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BUMI HERO: Integrating Touchless Interactive Education for Sustainable Waste Sorting to Grade 4, 5, and 6 Students in Jakarta's Public School

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Abstract

Indonesia faces challenges in waste management, which can be attributed to the large amount of waste produced and a lack of awareness within society. Early environmental education is crucial for instilling effective waste management behaviour. This study presents the application of a learning platform that uses a design-based research method in producing an interactive game. The interactive system uses hand pose estimation machine learning to improve user engagement in gaining knowledge of waste sorting. The study involved a sample of 30 students in grades 4, 5, and 6 at a public elementary school in Jakarta. A pretest and posttest design was utilised for the analysis of knowledge gains through the calculation of N-gain scores. Furthermore, a heuristic evaluation of children's e-learning applications was conducted to analyse users' experience. The analysis of the results revealed a medium gain in knowledge regarding waste sorting, with scores ranging from 0.31 to 0.60 for each grade level. The heuristic analysis results were positive regarding the visibility, consistency, and practical relevance of the system. Usability issues were identified, including hand detection and the visibility of some interface elements. The results suggest the potential of hand pose estimation gamified learning to aid environmental education for elementary school students, pending technical improvements in the stability and interface design of the system.

Keywords: *Gamification, Hand Pose Estimation, Waste Sorting*

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INTRODUCTION

In 2024, DKI Jakarta generated an average of 8,688.35 metric tons/day, with the majority coming from East, West, and South Jakarta. Compared with other cities, Surabaya generated an average of 1,805.57 metric tons/day, while Medan generated 1,731.92 metric tons/day (Kementerian Lingkungan Hidup dan Kehutanan, 2026). High waste generation, as observed in cities, is an important factor that defines the population, which is a major contributor to waste generation. According to data from Badan Pusat Statistik Provinsi DKI Jakarta (BPS Provinsi DKI Jakarta, 2024), Kementerian Lingkungan Hidup dan Kehutanan (2026), and BPS Kota Medan (2025), the populations of DKI Jakarta, Surabaya, and Medan are 10.68 million, 3.01 million, and 2.48 million, respectively. A wide gap between waste generation and population, compared with other cities, is a concern for waste management in the city. A study found that inadequate waste segregation in DKI Jakarta stems from citizens' expectations that the government should manage waste (Ismaya et al., 2023).

Consequently, the infrastructure is not capable of managing rapidly growing waste generation, creating a burden on waste management, leading to open dumping in landfills, and causing environmental pollution. The

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lack of accountability among residents regarding waste management is not limited to Jakarta. In 2025, the province of Bali encountered a disastrous flood, with 17 victims and 565 destroyed buildings (Pusdalops, 2025). This disaster was triggered by improper waste disposal, leading to the obstruction of waterways (Kementerian Lingkungan Hidup, 2025). Therefore, flooding in Bali is not merely classified as a natural disaster but rather a result of residents' neglect of their own waste disposal. This particular situation highlights that the lack of adequate education on waste management, as well as insufficient community engagement in dealing with waste, are major issues in the context of the Indonesian waste crisis. The Indonesian government's failure in terms of household waste segregation is indicated by only 7.95% of Indonesian residents who practice household waste segregation (Pemerintahan Provinsi DKI Jakarta, 2025).

In Jakarta, specific community-based programs have successfully contributed to improving household waste segregation practices primarily through education, local engagement, and assurance of proper waste management after collection. One such program focuses on building citizen perceptions around composting and segregation by addressing key incentives to encourage participation. Households in Jakarta have shown willingness to engage in segregation when they have guarantees that their segregated waste will not be mixed after collection and when composting sites are conveniently located nearby. This program emphasises strengthening decentralisation and improving training for both citizens and garbage collectors, thereby ensuring better control and evaluation of waste management practices at the community level (Widyatmika and Bolia, 2023). Based on the foregoing discussion, the current study views the provision of adequate education on correct waste segregation among community members as a viable strategy to enhance sustainable waste management practices. Despite the implementation of waste sorting education in Indonesian schools, students fail to understand appropriate waste sorting (Lestari et al., 2020).

