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GeneXPress card: development and evaluation of educational card game for DNA transcription subtopics in genetics

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ABSTRACT

Understanding deoxyribonucleic acid (DNA) transcription poses a substantial challenge in studying genetics, often due to lack of understanding and traditional teaching methods that fail to engage students. This study introduces GeneXPress, an innovative card game, aimed at enhancing the learning experience of DNA transcription for higher education biology students. Using the ADDIE model, this preliminary study assessed the usability of the GeneXPress card game through a survey of 169 biology education students at Universiti Pendidikan Sultan Idris, Malaysia. A quantitative approach was employed to analyze the survey data, evaluating the game's usability using descriptive statistics, including mean scores and standard deviations. The findings reveal high usability and positive views of GeneXPress, covering various aspects such as goals, design, components and organization, playability and usefulness, with average scores of above 3.79. The positive perception of GeneXPress among students highlights its ability to engage and motivate learners, making the study of complex genetic concepts more accessible and enjoyable. In conclusion, it underscores the vital role of innovative teaching aids in enhancing student engagement and understanding, paving the way for future explorations into educational tools that cater to the evolving needs of learners and educators alike.

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1. INTRODUCTION

Throughout its history, genetics has focused on unraveling the puzzle of how the genetic information encoded in deoxyribonucleic acid (DNA) influences an organism's phenotype and functionality. It also serves as a cornerstone of biological sciences, providing students with fundamental knowledge about inheritance, variation, and the molecular mechanisms underlying life processes. However, studies by Duncan and Reiser [1] and Osman *et al.* [2] highlighted the significant challenges inherent in comprehending genetics, particularly among students. This could be due several factors including a lack of understanding of the mechanisms involved in genetic information transfer, coupled with lacking in fundamental knowledge concerning genetic structures such as genes, chromosomes, and cells, as well as insufficient proficiency in mathematics, statistics, and the principles of introductory genetics. Moreover, Hawley *et al.* [3] further identify specific complexities within genetics, including meiosis, mutations, DNA replication, DNA transcription, protein translation, and recombination, which commonly present hurdles for students. This finding is further supported by a preliminary need analysis among undergraduate biology students from Universiti Pendidikan Sultan Idris (UPSI) which showed genetics is the most difficult subject, characterized by a high level of complexity (unpublished data).

Particularly, the concept of DNA transcription presents a significant obstacle in the learning process of students. As the initial phase of gene expression, transcription involves replicating a DNA molecule into asam ribonuklea (RNA) molecules. These RNA molecules are then utilized to convert genetic information into proteins. The sequential nature of DNA transcription, combined with the constraints imposed by the involved enzymes, contributes to the difficulty that students encounter in understanding these processes. Misconceptions arise, as evidenced by Wright *et al.* [4], where a considerable portion of students inaccurately defined transcription. The abundance of terminology, including exons, introns, and RNA polymerase, add complexity which resulting in gaps in comprehension and practical application. Confusion is intensified by similarities in term usage and pronunciation, as highlighted by Chu and Reid [5]. Moreover, the challenge in learning genetics, especially regarding DNA transcription and protein translation processes, is also attributed to traditional teaching methods. Haskel-Ittah and Yarden [6] points out that teacher-centered approaches hinder active engagement and genuine understanding among students.

Several studies have highlighted the benefits of transitioning from teacher-centered to more student-centered forms of teaching and learning. Student-centered learning environments encourage active participation, critical thinking, and a deeper understanding of the subject matter. A study conducted by Kember [7] found that university-wide initiative promoting student-centered teaching and learning led to significant improvements in teaching and learning environment quality over a 2-year period. Meanwhile, Markina and Mollá [8] observed that learner participation increased by 20% in learner-centered (LC) sessions compared to traditional teacher-centered (TC) sessions, suggesting that LC approaches using active and cooperative learning strategies significantly enhance student engagement in the learning process. Hence, effective instruction that promotes engaging learning sessions, where students participate in critical and inventive thinking to address problems, is vital. Hussain *et al.* [9] suggest that an approach incorporating elements of gamification can increase motivation, escalate engagement, and elevate students' academic performance. This emphasizes the idea that the creation of educational games not only stimulates students' interest in learning but also enables a simpler understanding of concepts related to specific subtopics.

