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PAPER

Interactive Tangible User Interface for Early Childhood Education: A Usability Study on Teaching Geometric Shapes in Kindergarten

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ABSTRACT

Tangible user interfaces (TUIs) offer significant educational benefits, but their use in kindergarten, particularly for teaching geometric shapes, remains underexplored, with research largely focused on elementary education or higher levels. Moreover, usability evaluations assessing the ease of use of such tools by teachers as end-users are rarely conducted. This study aims to address these gaps by designing and evaluating TUI interactive surfaces as an aid for teaching geometric shapes in kindergarten. The proposed TUI design was evaluated for usability using the System Usability Scale with kindergarten teachers, achieving a score of 97.43, categorized as 'Good' (Grade A). This score indicates superior and acceptable performance, placing it in the highest quartile (4th quartile). Furthermore, functionality testing of the TUI system demonstrated a 100% success rate in its application as a geometric shape learning media. These findings suggest that the proposed TUI design is a viable and effective tool for teaching geometric shapes in kindergarten, offering a practical and user-friendly solution for educators. The study's limited sample size, subject focus, and lack of teacher diversity affect generalizability, highlighting the need for future research to expand TUI applications, assess long-term impacts, and include diverse teacher demographics.

KEYWORDS

tangible user interface (TUIs), system usability scale, learning media

1 INTRODUCTION

The integration of technology in education is crucial for both academic success and the development of essential 21st-century skills, emphasizing the need for school reforms that incorporate digital tools to foster creativity, adaptability, and critical thinking in today's learner [1], [2]. Furthermore, integrating technological tools is essential for enhancing teaching skills and learning outcomes, as technology reshapes how we live, learn, and interact with information while transforming

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approaches to education [3], [4]. In this regard, the utilization of technology enhances access to education, improves its quality, and prepares children for their roles in society [5], [6], and recent studies further support this perspective by highlighting the integration of technology in early learning environments to enhance children's cognitive and social development [7], [8].

Currently, various technological tools have been integrated into early childhood education, emphasizing the importance of developmentally appropriate designs and structured curricula, as shown by research on an eight-week robotics curriculum that helps preschool to second-grade children learn basic and complex concepts [9], the evaluation of 30 computational toys providing guidance for effective tools to develop computational thinking (CT) skills in children aged 5–6 years [10], and the use of PhysGramming, a digital environment enabling preschoolers to learn physical sciences and programming through independent game creation [11]. This integration of technology paves the way for the adoption of innovative approaches such as the tangible user interface (TUI), a technological advancement that enables interaction with digital information through tangible objects and physical environments [12], [13], [14], and can be further incorporated into early childhood education to enhance learning experiences by aligning with young children's developmental needs, as illustrated in Figure 1, which compares graphical user interfaces (GUI) with the TUI paradigm. The primary goal of TUI development is to enhance collaboration, learning, and design by giving physical form to digital information. This approach leverages human capabilities to understand and manipulate physical objects and materials effectively [15].

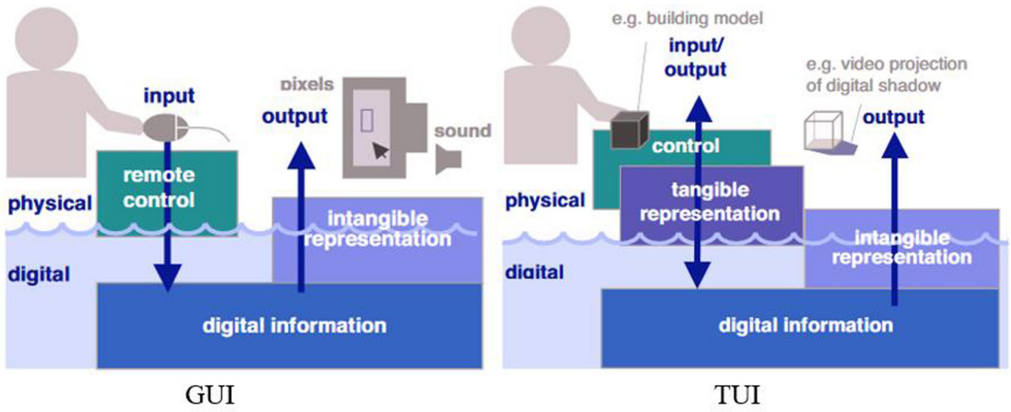

Fig. 1. GUI and TUI paradigms [12]

Research on TUIs has advanced significantly in the field of human-computer interaction (HCI) and is regarded as a cornerstone of modern HCI studies [16], [17], [18]. TUIs represent a novel interface that bridges the digital and physical worlds, potentially transforming the way users interact with digital information through tangible representations [19], [20]. TUIs have been applied to various domains, including education, where they show particular promise for children's learning [19], [21], [22], [23], [24]. In educational settings, TUIs offer several benefits, including being intuitive for beginners, fostering creativity and initiative in children, supporting cognitive development, and encouraging communication and teamwork in real-world contexts [25], [26]. These attributes make TUIs well-suited for development as learning media, particularly in kindergartens, where educational tools are essential for fostering knowledge, enhancing learning experiences, and achieving educational objectives [27], [28]. One key area of early education is the introduction of mathematics, including fundamental geometry, which serves as a critical mathematical skill [28], [29].

According to the National Council of Teachers of Mathematics (NCTM), geometry is one of the three foundational areas, along with numbers and measurement, that should be introduced to children aged 3–6 years [30]. This study demonstrates that TUI-based geometric shape learning media are acceptable and effective for use by teachers in kindergarten, offering a valuable tool for early geometry education.

2 LITERATURE REVIEW

Developmentally appropriate tools and resources play a crucial role in fostering essential 21st-century skills among young children. Research by Papadakis [31] demonstrated how tools specifically designed for early learners can effectively support the development of basic coding and CT skills, preparing children to meet future technological challenges. Furthermore, Kalogiannakis and Papadakis [32] also emphasize the critical role of teacher education programs in raising awareness of the benefits of innovative technologies by equipping future educators with the skills to effectively integrate STEM activities into preschool classrooms, thereby fostering engaging and meaningful learning experiences for young children.

Building on this broader understanding of developmentally appropriate tools and the importance of teacher engagement, TUIs have emerged as a particularly promising technology in early childhood education, garnering significant attention for their potential to enhance learning through physical interaction and developmentally appropriate designs. Several seminal studies have underscored the significant role of TUIs in fostering meaningful learning experiences for young children. For instance, Lin et al. [33] identified TUIs as an effective tool for teaching computational thinking skills to young learners, while Antle and Wise [34] examined the integration of cognitive and learning theories into TUI design, offering a robust theoretical foundation for their use in educational settings. Furthermore, research has demonstrated the effectiveness of TUIs in teaching abstract concepts, such as programming constructs like repetition cycles [35], as well as in enhancing tactile perception and spatial awareness [36]. Similarly, Horn et al. [37] emphasized the value of hybrid approaches that integrate tangible and graphical interfaces, highlighting their ability to support young learners' computational and creative thinking.

Tangible user interfaces have also been utilized in various forms to promote hands-on and collaborative learning experiences in early childhood education. Specifically, boards and cards have been designed to foster collaboration among kindergarteners [38], while concrete learning media, such as block tools, help cultivate young children's STEM attitudes, enhance their knowledge of science and engineering, and ignite curiosity about bioengineering through interactive, hands-on activities [39]. Somma and Desideri [40] further demonstrated that TUI-based storytelling tools enhance interaction and self-expression by incorporating diverse media such as pictures, videos, sounds, and tangible objects, promoting engagement, personalization, and adaptability, making these tools suitable even for children with disabilities or special needs. Chan [41] explored the perspectives of pre-service teachers on integrating tangible tools in early childhood classrooms, emphasizing their potential to enhance learning but also highlighting challenges related to classroom implementation, such as the need for comprehensive teacher training and adequate resources.

