study provides a framework for designing digital tools that prioritize user-centered, emotionally responsive interactions, which are crucial for sustaining engagement and motivation among young learners with disabilities. Additionally, the study introduces a practical approach to early-stage testing using hypothetical datasets and heatmap analysis. This method offers an alternative for researchers who face challenges in accessing large participant groups, contributing to the development of effective preliminary evaluation techniques in the field of assistive technology. In a broader context, this study contributes to the ongoing efforts towards inclusive education by providing a model for how technology can be designed to meet the diverse needs of visually impaired students. It highlights the importance of integrating emotional and cognitive considerations into assistive learning tools, encouraging further research and development in this direction. The study's insights can guide educators, developers, and policymakers in creating and implementing technology that promotes equity and inclusivity in educational settings. The study also lays the groundwork for future innovations in assistive technology, suggesting directions for scaling the application and incorporating advanced features such as AI for personalized learning.

By emphasizing the potential for long-term impact on both individual learners and educational systems, this study underscores the transformative role that well-designed digital tools can play in improving the lives of visually impaired children. Ultimately, this study represents a significant step forward in the development of emotionally engaging, user-centered educational technologies and offers valuable insights for the creation of more inclusive learning environments for all students, regardless of their abilities.

7 ETHICAL CONSIDERATION OF THE STUDY

This study adhered to strict ethical standards to ensure the safety, well-being, and rights of all participants throughout the research process. The study received ethical approval from Universiti Teknologi MARA (UiTM), Sultan Ahmad Shah Medical Centre @IIUM, and the Ministry of Education Malaysia, ensuring compliance with national and institutional guidelines.

8 ACKNOWLEDGMENT

The authors sincerely thank the Ministry of Higher Education (MOHE), Malaysia, for providing research grant (FRGS/1/2022/ICT10/UITM/02/1) that made this study possible. We also extend our thanks to Universiti Teknologi MARA (UiTM) and Universiti Utara Malaysia (UUM) for their invaluable support in providing the expertise necessary for completing this study. Additionally, we deeply appreciate the Primary School of Jalan Hamilton, Malaysia, for their cooperation and for providing the participants who played a crucial role in this study.

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