In the realm of educational strategies, game-based learning (GBL) stands out as an integrative approach that incorporates gaming elements to foster student collaboration and knowledge retention [10], [11]. This method effectively employs gaming as an educational tool, thereby introducing innovative practices into the educational system at large. It also offers students an active learning environment where the acquisition of knowledge occurs through engaging gameplay [12]. Such an environment not only makes learning enjoyable but also transforms students' perceptions of the subject matter, encouraging their active participation in both teaching and learning processes. GBL has been shown to boost motivation and engagement among students, creating a competitive yet cooperative setting [13]. It also aids in the deepening of students' comprehension of concepts, which in turn improves their academic outcomes. This aligns with previous findings [14], indicating that gamification can alleviate learning-related anxiety, particularly in mathematics, and enhance students' confidence and academic success. In another study, Zaki and Kadri [15] investigated the effects of game-based learning and gamification strategies on students' perceptions, motivation, and performance within a Food Preservation Technology course, revealing enhancements in knowledge retention and academic outcomes. Similarly, a study [16] on the impact of GBL in the context of planning education, discovering that it significantly boosts student engagement and promotes teamwork.

Hence, this study embarks on an innovative strategy to develop and evaluate the GeneXPress card game, an educational tool meticulously crafted to demystify the complexities of DNA transcription. This game transforms a challenging genetic concept into an interactive and captivating learning experience. By blending educational content with the excitement of gameplay, the GeneXPress card game aims to boost student engagement, enhance comprehension, and foster a deeper appreciation for the intricacies of genetic processes. This novel approach not only makes learning more enjoyable but also addresses common obstacles students face in mastering DNA transcription, thereby paving the way for more effective and lasting educational outcomes.

2. METHOD

2.1. Research design

The research design selected is based on the ADDIE model, which consists of five main phases: analysis, design, development, implementation, and evaluation. According to Stapa and Mohammad [17], the ADDIE model serves as a teaching design framework utilized in previous studies to create educational products and applications. This clearly demonstrates that the ADDIE model provides a structured and systematic approach for developing both products and applications. The study also aims to evaluate the validity and usability of the developed product through a survey conducted via the Google Form platform. A quantitative approach is employed to analyze the collected data.

2.2. Sample

A total of 169 respondents majoring in Biology Education at UPSI currently enrolled in semesters 3 to 7 involved in this study. The research employed a simple random sampling technique from a population of 300 individuals. A total of 30 students were excluded from the study sample to conduct a pilot study. This pilot study assessed the reliability of the study questionnaire using the Cronbach's alpha coefficient on respondents other than those included in the main study.

2.3. Instrument

This study employs a questionnaire divided into two main sections: demographic details of participants and their evaluation of the usability of the GeneXpress card game. The purpose of the survey is to gather insights into students' perceptions of the game's usability. The questionnaire items were adapted and modified from the work of Gutierrez [18], who used a five-point Likert scale for assessing each item. Additionally, two biology experts reviewed the questionnaire for its validity. Based on their feedback, improvements were made to both the questionnaire and the game itself. Moreover, these experts evaluated the face and content validity of the GeneXpress card game, providing valuable opinions and agreement levels on the game's development. This feedback is essential for implementing necessary changes to the questionnaire and the game before conducting pilot studies or the main research project.

2.4. Data analysis

The questionnaire and card game underwent assessment for face and content validity using the Cohen kappa index and the content validity index (CVI), respectively [19]. The reliability of the questionnaire was analyzed using Cronbach's alpha index, while the perceptions of the card game were analyzed using descriptive analysis. The perceptions of the GeneXpress were evaluated based on five constructs: goal, design, component and organization, playability and usefulness. Descriptive methods were employed to analyze the study data using percentage, mean, and standard deviation.