Recent studies have shown that some schools can teach about waste sorting. These include environmental lessons in daily life. Activities such as cleaning the canteen, spring cleaning, and character building are helpful. These activities stress the need to pick up trash immediately and build habits of caring for the environment (Wulandari and Matfuha, 2025). Schools are trying to improve garbage sorting; however, they are facing problems. It is difficult to ensure that sorting is consistent at home and at school. The school system is special because it works with a waste bank for recycling. Older students know more about recycling, but third graders have not yet learned about it. In addition, students do not know about hazardous and toxic waste (B3) or electronic waste because the school is still building the right facilities. Education plays a crucial role in overcoming these barriers by informing students early on the importance and methods of waste sorting (Setiawan, 2020). Unfortunately, these frequently fail because they do not account for the cognitive developmental stages of primary students, such as cognitive overload, engagement barriers, and consistency.

The school uses hands-on learning and strong visual tools like 'The Bantargebang Garbage Dump' and 'The Great Pacific Garbage Patch' to meet educational standards. These tools make sixth graders curious. According to a principal in Jakarta, even without a waste education program, the school teaches the importance of a clean environment through regular cleaning and reminders during ceremonies. However, students often misuse the new bins for organic, inorganic, and B3 waste because they lack proper knowledge (Purnamawati, 2025). The major drawbacks in the implementation of a new program would be the short concentration span of the students, only being able to focus for a period of 2-5 minutes, and the need to keep the teaching staff on the same page in encouraging good habits. The school believes that using hands-on learning methods, like interactive learning and Project-Based Learning (PBL), is the best way to teach students about a clean environment and proper waste disposal.

In these methods, students can make and test their own products, like fertiliser and recycled crafts. In East Jakarta, web-based animation videos were created to help elementary students learn about waste sorting and other environmental topics like climate change and biodiversity. This method was effective in satisfying students' curiosity, increasing their environmental awareness, and promoting conservation values among elementary school students in Jakarta (Safitri et al., 2021). However, these solutions are often passive. Animations provide information but do not allow for the exploration required to build muscle memory for waste sorting. This implies that the key to improving waste disposal behaviour in Indonesia is the lack of education and, thus, the need to improve waste disposal behaviour through a new approach, which combines Game Development and PEML.

Unlike static animations or physical bins that students often misuse, a game-based approach provides an active feedback loop. By utilising PEML within a gamified environment, students are required to predict the category of a waste item, observe the digital consequence of their choice, and learn from immediate feedback. This method transforms waste education from a chore into a high-engagement cognitive exercise, specifically

designed to bypass the 5-minute concentration barrier. This study seeks to evaluate how this interactive synergy can foster long-term behavioural shifts that traditional Indonesian environmental education has yet to achieve.

METHOD

The production method of Bumi Hero used design-based research (DBR). DBR is a dynamic, iterative methodology gaining traction for its capacity to produce contextually relevant and practically useful educational innovations. Researchers note DBR's potential to tackle "wicked" educational problems through collaborative design and iterative cycles, but also recognise challenges such as the demanding nature of interdisciplinary collaboration and resource requirements (Minichiello and Caldwell, 2021; Tinoca et al., 2022). A common DBR framework includes the following four key phases, as shown in Figure 1, which are 1) Analysis and Exploration of the problems or topics, 2) Design and Development of a prototype for the solution of the problems or topics, the result as shown in Figure 2, 3) Implementing and Testing the prototype with relevant users, and 4) Evaluation and Reflection of the testing result.