Additionally, Chettaoui et al. [42] examined Montessori-inspired TUIs designed to improve retention skills in preschoolers, finding that tangible interactions positively impacted both short-term retention and user experience. Pugnali et al. [43] identified unique advantages of TUIs such as the KIBO robotics kit in developing young children's computational thinking, outperforming graphical tools such as ScratchJr. Similarly, Michailidis et al. [44] demonstrated that tangible devices like Makey Makey foster collaboration and improve learning outcomes in language education for young learners. Beyond academic contexts, Woodward et al. [45] introduced "TangToys," TUIs designed to support children's emotional well-being by enabling non-intrusive emotional expression through play, showcasing the versatility of TUIs for addressing both cognitive and emotional development. Collectively, these findings highlight that TUIs naturally facilitated interdependent collaborative activities and enhanced engagement during the learning process.

Despite these advancements, the application of TUIs for teaching geometric shapes in kindergarten remains largely underexplored, as most research has primarily focused on higher education levels [46], [47], [48], [49]. This has created a gap in understanding how TUIs can be effectively designed and tailored to introduce foundational geometric concepts to young learners. Moreover, no usability evaluations have been conducted to assess the ease of use of TUIs as teaching aids for kindergarten teachers, even though teacher involvement in usability testing is essential to ensure that learning media align with their intended functions and are user-friendly [35–38], as highlighted in previous studies on educational tools and applications [50], [51], [52].

In addressing these gaps, the study aims to design a TUI in the form of interactive surfaces, specifically tailored as learning media for teaching basic geometric shapes while supporting kindergarten teachers as effective teaching aids, which further identifies the teacher involvement in usability testing to ensure that the TUIs are practical, intuitive, and user-friendly tools for early learning. This focus on teacher involvement in usability testing underscores its broader significance, as usability testing plays a pivotal role in the successful adoption of educational technology by ensuring that systems meet user needs, facilitate ease of use and learning, and minimize potential challenges [53], [54], [55], [56]. By combining pedagogical effectiveness with practical usability, this research offers a novel contribution to early childhood education and the field of educational technology, advancing the integration of tangible technologies into early learning environments.

3 METHODS

3.1 TUI hardware design

The development of the TUI as a learning media for teaching basic geometric shapes in kindergarten requires specific hardware components. The hardware specifications for this study are listed in Table 1, and the TUI hardware design is depicted in Figure 2.

Table 1. Hardware

No	Hardware	Specification
1	Convertible Laptop ThinkPad Helix (2nd Gen)	Windows 10, 10-inch, Intel Core M-5Y71 Processor (4M Cache, 1.2GHz), Memory 8GB 1600MHz DDR3L, Storage 256GB M.2 SSD.
2	Board Microcontroller Arduino Uno	ATmega328P, Clock Speed 16 MHz, Input Voltage 7-12V.
3	Sensor E18-D80NK infrared proximity (IR)	5VDC, 100mA, Effective distance 3-80CM Adjustable, Response time <2ms.

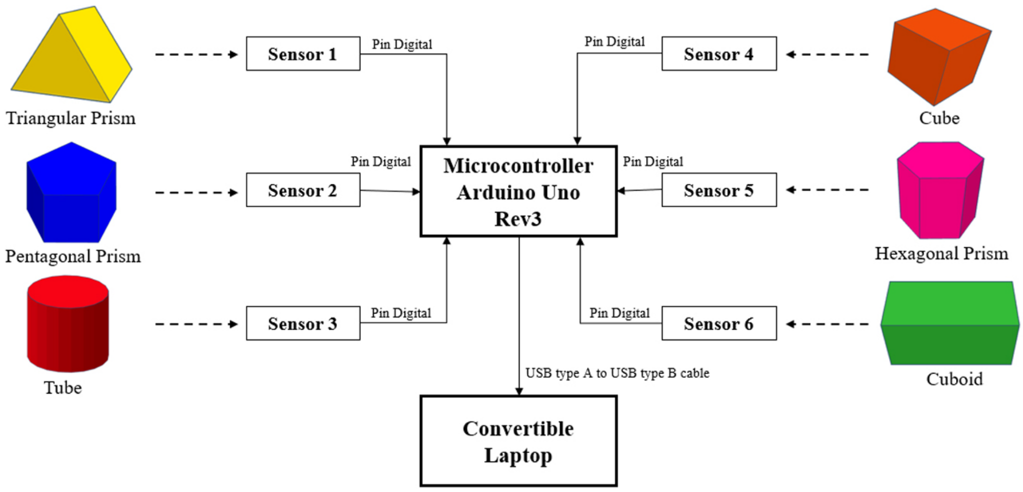

Fig. 2. TUI hardware design

As shown in Figure 2, the TUI developed in this study is sensor-based, employing sensor technology to support the TUI interface system [57], [58]. Six E18-D80NK infrared proximity sensors are utilized to detect each geometric shape. These sensors are connected to an Arduino Uno microcontroller board via digital pins, and the microcontroller is linked to a laptop using a USB Type-A to USB Type-B cable. The E18-D80NK sensor was selected for its functionality as a photoelectric sensor that integrates transmitter and receiver capabilities, enabling obstacle detection within a range of 3–80 cm with an adjustable detection distance, all at a low cost [59], [60]. The Arduino Uno microcontroller board was chosen for its compatibility with a variety of inputs and outputs, providing flexibility for controlling devices that interact with the environment through sensors. Its open-source support, affordability, and versatility make it ideal for educational applications and diverse electronic projects [61], [62]. A portable convertible laptop is used as the platform for running the TUI application and serves as the visual display output, showcasing digital representations of geometric shapes based on sensor readings.

In this study, obstacle detection via the E18-D80NK sensor is utilized to identify geometric shapes, with each sensor corresponding to a specific shape. The minimum detection distance is configured at approximately 3 cm. An illustration of geometric shape detection using the E18-D80NK sensor is presented in Figure 3.

The TUI learning media includes six 3D geometric shapes—a triangular prism, pentagonal prism, tube, cube, hexagonal prism, and cuboid—designed and fabricated using a 3D printer. The decision to use 3D printing is based on the widespread use of 3D geometric models as teaching aids in shape learning. Figure 4 shows the design of the geometric shape learning media.

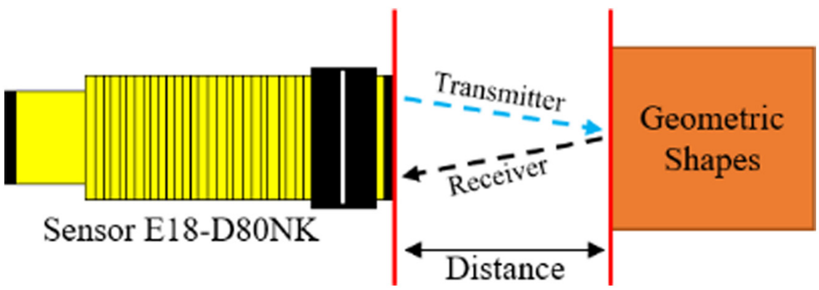

Fig. 3. Illustration of geometric shape detection using the E18-D80NK sensor

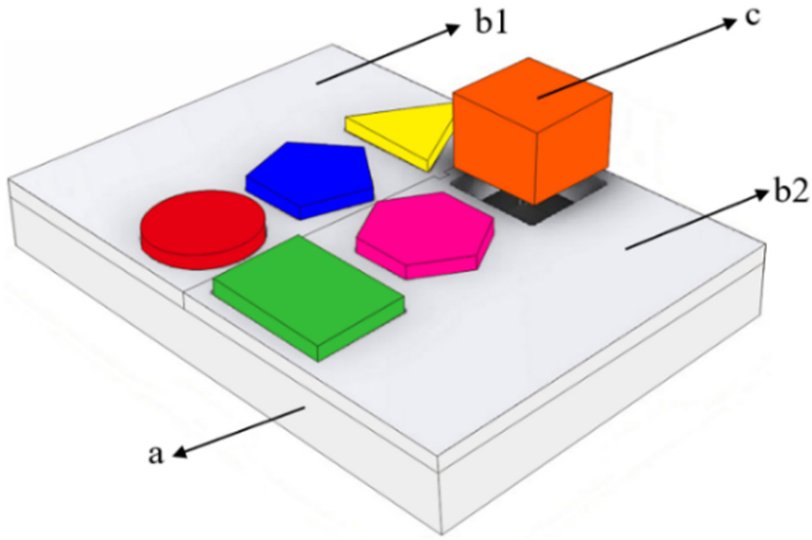

Fig. 4. TUI hardware design as a learning media for geometric shapes in kindergarten: a) bottom design, b1) top left design, b2) top right design, c) geometric shape design

As shown in Figure 4, the design of the TUI-based learning media comprises several components. Part "a" represents the base section of the learning media, which houses six E18-D80NK sensors and an Arduino Uno microcontroller board. Part "b1" corresponds to the upper left section, featuring designated spaces for matching geometric shapes such as a triangular prism, pentagonal prism, and tube. Part "b2" refers to the upper right section, designed to accommodate geometric shapes including a cube, hexagonal prism, and cuboid.