2.5. Product development

The GeneXpress card game was meticulously developed following the ADDIE model, a structured framework that guides the process through five critical phases: analysis, design, development, implementation, and evaluation. This comprehensive approach ensured the creation of a well-designed educational tool aimed at simplifying complex genetic concepts for students. The game's purpose is to facilitate interactive learning and enhance understanding of genetics through engaging gameplay. The development process involved careful planning, creation of engaging materials, practical testing in educational settings, and continuous refinement based on feedback. As a result, GeneXpress effectively meets learning objectives, making the learning process both educational and enjoyable for users, and demonstrating the successful outcomes of using the ADDIE model in educational product development.

2.5.1. Analysis phase

Analysis serves as the foundational stage for progressing to subsequent steps. Its purpose is to identify the topic to be taught, the learning objectives to be achieved, the subject content to be delivered, and the suitability of the target population [20]. A needs analysis was conducted via Google Form with students majoring in biological education. The goal was to identify challenges related to subjects and topics within the field of Biology at the higher education level. Additionally, potential solutions to the identified problems were thoroughly evaluated. The results of this needs analysis revealed that the subtopic of DNA transcription within the subject of Genetics presents significant difficulty and challenge. Furthermore, game-based learning in the form of card game emerged as a viable solution. During this phase, the researcher formulated the research objectives and questions. The study sample consisted of undergraduate students majoring in Biology education, specifically those in semesters 3 to 7, selected through a simple random sampling.

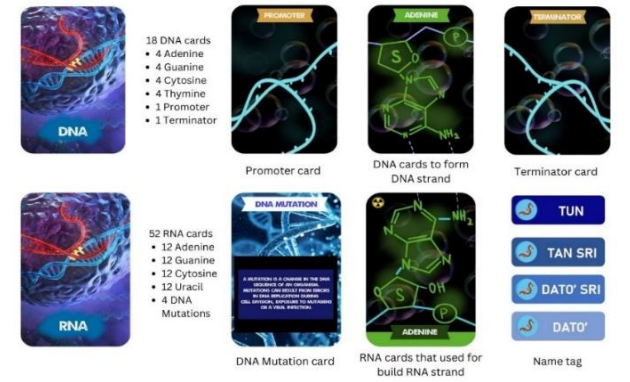
2.5.2. Design phase

The design phase transforms analytical data into a clear and actionable plan for the educational product. At this stage, the research objectives are clearly defined to align with the educational goals and the content concerning the DNA transcription topic. The core learning theories underpinning this project are Constructivist learning theory, cognitive load theory, and experiential learning theory. To create the entire card game, Medibang Paint Pro and Canva were selected for their exceptional online graphic design capabilities and versatile editing features, facilitating the creation of engaging visual images. These tools also enable the customization of numerous visuals and images for the card game's packaging. Furthermore, a visual discovery engine like Pinterest and Google Images were referred to inspire the visuals and graphics of the GeneXPress game, enhancing its educational impact.

2.5.3. Development phase

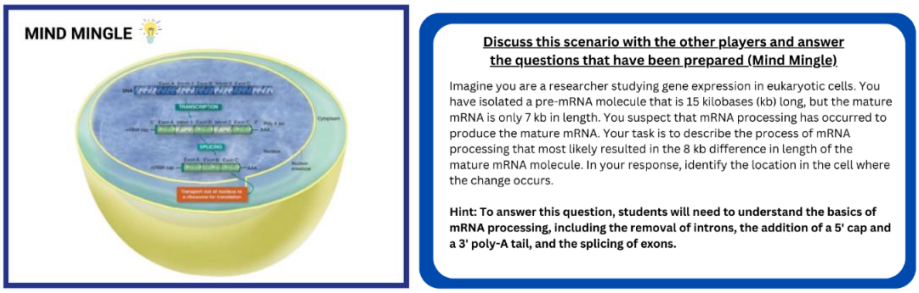
The components within the GeneXPress card game were developed using the Medibang Paint Pro and Canva applications. The researcher carefully chose relevant images and graphics for these components, crafting the entire game according to their creative vision using both applications. Each card measures 6 cm × 9 cm and is printed on Ivory paper. In the MediBang Paint Pro application, the font used is VF-Umbrage, with a font size of 14, designed to enhance player readability and comprehension of the components. Additionally, the researcher drew inspiration from the Pinterest and Google Image applications while generating ideas for the images featured in this card game.