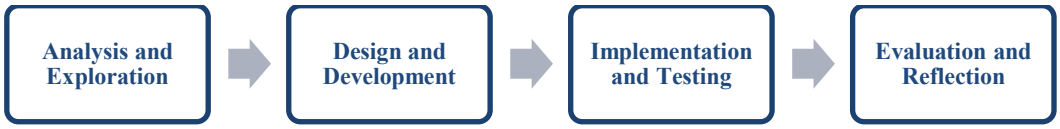


Figure 1. DBR Workflow



Figure 2. Bumi Hero Screenshots

An example of an educational game developed using DBR is an Android-based game focused on arithmetic learning for children with learning disabilities in mathematics. The study found that educational game media using Android technology could significantly support learning needs for arithmetic material and potentially benefit a broader range of students beyond those with learning disabilities (Juhanaini J et al., 2024). Another related work develops gesture recognition methods involving hand pose estimation, which are crucial for human-computer interaction, including gaming contexts. Although not specific to games, the technology to robustly estimate 3D hand poses and recognise dynamic hand gestures supports gesture-based game controls. For example, a method based on 3D hand pose estimation combined with deep neural networks achieved high accuracy (92.4%) in recognising dynamic gestures, a core feature for controlling virtual environments or robots, which can be extended to game applications (Gao et al., 2022). Together, these examples underscore the value of DBR in producing innovative, user-centred educational and gaming technologies that leverage cutting-edge interaction models, which is reflected in the final design as shown in Figure 2. According to the public school's principal, the integration of gesture-based mechanics such as 'drag-and-drop' interactions serves as a cognitive bridge that translates digital engagement into real-world environmental consciousness and waste-sorting recall.

To obtain representative, accurate, and reliable results, this study utilised probability sampling techniques, namely stratified sampling. Recent studies compare stratified sampling with other probability techniques like simple random, systematic, and cluster sampling, as well as with non-probability methods such as convenience, purposive, quota, and snowball sampling. Stratified sampling stands out for its ability to reduce bias and improve population representativeness through controlled subgroup sampling (Mukti, 2025; Zrineh et al., 2026). The population of focus in the research consisted of pre-adolescents aged 9–12 years. The choice of age bracket is informed by the fact that it represents a critical period during which the promotion of awareness, ethics, and morality in the environment needs to be cultivated (Liu and Green, 2024). A meta-analysis focusing on children aged 6–12 years underscores the moderate positive influence of motivational, social, and emotional factors on academic achievement. This study emphasises that motivational and social factors, such as self-

concept, social competence, and social skills, significantly contribute to academic performance in this age group. It also finds that age moderates the effects of social factors, indicating developmental shifts in how these characteristics manifest and influence academic outcomes across childhood into early adolescence. The findings stress the necessity for educational programs that support motivational and social development alongside cognitive skills to foster academic success (Quílez-Robres et al., 2021). At the same time, the group in question has attained a certain number of cognitive abilities, namely the ability to understand the principles of cause and effect, classify objects, and perform higher-order logical thinking, which is necessary for playing the game. The sample population included elementary school students in grades 4 to 6 in Jakarta, specifically in elementary schools.

To test the effectiveness of the game in improving students' knowledge, a paired-sample t-test analysis was conducted to establish the difference in the pretest and posttest values, as shown in Table 1. This analysis primarily focuses on applying the N-Gain formula as a measure of learning effectiveness and improvement in educational settings (Am et al., 2025). The gain score formula was established using the difference between the pre-test and post-test scores. The average gain score formula was then applied to determine the difference in the knowledge levels of the students before and after the intervention. The formula used to establish the average gain score is shown in Equation 1. Subsequently, the gain scores attained by the students were measured using the N-gain classification.

$$g = \frac{Mean_{post} - Mean_{pre}}{Maximum\ Score - Mean_{pre}} \quad (1)$$

The N-gain scores were subsequently interpreted based on Hake's classification (Hakke, 1998), which categorizes learning improvement into three levels: high, medium, and low. The classification criteria are presented in Table 1.