Both "b1" and "b2" serve as interactive surfaces that are detachable and modular, enabling future expansion to incorporate additional geometric shapes. Part "c" consists of the geometric shapes themselves, which function as tangible learning tools. The TUI design in this study adopts the concept of interactive surfaces, where tangible objects are placed and manipulated on a flat surface. The system interprets the spatial arrangement and relationships of the objects, such as their placement sequence, to enhance the learning experience [19].

3.2 TUI system design

The TUI system design adheres to the TUI paradigm, as depicted in Figure 1, and the TUI interaction model, as shown in Figure 5. The system's algorithms and programs are developed entirely using Scratch-based visual programming through the PictoBlox application. Scratch is recognized as an effective platform for children's learning [63], [64]. PictoBlox, an extension of Scratch, offers enhanced capabilities for hardware interaction and integration of advanced technologies such as robotics, artificial intelligence (AI), and machine learning. These features make programming activities more engaging and interactive. Additionally, PictoBlox is compatible with multiple operating systems, including Windows, macOS, Linux, and Android [65], [66]. Interaction with the Arduino Uno microcontroller board is facilitated through the Interaction with the Arduino Uno microcontroller board is facilitated through the PictoBlox application. This is achieved by selecting the appropriate firmware, specifying the type of Arduino board in use, and identifying the port connecting the board to the PictoBlox application.

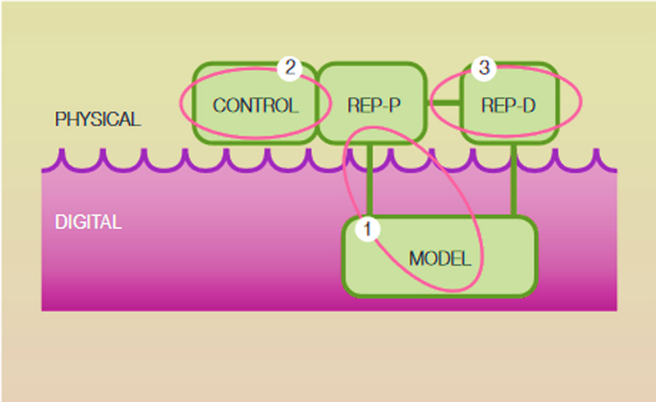

Fig. 5. TUI interaction model [12]

As shown in Figure 5, TUI exhibits three main characteristics [12], [67]:

1. Physical Representations (REP-P): Tangible elements computationally integrated with underlying digital information (MODEL).
2. Interactive Control Mechanism (CONTROL): The physical representations function as a mechanism for controlling the interface.
3. Combined Representations (REP-D): Physical representations perceptually integrated with actively mediated digital representations.

In this study, following the TUI paradigm and interaction model design, the physical component comprises the input system, which includes geometric shapes serving as interactive controls (tangible representations). These are detected through sensor readings connected to the Arduino Uno microcontroller board. The inputs are processed into digital information using the Scratch-based PictoBlox application. The tangible geometric shapes are then integrated with digital (intangible) representations and displayed visually on a convertible laptop as the output. Figure 6 illustrates the TUI interaction model design as a learning media for teaching geometric shapes in kindergarten.

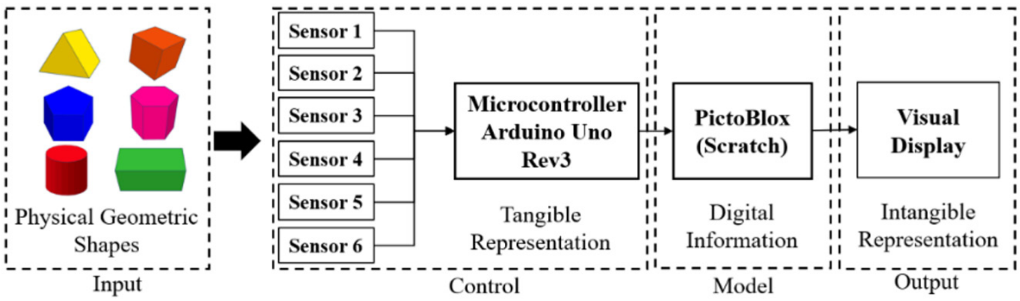

Fig. 6. Design of the TUI interaction model as a learning media for geometric shapes

After establishing the TUI interaction model, the subsequent step involved designing the visual display. In this study, the visual display represents the transformation of physical geometric shapes into digital forms based on data from Sensors 1 to 6. Each sensor is programmed to detect a specific geometric shape and assign it a unique color: Sensor 1 detects the triangular prism, represented in yellow; Sensor 2 detects the pentagonal prism, represented in blue; Sensor 3 detects the tube, represented in red; Sensor 4 detects the cube, represented in orange; Sensor 5 detects the hexagonal prism, represented in pink; and Sensor 6 detects the cuboid, represented in green. The visual display was developed using the PictoBlox application, which also operates the TUI system, ensuring that the entire system is executed within the same platform. The visual display design is depicted in Figure 7.

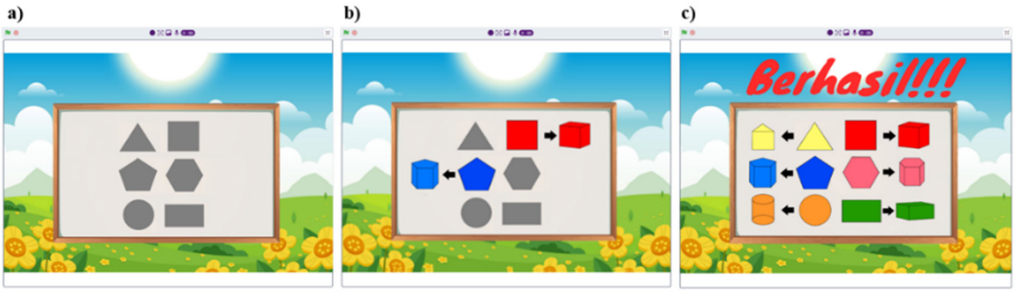

Fig. 7. Design of the TUI visual display: a) shows the initial visual display when the geometric shapes have not yet been detected by the sensors, b) the visual display shows the detection of the pentagonal prism and the cube by the sensors, c) shows the visual display when all six geometric shapes are detected by the sensors

As illustrated in Figure 7, the TUI's visual display corresponds directly to the sensor detection results, transforming physical geometric shapes into their digital counterparts. In the initial state, where no geometric shapes have been detected, the display background is a whiteboard that shows the geometric shapes arranged according to the TUI hardware layout, as shown in Figure 4. When a sensor detects a geometric shape, the visual display on the whiteboard updates to reflect the detected shape's color and form. As additional shapes are detected, the display continues to update incrementally until all six geometric shapes have been identified. Once all sensors detect the six shapes, the visual display shows the corresponding colors and shapes along with a success message ("Berhasil" in Indonesian), indicating that the shapes have been correctly arranged. To further enhance the TUI interaction design, several sound effects were integrated. A total of nine sounds were incorporated, with the corresponding sound data presented in Table 2.

Table 2. Data sound

Sound	Descriptions
Sound 1	Background sound when the TUI application is running
Sound 2	Command to place six geometric shapes according to their shape
Sound 3	Notification sound indicating the Triangular Prism has been successfully placed in its appropriate place
Sound 4	Notification sound indicating the Pentagonal Prism has been successfully placed in its assigned position.
Sound 5	Notification sound indicating the Tube has been successfully placed in its intended place
Sound 6	Notification sound indicating the Cube has been successfully placed in its accurate placement
Sound 7	Notification sound indicating the Hexagonal Prism has been successfully placed in its precise location
Sound 8	Notification sound indicating the Cuboid has been successfully placed in its proper place
Sound 9	Success notification sound indicating that all geometric shapes have been successfully placed in their correct positions

As detailed in Table 2, each sound serves as a source of information and notification, enhancing the TUI interaction experience as a learning media for geometric shapes. This auditory feedback complements the visual design of the TUI system, as illustrated in Figure 8.

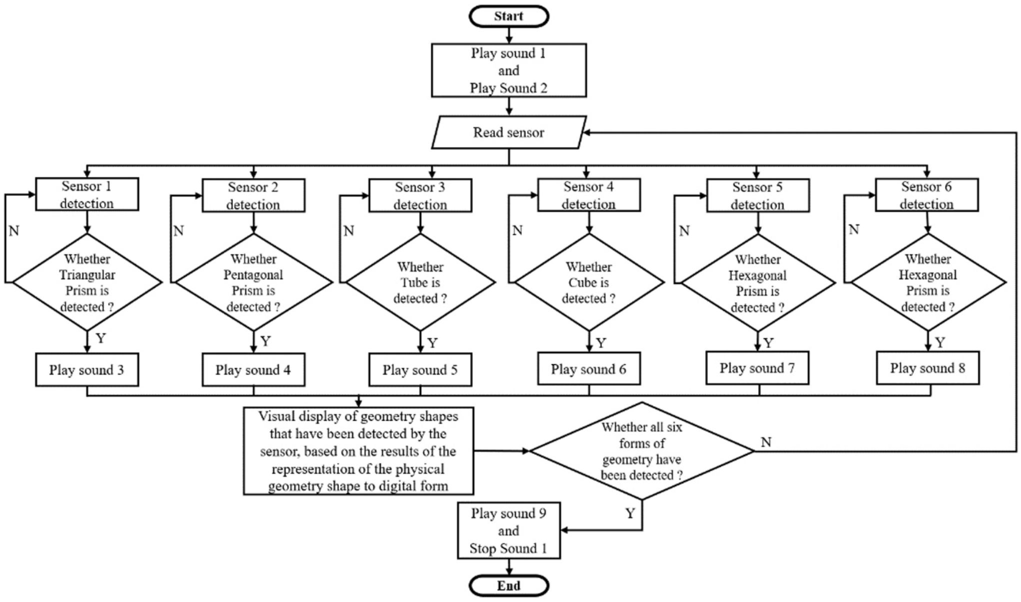

Fig. 8. TUI system design flowchart

3.3 Usability testing

Usability testing was conducted to evaluate the effectiveness of the TUI system as a learning media for geometric shapes in kindergartens, particularly for teachers who will utilize the system as an educational tool in the teaching and learning process. In this study, the system usability scale (SUS) was employed as the usability testing tool. Since its introduction by Brooke, the SUS has been widely recognized for assessing the usability of various products and systems. It is considered a highly robust, popular, valid, and reliable instrument for usability evaluation [68], [69], [70], [71], [72]. Furthermore, several studies have highlighted the application of SUS testing by teachers to evaluate usability [50], [51], [52]. It remains one of the most commonly used tools in human-computer interaction (HCI) research for usability assessments [73], [74], [75]. The SUS can be applied to evaluate a wide range of products, including websites, hardware, software, games, and mobile devices [76], [77].

The SUS questionnaire comprises ten items presented in a Likert scale format, with scores ranging from 1 (strongly disagree) to 5 (strongly agree). Table 3 presents the SUS questionnaire, translated into Bahasa Indonesia for this study [78].

Table 3. The Indonesian version of the SUS questionnaire [78]

No	The Original SUS Questionnaire	The Indonesian Version of SUS Questionnaire
Q1	I think that I would like to use this system.	Saya berpikir akan menggunakan sistem ini lagi.
Q2	I found the system unnecessarily complex.	Saya merasa sistem ini rumit untuk digunakan.
Q3	I thought the system was easy to use.	Saya merasa sistem ini mudah untuk digunakan.

(Continued)

Table 3. The Indonesian version of the SUS questionnaire [78] *(Continued)*

No	The Original SUS Questionnaire	The Indonesian Version of SUS Questionnaire
Q4	I think that I would need the support of a technical person to be able to use this system.	Saya membutuhkan bantuan dari orang lain atau teknisi dalam menggunakan sistem ini.
Q5	I found the various functions in the system were well integrated.	Saya merasa fitur-fitur sistem ini berjalan dengan semestinya.
Q6	I thought there was too much inconsistency in this system.	Saya merasa ada banyak hal yang tidak konsisten (tidak serasi) pada sistem ini.
Q7	I would imagine that most people would learn to use this system very quickly.	Saya merasa orang lain akan memahami cara menggunakan sistem ini dengan cepat.
Q8	I found the system very cumbersome to use.	Saya merasa sistem ini membingungkan.
Q9	I felt very confident using the system.	Saya merasa tidak ada hambatan dalam menggunakan sistem ini.
Q10	I needed to learn a lot of things before I could get going with this system.	Saya perlu membiasakan diri terlebih dahulu sebelum menggunakan sistem ini.

Of the ten SUS items, five are positive statements (odd-numbered: 1, 3, 5, 7, and 9), and five are negative statements (even-numbered: 2, 4, 6, 8, and 10). For each positive statement, the score obtained is reduced by 1, while for each negative statement, the final score is calculated by subtracting the user's score from 5. The SUS score is derived by summing the individual scores and multiplying the total by 2.5 [70–72], [52], [74–79], [80], as shown in Equation 1 [81]. To calculate the average SUS score across respondents, the total score is divided by the number of participants, as indicated in Equation 2 [79]. This calculation provides the overall SUS score, representing the usability assessment result, as illustrated in Figure 9.

$$SUS = [\Sigma(Score_{Odd\ Number} - 1) + \Sigma(5 - Score_{Event\ Number}) * 2.5] \tag{1}$$

$$\bar{X} = \frac{\Sigma x}{n} \tag{2}$$

Where, $\bar{X}$ the average score, Σx the total SUS score and n number of respondents

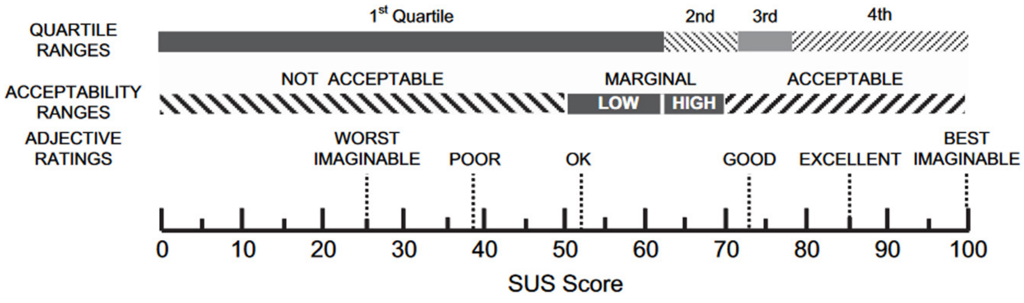

Fig. 9. A comparison of the overall SUS score [68]

As shown in Figure 9, a higher SUS score indicates a more acceptable and user-friendly system. Additionally, SUS scores can be categorized into letter grades ranging from A to F, with A representing the highest level of usability and F the lowest [79]. In this study, the SUS scores were calculated both manually and using the SUS Analysis Toolkit for a more comprehensive evaluation. The SUS Analysis Toolkit is an open-source, web-based tool developed by the Mixality Research Group for analyzing single and multivariable SUS usability studies [82]. Before performing the SUS analysis, statistical evaluations of the SUS questionnaire responses were conducted to determine the validity and reliability of the questionnaire items. These evaluations ensured the appropriateness of the SUS instrument for use in this study.