Table 1. Hake's N-gain Classification (Hakke, 1998)

N-gain Value	Categories
$\langle g \rangle \geq 0.7$	High
$0.7 > \langle g \rangle \geq 0.3$	Medium
$\langle g \rangle < 0.3$	Low

The authors declare that this study was classified as low or negligible risk and did not require formal Ethical Clearance under the applicable institutional requirements. Permission to conduct the research was obtained from the relevant school/institution, and appropriate ethical safeguards, including voluntary participation, consent where applicable, and protection of participant confidentiality, were implemented.

RESULTS AND DISCUSSION

The testing was conducted to 30 students ranging from grades 4 to 6, which is adequate for user testing, where typical User Sample Sizes in Usability Testing Studies report varying numbers, but common usability testing studies involve around 5 to 16 users (Maguire and Isherwood, 2018). After completing the testing phase, students were given both pretest and posttest questions, as detailed in Table 2. These assessments were designed to evaluate their understanding and knowledge of waste sorting before and after the intervention. Each student responded to the questions based on their current level of knowledge, allowing for a comparison of their progress and the effectiveness of the educational activity. This approach provided a clear measure of learning outcomes by capturing changes in students' awareness and comprehension of waste sorting principles. By analysing the differences between pretest and posttest responses, researchers could identify areas where students improved, as well as aspects that might require further reinforcement or clarification in future instruction.

Table 2. Pretest and Posttest Questions

No.	Questions
1	**Organic waste is waste that…** 1. Can rot or decompose naturally. 2. Contains chemicals. 3. Made of plastic and paper. 4. Cannot be broken down by nature.

No.	Questions
2	**What kind of waste can be processed into new items?** 1. Lamp 2. Can 3. Face Mask 4. Leaves
3	**B3 waste is waste that…** 1. Bad smell. 2. Made of metal and plastic. 3. Can be used as animal feed. 4. Dangerous for humans and the environment.
4	**Why do we have to sort waste according to type and location?** 1. So that there is more rubbish. 2. Because the colors of the trash cans are different. 3. So that it can be recycled and does not pollute the environment. 4. Because the teacher told me to
5	**The used mosquito spray can was thrown away in…?** 1. Hazardous and Toxic waste bin, because there are chemical residues. 2. Regular waste bin, because it's empty. 3. Inorganic waste bin, because it's made of metal and plastic. 4. Organic waste bin, because it's biodegradable.
Scoring: 100% - Complete understanding, as all key concepts are accurately identified 75% - Somewhat correct, there is awareness, but there is still a misunderstanding 50% - Relevant answer, but incomplete understanding 25% - Irrelevant and opposite answer	

Throughout gameplay, the students were asked 15 heuristic questions to evaluate the game's usability, as shown in Table 3, since usability directly affects how students interact with the game. The students were asked a series of 15 heuristic questions to evaluate the game's usability, as outlined in Table 3. These questions were prepared to assess how well the game environment reflects real-world situations and the ease with which users can control and navigate the game. The heuristic questions assessed the game's challenge level, including whether the progression of difficulty is manageable for users and whether the reward system effectively motivates continued engagement. The comprehensive heuristic evaluation was essential because usability directly impacts how students interact with the game, influencing both their learning experience and overall engagement with the educational content. These heuristics synthesise usability and educational criteria commonly highlighted in game-based learning research to help designers and evaluators ensure that educational games are effective, usable, and engaging for their target learners (Chang and Johnson, 2021; Gris and Bengtson, 2021; Yu et al., 2021).

Table 3. Heuristic Evaluation Questions

Heuristic	Questions
1. Visibility of System Status	Q1. Can you see your current score, level, and goal of the game?
2. Match Between System and Real World	Q2. Do the assets and environments reflect the real-world situation?
3. User Control and Freedom	Q3. Is it difficult to start and exit the game? Q4. Are you aware of the Hint feature, and do you use it?
4. Consistency and Standards	Q5. Are the instructions and texts in-game readable? Q6. Are the colours used in the game visually pleasing?
5. Error Prevention	Q7. Are there any errors when playing the game?
6. Recognition Rather than Recall	Q8. If asked to play the game again, do you understand how to play the game?
7. Flexibility and Efficiency of Use	Q9. Does prior experience improve the user's gameplay performance?
8. Aesthetic and Minimalist Design	Q10. Is information presented clearly without unnecessary text or visuals?