3.4 Statistical analysis: Validity and reliability tests

In this study, statistical analysis was conducted as part of the SUS questionnaire usability test to assess the validity and reliability of responses provided by kindergarten teachers before analyzing the SUS scores. Several studies have also highlighted the use of statistical analysis, including validity and reliability tests, to evaluate SUS questionnaires [73], [79], [83]. The validity test evaluates the accuracy of the questionnaire instrument. It was conducted using the Pearson Product-Moment correlation formula, as shown in Equation 3. The reliability test, which assesses the consistency of the instrument in producing similar results under identical conditions, was performed using the Cronbach alpha formula, as outlined in Equation 4 [84].

$$r_{xy} = \frac{N\left(\sum XY\right) - \left(\sum X\right)\left(\sum Y\right)}{\sqrt{\left\{N\sum X^2 - (\sum X)^2\right\}\left\{N\sum Y^2 - (\sum Y)^2\right\}}} \tag{3}$$

Where, r correlation coefficient between variables X and Y, N the number of respondents, $\sum XY$ number of multiplying the score of X and Y, $\sum X^2$ number of X squared, $\sum Y^2$ number of Y squared, $\sum X$ total score X and $\sum Y$ total score Y.

$$r_{11} = \left[\frac{k}{k-1}\right]\left[1 - \frac{\sum \sigma_b^2}{\sigma_t^2}\right] \tag{4}$$

Where, r_{11} coefficient of reliability, k the number of question item, $\sum \sigma_b^2$ total item variance, σ_t^2 total variance.

For the validity test, the decision-making criterion is as follows: if the calculated r-value exceeds the r-table value, the questionnaire is considered valid; otherwise, it is deemed invalid. For the reliability test, a Cronbach Alpha value greater than 0.7 indicates that the questionnaire is reliable [79]. In addition to manual calculations of validity and reliability based on Equations 3 and 4, Minitab statistical analysis software was used to ensure the accuracy of the test results. Figure 10 illustrates the process flow for conducting validity and reliability tests on the SUS questionnaire responses provided by kindergarten teachers before performing the SUS score analysis.

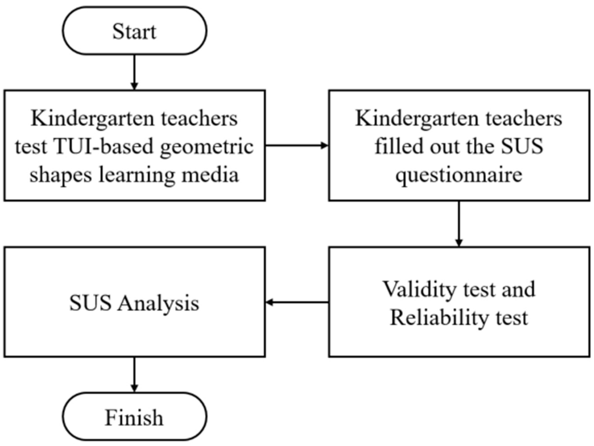

Fig. 10. Validity test and reliability test flow

3.5 Research Object

In this study, the research object is the result of modeling a TUI as a learning media for geometric shapes in kindergarten. As illustrated in Figure 11, the proposed TUI model will be tested by kindergarten teachers using usability testing to determine whether the TUI learning media meets the needs of its intended users.

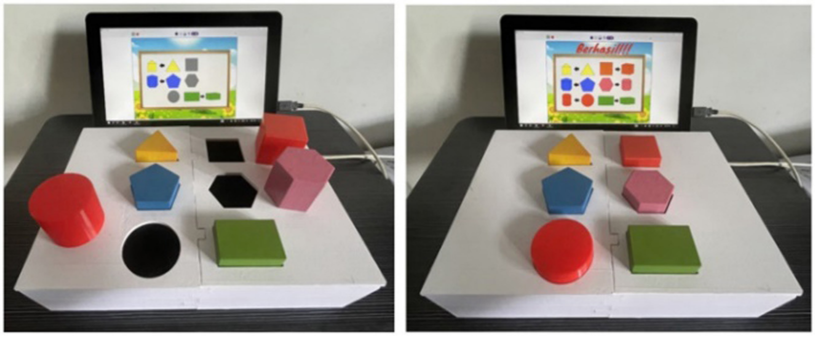

Fig. 11. TUI design results as a learning media for geometric shapes

3.6 Research participants

The participants in this study are kindergarten teachers who will conduct usability testing using the SUS to evaluate the TUI model as a learning media for geometric shapes. Usability experts and prior studies suggest that five users (the "magic number 5") are sufficient for a usability test, as this sample size can identify 80% of usability issues [85], [86], [87]. However, some studies indicate that, in certain situations, a larger sample of participants is necessary for usability testing [88].

In this study, 22 kindergarten teachers from 12 different schools in Kendari City, Southeast Sulawesi, Indonesia, tested the TUI system as a learning media for geometric shapes. The teachers' ages ranged from 22 to 52 years, with a mean age of 28.04 years and a standard deviation of 6.83 years. For SUS testing, a minimum of 12 participants is required to achieve statistically conclusive results [83], [89], [90], [91]. Therefore, the sample size of 22 teachers was deemed sufficient for conducting usability testing in this study.

3.7 Experiment procedure

The procedure for testing the TUI system was divided into several stages, as follows:

a) The first stage involved introducing the TUI system to the teachers, explaining its function as a learning media for geometric shapes and how it can be used in kindergarten education.
b) In the second stage, the 22 kindergarten teachers tested the TUI system individually, with each teacher tasked with arranging geometric shapes on the TUI platform.
c) The third stage required each kindergarten teacher to complete the SUS questionnaire after testing the TUI system.

In addition to conducting usability testing, we also evaluated the functionality of the TUI media design based on the success rate of the TUI system in detecting and displaying six geometric shapes as identified by the sensors. By observing and analyzing the teachers' performance during the TUI learning media testing tasks, we determined the system's success rate based on its ability to detect and display the six geometric shapes arranged by the teachers. If any sensor failed to detect a geometric shape or displayed the incorrect detection result for a shape arranged by the teacher, the task was considered a failure. Conversely, if the sensors in the TUI system successfully detected all the arranged geometric shapes, the system was deemed successful. The success rate of the TUI system in this study is determined by Equation 5.

$$Success\,rate = \frac{Number\ of\ successful\ tasks}{Number\ of\ total\ task} \times 100\% \tag{5}$$

3.8 Qualitative feedback evaluation

In addition to quantitative usability testing, we also incorporate qualitative feedback from teachers to provide a more holistic evaluation of the TUI system. This approach allows for deeper insights into user experiences, practical challenges, and potential areas for improvement. Collecting qualitative data through interviews and structured feedback can ensure that the system aligns with the real-world needs of educators and enhances its usability and effectiveness in diverse classroom settings. By addressing the perspectives of teachers, qualitative evaluation contributes to the iterative refinement and broader adoption of the TUI system in early education.

4 RESULTS AND DISCUSSION

The design of the TUI as a learning media for basic geometric shapes is presented in Figure 10. After completing the TUI design and conducting functional testing, the next step was to test the TUI as a learning tool for geometric shapes with kindergarten teachers, who will use the media in their educational practices. Figure 12 shows one of the kindergarten teachers performing a TUI test. The testing procedure for the teachers followed several steps, as outlined in the experiment procedure. After the 22 teachers completed the TUI media testing, they were asked to fill out the SUS questionnaire.

Fig. 12. Documentation of a kindergarten teacher conducting a TUI test

The next step, after the teachers completed the initial SUS questionnaire, was to conduct statistical analysis based on validity and reliability tests before proceeding with the SUS analysis.

4.1 Validity and reliability test

At this stage, we gathered the initial results of the SUS questionnaire to conduct a validity test and assess the validity of the SUS questionnaire instrument completed by the kindergarten teachers. The results are presented in Table 4.

Table 4. Results of the SUS questionnaire completed by each kindergarten teacher

No Teacher	Questionnaire Results										Sum
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	
T1	5	2	4	3	4	3	4	2	3	4	34
T2	4	2	4	3	4	2	4	2	3	4	32
T3	4	1	4	1	4	1	4	1	2	1	23
T4	5	2	4	1	5	1	4	1	5	1	29
T5	4	2	4	2	4	2	5	2	4	4	33
T6	5	2	5	2	5	5	5	2	5	4	40
T7	4	2	4	1	4	2	4	1	2	4	28
T8	5	2	5	2	5	1	5	2	5	4	36
T9	5	2	5	1	4	1	5	2	5	1	31
T10	4	1	4	1	4	2	5	2	4	4	31
T11	4	2	4	1	4	2	4	2	4	4	31
T12	4	2	4	2	5	1	4	2	4	3	31
T13	4	2	4	1	4	2	4	2	5	2	30
T14	4	2	4	2	4	2	4	2	5	4	33
T15	4	2	4	1	4	1	4	1	5	2	28
T16	4	1	4	1	4	1	4	1	4	1	25
T17	4	1	5	1	4	1	5	1	5	1	28
T18	4	2	4	2	4	2	4	2	5	4	33
T19	4	2	4	2	4	2	4	1	3	2	28
T20	5	2	5	2	5	2	5	2	5	2	35
T21	5	2	5	2	4	2	4	2	5	2	33
T22	4	1	4	1	4	1	4	2	4	2	27
Average											30.86

Furthermore, after gathering the initial SUS questionnaire data, we proceeded with a validity test using Equation 3 to evaluate the validity of the responses provided by the teachers. The results are displayed in Table 5.

Table 5. Validity test results

Questionnaire	r-Count	r-Table	Description
Q1	0.576	0.422	Valid
Q2	0.592	0.422	Valid
Q3	0.489	0.422	Valid
Q4	0.615	0.422	Valid
Q5	0.486	0.422	Valid
Q6	0.682	0.422	Valid
Q7	0.471	0.422	Valid
Q8	0.609	0.422	Valid
Q9	0.454	0.422	Valid
Q10	0.618	0.422	Valid

In addition to performing the manual calculations, we compared the r-count values presented in Table 5 with the results obtained using Minitab statistical analysis software to ensure the accuracy of the calculations. The comparison is shown in Figure 13.

Correlations

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Q2	0,370									
Q3	0,677	0,089								
Q4	0,279	0,492	0,071							
Q5	0,561	0,294	0,399	0,174						
Q6	0,281	0,345	0,154	0,462	0,137					
Q7	0,371	-0,095	0,677	-0,020	0,328	0,172				
Q8	0,257	0,328	0,199	0,470	0,138	0,369	0,257			
Q9	0,370	0,211	0,510	-0,097	0,341	-0,005	0,370	0,325		
Q10	-0,085	0,402	-0,193	0,533	0,032	0,550	0,071	0,554	-0,145	
Total	0,576	0,592	0,489	0,615	0,486	0,682	0,471	0,709	0,454	0,618

Fig. 13. The results of the validity test using Minitab which displays the total r-count on the 10 SUS questionnaire items

According to the findings from the Minitab validity test in Figure 13 and the validity test results displayed in Table 5, the total r-count value is consistent, indicating that the 10 items in the SUS questionnaire completed by the teachers regarding the TUI media were deemed valid. This is because the r-count for all 10 questionnaire items exceeded the r-table value of 0.422 at a 5% significance level (the value of 0.422 is obtained from the distribution table of the r-table value of 5% significance). This outcome aligns with the criteria for validity test decisions, which state that if the r-count value exceeds the r-table value, the questionnaire is considered valid [79].

Following the validation of the questionnaire in the validity test, the next step was to conduct a reliability test using Cronbach's alpha, based on Equation 4. The reliability test results showed a Cronbach's alpha value of 0.712 for the 10 questionnaire items, as presented in Table 6. Similar results were obtained through Minitab, as shown in Figure 14.

Table 6. Reliability assessment result

Items number	Cronbach's Alpha	Description
10	0.712	Reliable

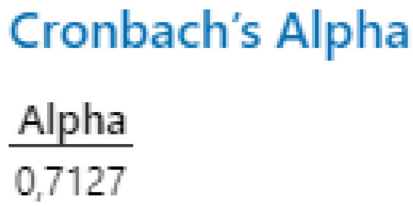

Fig. 14. The results of the reliability test using Minitab

The reliability test results, as shown in Table 6 and Figure 14, indicate that the SUS questionnaire responses are reliable, with a score exceeding 0.7. This meets the standard criteria for reliability decisions, whereby a Cronbach's alpha value greater than 0.7 confirms the questionnaire's reliability [79].

Based on the results of the validity and reliability tests, the initial SUS questionnaire completed by the kindergarten teachers is considered both valid and reliable, thus enabling the subsequent calculation of the SUS scores.

4.2 Analysis of SUS and TUI media functionality

Following the validity test, which yielded valid results, and the reliability test confirming consistency, the next step involved manually analyzing the SUS score calculation using Equation 1 and Equation 2. The results of this SUS score calculation are presented in Table 7.

Table 7. SUS score calculation results

No Teacher	SUS Data Results										SUS Score
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	
T1	4	3	3	2	3	2	3	3	2	1	65
T2	3	3	3	2	3	3	3	3	2	1	65
T3	3	4	3	4	3	4	3	4	1	4	82.5
T4	4	3	3	4	4	4	3	4	4	4	92.5
T5	3	3	3	3	3	3	4	3	3	1	72.5
T6	4	3	4	3	4	0	4	3	4	1	75
T7	3	3	3	4	3	3	3	4	1	1	70
T8	4	3	4	3	4	4	4	3	4	1	85
T9	4	3	4	4	3	4	4	3	4	4	92.5
T10	3	4	3	4	3	3	4	3	3	1	77.5
T11	3	3	3	4	3	3	3	3	3	1	72.5
T12	3	3	3	3	4	4	3	3	3	2	77.5

(Continued)

Table 7. SUS score calculation results *(Continued)*

No Teacher	SUS Data Results										SUS Score
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	
T13	3	3	3	4	3	3	3	3	4	3	80
T14	3	3	3	3	3	3	3	3	4	1	72.5
T15	3	3	3	4	3	4	3	4	4	3	85
T16	3	4	3	4	3	4	3	4	3	4	87.5
T17	3	4	4	4	3	4	4	4	4	4	95
T18	3	3	3	3	3	3	3	3	4	1	72.5
T19	3	3	3	3	3	3	3	4	2	3	75
T20	4	3	4	3	4	3	4	3	4	3	87.5
T21	4	3	4	3	3	3	3	3	4	3	82.5
T22	3	4	3	4	3	4	3	3	3	3	82.5
The Average of SUS Score											79.43

As shown in Table 7, the SUS score calculation results indicate an average score of 79.43. According to the SUS score assessment [68], the TUI model, which is used by teachers as an educational tool for teaching geometric shapes in kindergarten, falls within the "good" and "acceptable" categories and ranks in the 4th quartile (highest). In addition to the manual calculations, we also employed the SUS analysis toolkit for further analysis [82].

Using the SUS analysis toolkit, we can assess the conclusiveness of the SUS study score for each system or variable based on the number of participants. In this study, with 22 kindergarten teachers completing the SUS questionnaire, the results of the conclusive SUS study score are displayed in Figure 15.

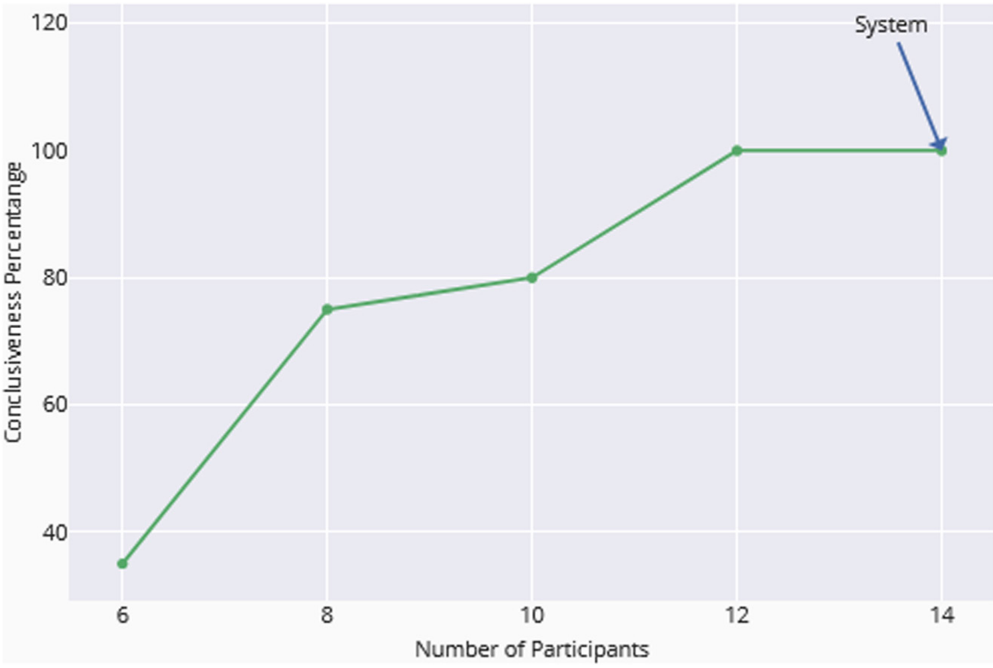

Fig. 15. Conclusive results of SUS study scores

The number of participants (22 kindergarten teachers) in this study is considered sufficient for conducting usability testing because, as shown in Figure 15, the SUS analysis toolkit's conclusiveness graph indicates that a participant size of 14 has achieved 100% conclusiveness. This means that the average score in this study has reached a correct conclusion based on the entire dataset. This aligns with findings from previous studies, which state that SUS testing requires a minimum of 12 participants or more to achieve 100% conclusiveness [83–91].