9. Help User Recognize, Diagnose and Recover from errors the Child	Q11. If you were wrong, do you understand what the issue is and how to resolve it?
10. Help and Documentation	Q12. Can you play the game independently without needing instructions from the researcher/teacher?
11. Appropriate hardware devices	Q13. When using hand gestures to play the game, did you find it easy or difficult to use? What do you feel when using it?
12. Challenge the Child	Q14. Is the progression of level difficulty easy for the user to follow, and does it help them learn and improve Q15. Do the rewards encourage children to keep playing the game?

The normalisation process for the gain scores was carried out by calculating the difference between the pretest and posttest scores for each student, followed by applying the N-gain formula to obtain a standardized measure of knowledge improvement. The detailed results of this normalization and categorization are subsequently shown in Table 4, which presents the average pretest and posttest scores, the calculated N-gain for each grade, and their corresponding gain categories. These thresholds classify the level of learning improvement, with a higher N-gain indicating a more effective learning process or instructional method. For example, a study using Hake's formula obtained an N-gain result of 0.8 and categorized this as effective, aligning with the "high gain" range (Agustini et al., 2020). Another study reported a medium category N-gain score of 0.68 and a low category of 0.17 in their evaluation of web-assisted learning multimedia, illustrating the medium and low categories of gain, respectively (Satriani and Prasojo, 2024).

Overall, based on the normalized gain scores in Table 4, Grade 5 students showed the greatest improvement, with a normalized gain of 0.60. Grade 4 students also demonstrated notable improvement, with a normalized gain score of 0.48. Finally, Grade 5 students showed the lowest improvement in their normalized gain score. The lower normalized gain score for Grade 6 may be affected by Grade 6 students' strong prior knowledge, as evidenced by many students having already achieved the maximum pre-test score. Consequently, these findings suggest that all grades improved their waste-sorting knowledge after playing the game, as indicated by the normalized gain values. However, according to Hake's N-gain classification, the improvement achieved by these grades falls within the medium categories. In comparison, the study titled "The Effectiveness of Game-Based Learning on The Logic Gate Topics" reports a quantitatively measured n-gain score of 0.703 resulting from the application of game-based learning on logic gate material for physics education students (Dewantara et al., 2020).

This value indicates a high category of effectiveness according to common interpretations of Hake's n-gain scale (where typically 0.7 and above is considered high gain). This means that the game has not sufficiently increased users' knowledge to a high level of effectiveness, which is the goal of this study. Further development is needed to achieve a high normalized gain score. In contrast, the test result is considered successful if we compare it with the retrospective pretest-posttest (RPP) design, which is not based on fixed score categories; instead, it reflects a valid measure of perceived change (Little et al., 2020).

Table 4. Normalization Gain of Pretest and Posttest Scores

Grade	$\bar{x}$ Pre-test	$\bar{x}$ Post-test	N-Gain	Criteria
4	86.5	93	0.48	Medium
5	92.5	97	0.60	Medium
6	93.5	95.5	0.31	Medium

As shown in Table 5, several positive user responses were observed for students in grades four to six. All users had a positive experience with the game's visibility, as they reported being clearly aware of the score, current level, and main objective. Almost all users (28 out of 30 students) agreed that they felt familiar with the game's objects and environments and recognised similarities to real-world situations. Regarding design consistency, all students found the text, instructions, and colours readable and visually appealing. Another positive response was the recognition of how to use the game input; all users

understood and demonstrated their finger movements to the class when requested. Additionally, 26 users were confident that they could play independently without guidance from a researcher or teacher.