Through the SUS analysis toolkit, we also analyzed the contribution of each SUS question item to the overall score. The score for each item is a normalized value between 0 and 10, representing its contribution to the SUS study score, rather than a Likert scale value in the questionnaire, where even-numbered questions are negatively formulated. Table 8 displays the score per SUS question item, while Figure 16 illustrates the score contribution of each SUS question.

Table 8. Score per SUS question item by kindergarten teachers

Score	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
	8.3	8.07	8.18	8.52	8.07	8.07	8.3	8.3	7.95	5.68

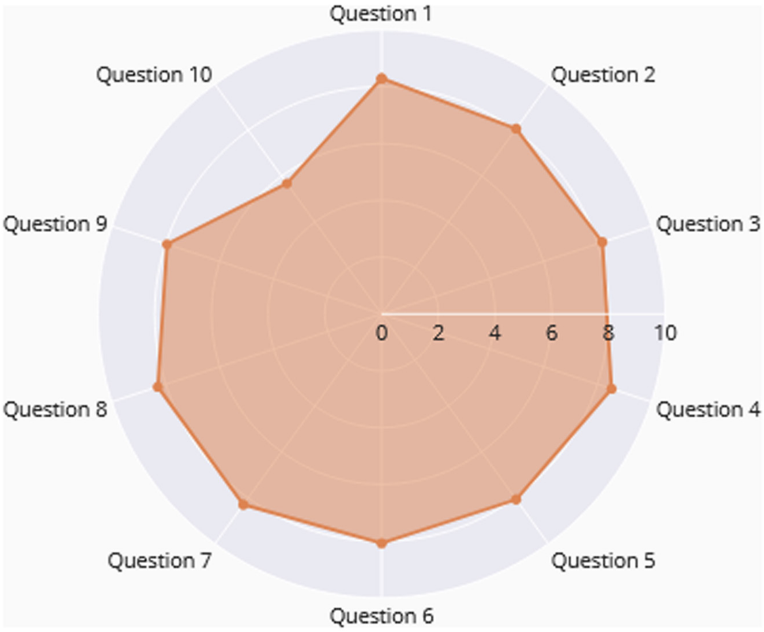

Fig. 16. Visualisation of the score contribution of each SUS question

As shown in Table 8 and Figure 16, SUS questions 1 to 8 have an average score of 8, while question 9 has a value of 7.95, which is close to 8. In contrast, SUS question 10 ("I needed to learn a lot of things before I could get going with this system") has the lowest score of 5.68 among all the SUS questions. This indicates that kindergarten teachers needed time to familiarize themselves with using the TUI-based geometry shapes learning media. Despite this, the overall SUS score rated the TUI-based geometry shapes learning media proposed in this study as "acceptable" for use as an educational tool.

The results of the overall SUS analysis, including those from the SUS analysis toolkit, are presented in Table 9 and Figure 17.

Table 9. Results of the calculation using the SUS analysis toolkit

SUS Score	Median	Standard Dev	Adjective	Grade	Acceptability	Quartile
79.43	78.75	8.59	Good	A	Acceptable	4th

As shown in Table 9, the results from the SUS analysis toolkit reveal a SUS score of 79.43, with a median score of 78.75 and a standard deviation of 8.59. Based on these values, the TUI learning media is rated as "good" and categorized as grade A, indicating superior performance. Additionally, the system is deemed "acceptable" in terms of its acceptability and ranks in the 4th quartile (the highest). Figure 17 shows the visualization of the SUS calculations through the SUS analysis tool in a box plot format. The SUS score obtained through the toolkit is consistent with the manually calculated results.

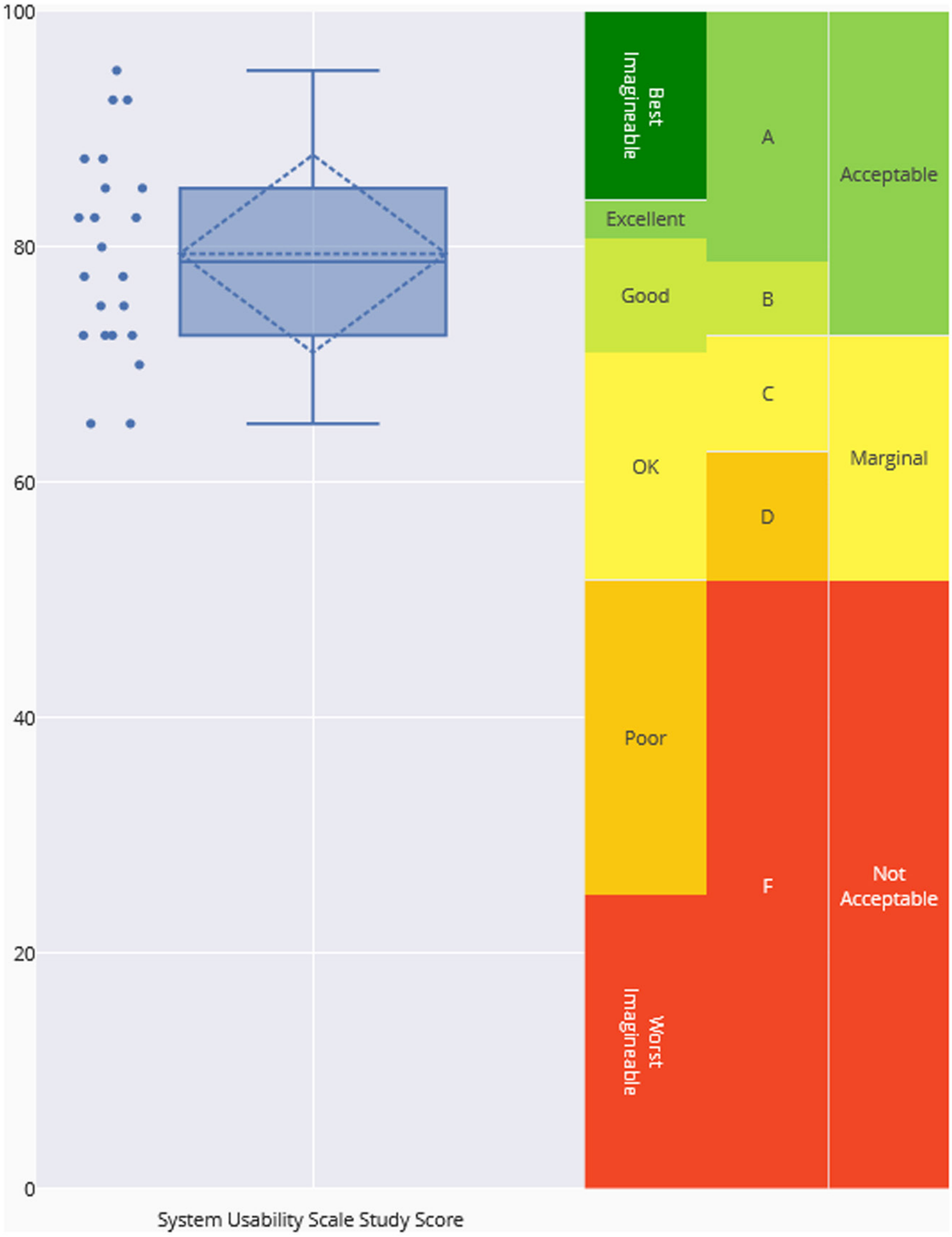

Fig. 17. Visualization of calculation results using the SUS analysis toolkit

In addition to the SUS analysis, functionality testing of the TUI media design was based on the system's success rate in displaying geometric shapes. The experimental results showed a 100% success rate, as calculated using Equation 3. This was demonstrated in the trials conducted by 22 kindergarten teachers, as shown in Table 10.