Finally, most participants believed that level progression was manageable and not too difficult. The game improved users' knowledge of the current level of progression. Thus, these findings suggest that the game concept, progressive level design, mechanics, and interaction received overall positive feedback, indicating that it was intuitive and suitable for these users.

Table 5. Heuristic Evaluation Response Sentiment (Positive (+)/Negative (-)/Mixed (±)).

Grade	Visibility of System Status	Match Between System and Real World	User Control and Freedom		Consistency and Standards		Error Prevention	Recognition Rather than Recall	Flexibility and Efficiency of Use	Aesthetic and Minimalist Design	Help User Recognize, Diagnose and Recover from errors the Child	Help and Documentation	Appropriate hardware devices	Challenge the Child	
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15
4	+	+	-	-	+	+	-	+	±	+	+	+	±	+	+
5	+	+	±	-	+	+	-	+	+	+	±	+	±	+	+
6	+	+	±	±	+	+	-	+	±	+	±	±	±	±	-

However, several usability issues were consistently experienced by many users across all grades. All users in grades 4, 5, and 6 experienced errors in hand detection, with some users reporting that their hands were either not detected or detected randomly by the camera. Similarly, other studies reveal that game-based learning materials often provide inconsistent error messages and feedback mechanisms across different learning units. Furthermore, the feedback sometimes fails to be helpful and does not promote effective error recovery, which frustrates learners and interrupts the learning process (Chang and Johnson, 2021). Subsequently, 29 users expressed verbal and behavioural frustration, although they also felt excited and pleased when the detection worked well. In addition, navigation within the game still confused users, as all Grade 6 users felt confused about how to exit the game, despite having no issues with clicking the start game button. This suggests that the exit button may not be sufficiently visible and requires further improvement. Conversely, grade 4 users initially felt unfamiliar with the game's inputs, which led to confusion at the start. This also occurs in other studies, where users often struggle with inefficient operations within the game that could be streamlined. Moreover, guidance on how to perform tasks is sometimes lacking or inadequate, leaving learners uncertain on how to proceed or recover from mistakes. This gap impedes smooth navigation and reduces the instructional value of the game (Chang and Johnson, 2021).

In addition, the appearance and function of hints seemed to have little impact on users, with only 18 noticing them and only one choosing to use them. This indicates that the hint feature is not particularly useful in this game. Moreover, most students recognised the incorrect icon when sorting incorrectly; however, a few users in Grades 5 and 6 continued to make the same mistakes despite visual feedback. It is believed that there may be confusion between human and technical errors owing to many misdetections, which makes it difficult to distinguish between these two aspects of error. Finally, while Grades 4 and 5 students were motivated by rewards such as candy, Grade 6 students demonstrated greater motivation through score comparisons with their peers rather than through tangible rewards. This suggests that both rewards and scores can serve as strong motivators to encourage participation in learning and gameplay sessions.

The main limitation of this game is its technical system and minor interface visibility, indicating a need for the designer to minimise error possibilities and improve the interface design to be clearer and avoid confusion. However, this is still a positive result, because the usability and its educational value are nearly optimised to ensure that the game is not only usable but also pedagogically effective by embedding educational content within an engaging and motivating game environment (Vieira et al., 2019).

A research gap exists in the transition from conceptual knowledge to mastery-level proficiency within the game. While current findings demonstrate that the game effectively facilitates "Medium" knowledge gains ($0.31 \leq g \leq 0.60$), there is a clear disconnect in achieving "High" normalized gains due to two primary factors: the technical-pedagogical interference caused by inconsistent hand-detection, which

confuses learner feedback loops, and a lack of adaptive content for advanced learners (Grade 6), resulting in a measurable ceiling effect. Furthermore, the underutilisation of passive scaffolding, such as the ignored hint system, suggests that Bumi Hero has not yet optimised the visibility of instructional support for primary school users.

A primary limitation of this study is the technical-pedagogical interference caused by inconsistent hand detection, which causes confusion or passive learning rather than active engagement (Chen et al., 2023). Although gesture-based input was intended to enhance immersion, frequent camera-tracking errors led to user frustration and a breakdown in the feedback loop; students often struggled to distinguish whether a sorting error resulted from their own lack of knowledge or a system failure. Additionally, the study found a notable ceiling effect among Grade 6 participants, whose high pre-test scores ($\bar{x} = 93.5$) left little room for mathematical improvement. This suggests that the current game content may not be sufficiently complex to challenge students with strong prior knowledge, thereby capping the potential for "high" normalized gain scores. Finally, the passive nature of the educational scaffolding, evidenced by the fact that the hint system was almost entirely ignored, indicates that the user interface did not effectively guide students toward available instructional support when they encountered difficulty. Consequently, continual refinement and evaluation of technology-mediated education platforms, including those enhanced by AI, are needed to support equitable access and personalised pedagogical effectiveness, thus reducing interference caused by technical limitations or misapplications (Morgado et al., 2025).

A research study on the "BUMI HERO" learning platform demonstrated that gamifying waste sorting through hand pose estimation effectively increased environmental knowledge among elementary students in Jakarta, achieving a medium gain across grades 4 to 6. While the game's core design, characterised by high visibility, consistency, and real-world relatability, was well-received and fostered student autonomy, significant technical barriers, such as inconsistent hand detection and poor interface visibility for certain elements, like the exit button, were identified. Furthermore, the findings highlight a shift in motivational drivers as children age, moving from a preference for tangible rewards in younger grades to a focus on competitive social scoring in older students. Ultimately, the study suggests that while interactive machine learning tools have high educational potential, future iterations must prioritise technical stability and interface refinement to overcome user frustration and maximise learning outcomes.

CONCLUSION

In conclusion, the developed game was effective in improving users' knowledge, as evidenced by the normalized gain scores from the pre- and post-tests. The heuristic evaluation indicated that the game's core design, specifically its visibility, consistency, and real-world relatability, is well-suited for students in grades 4, 5, and 6. Most users found the game to be intuitive, manageable, and visually appealing, demonstrating a high level of autonomy during play. However, the study identified critical usability challenges, primarily stemming from technical limitations rather than conceptual flaws. The most significant barrier was inconsistent hand detection, which caused frustration across all grade levels and made it difficult for users to distinguish between technical glitches and their own errors. Additionally, interface elements, such as the exit button and hint system, require redesign to improve their visibility and utility. Finally, the findings highlight distinct motivational drivers among age groups, with younger students responding to tangible rewards and older students being motivated by competitive scoring. Future iterations should prioritise technical stability and interface refinement to maximise the educational potential of the game.

AUTHOR CONTRIBUTIONS

Samantha Ingrid: Writing - Original Draft, Investigation, and Software; **Arya Harditya**: Methodology, Writing – Review & Editing, and Formal Analysis, and Resources; **Erwin Dipo**: Conceptualisation and Methodology; and **Desyari Safarini**: Investigation, Validation, and Methodology. All authors have read and approved the final version of this manuscript.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available subject to applicable access conditions. Depending on the nature of the data, access may be provided publicly or upon reasonable request, unless restricted by ethical, legal, privacy, or institutional requirements.

DECLARATION OF COMPETING INTEREST

The authors declare no known financial conflicts of interest or personal relationships that could have influenced the work reported in this manuscript.

DECLARATION OF ETHICS

The authors declare that the research and writing of this manuscript adhere to ethical standards of research and publication, in accordance with scientific principles, and are free from plagiarism.

DECLARATION OF ASSISTIVE TECHNOLOGIES IN THE WRITING PROCESS

The authors declare that generative artificial intelligence (Gen AI) and other AI-assisted tools were used prudently, not excessively, during the research and preparation of this manuscript. Specifically, Gemini was used for research gap analysis and proofreading. All AI-generated material was reviewed and edited for accuracy, completeness, and compliance with ethical and scholarly standards. The authors accept full responsibility for the final content of the manuscript.

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