Table 10. TUI system testing results

No Teacher	Testing Status	Success Rate
T1	Success	100%
T2	Success	100%
T3	Success	100%
T4	Success	100%
T5	Success	100%
T6	Success	100%
T7	Success	100%
T8	Success	100%
T9	Success	100%
T10	Success	100%
T11	Success	100%
T12	Success	100%
T13	Success	100%
T14	Success	100%
T15	Success	100%
T16	Success	100%
T17	Success	100%
T18	Success	100%
T19	Success	100%
T20	Success	100%
T21	Success	100%
T22	Success	100%

As indicated in Table 10, the TUI system successfully detected all tasks involving the arrangement of geometric shapes and functioned without any detection failures during the trials conducted by the kindergarten teachers. Therefore, based on the SUS analysis and system success rate, the findings suggest that the TUI learning media design is both acceptable and effective for use as a teaching tool by kindergarten teachers for teaching geometric shapes.

Based on the results of experiments with TUI-based learning media for teaching geometric shapes in kindergartens, there is strong evidence of its significant potential to enhance children's learning outcomes. The findings emphasize its effectiveness in improving children's understanding, equipping educators with practical classroom tools, and providing policymakers with opportunities to advance educational technologies. Building on these insights, TUIs offer long-term potential to support cognitive development, encourage collaboration, and promote inclusive learning through engaging, hands-on, and interactive experiences. By empowering educators and equipping children with skills for lifelong learning in a technology-driven world, TUIs highlight the need for thoughtful and strategic integration into educational frameworks.

This is further supported by research from Sapounidis et al. [92] which shows that TUIs improve children's understanding of computational concepts and engagement, and Baykal et al. [21] who highlight their potential to enhance spatial reasoning, both of which are critical for long-term cognitive development and academic success. Other researcher also highlights that technology-mediated activities using tangible toys foster collaboration, social skills, and role-taking among 3–4-year-old children, as most demonstrated teamwork, helping behaviors, and leadership abilities during group play, indicating that TUI offer long-term benefits by fostering foundational social and collaborative skills essential for academic success, teamwork, and adaptability, while laying the groundwork for lifelong interpersonal abilities through engaging, interactive environments [93].

Extending the discussion to teacher education, Kalogiannakis and Papadakis [94] demonstrate how ScratchJr enhances pre-service kindergarten teachers' self-confidence in using programming and computational thinking for science instruction, helping them acquire programming skills, engage in tasks, and foster a positive attitude, while being widely recognized for its usefulness and ease of use, making it ideal for introducing basic programming concepts and CT and developing educational applications. These findings highlight the long-term impact of TUIs, as they not only enhance computational skills but also boost confidence and interest in technology, equipping educators and learners with essential competencies for success in a technology-driven world.

Building on the demonstrated benefits of TUIs in teacher education, their application in classrooms has further revealed key insights into the effectiveness and practicality of the TUI system. Teachers emphasized that the system significantly enhanced children's understanding of abstract geometric shapes by providing tangible and interactive experiences, making complex concepts more accessible. They also noted that the TUI system introduced a novel approach to learning, capturing children's attention more effectively than traditional or touchscreen-based tools, which often rely solely on visualization. In addition to its educational value, teachers found the TUI system to be a versatile teaching aid, capable of not only supporting the teaching of geometric shapes but also fostering curiosity and encouraging hands-on exploration among students.

This study has certain limitations that may affect the generalizability of its findings. Firstly, all 22 participating kindergarten teachers were female, as no male kindergarten teachers were identified during the study period. This gender homogeneity precludes comparisons between male and female teachers regarding the usability of the learning media, Qazi et al. [95] conducted a systematic review and meta-analysis on gender differences in information and communication technology use and skills, highlighting disparities that could influence technology integration in classrooms. Similarly, Teo et al. [96] examined technology acceptance among pre-service teachers and found that gender differences exist in perceived ease of use, with female pre-service teachers reporting lower scores, indicating that technology use may be more challenging for them.

Secondly, the study's sample was geographically concentrated, encompassing 12 schools within a specific region. This geographic limitation may restrict the applicability of the results to other regions with differing educational practices, resources, or cultural contexts. Research by the Institute of Education Sciences emphasizes that geographic concentration can impact the generalizability of educational research findings, underscoring the need for diverse sampling to enhance external validity [97]. Additionally, Olsen and Gleason [98] discuss the balance between generalizability and feasibility in defining target populations for impact studies, highlighting challenges associated with geographically concentrated samples Future research should aim to include a more diverse sample of teachers, encompassing various genders and broader geographic areas, to enhance the generalizability of the findings.

5 ETHICAL CONSIDERATION

This study adheres strictly to ethical principles in research involving human participants. Informed consent was obtained from all participants, ensuring they were fully aware of the study's purpose, procedures, and their right to withdraw at any time. Participants' confidentiality and anonymity were rigorously maintained, with all personal identifiers removed, and only aggregated score data reported in the analysis.

Future stages of research involving children will require additional ethical safeguards. Parental or guardian consent will be mandatory, alongside child assent, to ensure their voluntary participation. The study will follow ethical guidelines specific to research with minors, such as minimizing potential risks, ensuring age-appropriate explanations, and prioritizing their well-being throughout the process.

Data protection protocols were implemented to secure sensitive information, including encrypted storage and restricted access to authorized personnel only. This ensures compliance with data protection regulations, such as GDPR or local equivalents, depending on the study's jurisdiction.

Efforts were made to minimize biases in the usability testing process. However, potential biases may arise due to the homogeneous sample of participants in this study, limited to female kindergarten teachers from a specific region. Future studies will aim to include more diverse participant demographics to enhance representativeness and generalizability. Additionally, steps will be taken to standardize testing conditions and mitigate any researcher influence during evaluations.

The authors affirm that no conflicts of interest exist in the conduct of this study or its reporting, ensuring the integrity and objectivity of the research. These measures collectively underscore the study's commitment to upholding the highest ethical standards in research.

6 CONCLUSION

Our study successfully developed and evaluated a sensor-based TUI system featuring interactive surfaces for six basic geometric shapes—triangular prism, pentagonal prism, tube, cube, hexagonal prism, and cuboid—designed as a learning tool for kindergarten geometry instruction. Usability testing with 22 kindergarten teachers using the SUS resulted in a score of 97.43, categorized as "Good" (Grade A), reflecting superior performance. The system also received an "acceptable" usability rating and ranked in the highest quartile. Additionally, functionality testing confirmed a 100% success rate in detecting and displaying geometric shapes, establishing the system as effective and suitable for classroom use.

Future studies need to address practical implementation strategies for TUIs in diverse educational contexts to maximize their impact and ensure adaptability across various learning environments. Practical strategies for implementing requires targeted teacher training programs to equip educators with the skills necessary to integrate TUIs into their classrooms. Lesson plans should be flexible and align with local curricula in subjects such as mathematics, science, and language to ensure relevance.

Pilot projects in schools with varying socio-economic and cultural conditions are al essential to evaluate the real-world effectiveness of TUIs. Efforts should also focus on designing affordable and accessible TUI systems to support under-resourced schools. Inclusivity must be a priority, with TUIs tailored to accommodate diverse learning needs, including those of students with disabilities, through customized features. Collaborative initiatives among educators and institutions worldwide can further refine TUI implementation strategies. Incorporating continuous feedback from teachers, students, and administrators is critical to maintaining the relevance, usability, and effectiveness of tangible user interfaces.

Furthermore, diversifying the sample by including participants from various regions or cross-national, socio-economic backgrounds, and cultural contexts can enhance the generalizability of findings, providing a more comprehensive understanding of the intervention's effectiveness across diverse educational settings. Additionally, investigating the long-term effects of TUI-based learning on children's cognitive and motor skill development would provide valuable insights into its sustained benefits. These efforts will improve the generalizability, usability, and global application of TUIs, fostering the creation of more interactive and engaging learning environments.

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