Figure 1 illustrates the various components of the GeneXpress card game. The card game serves as the key to this game, comprising components such as 52 RNA cards, 18 DNA cards, instruction cards, flashcards (transcription notes), question and answer cards, Mind Mingle cards (pre-transitional mRNA process), name tags, and six-sided dice. In Figure 1(a), the DNA and RNA cards along with the name tags (*Tun*, *Tan Sri*, *Dato Sri*, and *Dato*) are shown. The DNA cards serve as templates that players use to create corresponding RNA sequences, simulating the process of transcription. These cards are crucial for teaching the fundamental principles of how genetic information is transcribed from DNA to RNA. The name tags are used to denote different ranks achieved by players, adding a competitive element to the game that helps maintain engagement. Figure 1(b) presents the game instruction cards, flashcards (DNA transcription notes), question and answer cards (while playing), question and answer cards (Mind Mingle) and six-sided dice. The game instruction cards provide clear, concise rules to ensure players understand how to play the game correctly. Flashcards with DNA transcription notes are included to reinforce key concepts and terminology, making it easier for students to remember important information. The question and answer cards are intended to test players' knowledge and understanding, promoting active recall and discussion among students while playing the game. The question and answer cards (Mind Mingle) are utilized after the game to foster discussions among players about the pre-transitional mRNA process that takes place following transcription in eukaryotic cells. Moreover, the questions designed for use in these card game align with the proforma for this subtopic and are suitable for the understanding and mastery level of Bachelor of education students majoring in Biology. The six-sided dice are used to introduce an element of chance and variability, making the game more dynamic and engaging. These components collectively facilitate the learning process, making the game interactive and comprehensive for the students, ensuring that they not only learn but also enjoy the process of understanding DNA transcription. Figure 1(c) presents the Mind Mingle cards (pre-transitional mRNA process. These cards are designed to promote discussions among players about the pre-transitional mRNA process that occurs after transcription in eukaryotic cells with question-and-answer interactions.



(a)

(b)



(c)

Figure 1. GeneXPress playing card components: (a) DNA card and RNA card, name tag; (b) game instruction cards, flashcards (DNA transcription notes), question and answer cards, six-sided dice; (c) mind mingle cards (pre-transitional mRNA process)

2.5.4. Implementation phase

The implementation phase involves utilizing products in practical or educational contexts. The validity of both the face and content of the research instrument, as well as the GeneXPress card games, has been assessed by two Biology experts. The research instrument's validity and that of the product were analyzed using Cohen's Kappa coefficient (k) and the content validity index (CVI). According to Sürücü and Maslakçi [21], in order for the research to yield beneficial results, the measuring instrument must accurately measure what it is intended to measure. A pilot study was conducted with 30 Biology education students in their sixth semester to assess the reliability of the developed questionnaire. Table 1 shows questionnaire reliability with the overall Cronbach's alpha value of 0.954. An agreement coefficient (Cohen's Kappa) exceeding 0.90 is considered nearly perfect consensus among experts [22].

2.5.5. Evaluation phase

The evaluation phase aimed to assess the implementation process and the quality of the GeneXpress card game's suitability as an educational tool for teaching DNA transcription. The evaluation was conducted through a structured survey using a four-point Likert scale, focusing on five key constructs: goals, design, components and organization, playability, and usefulness as described in Table 2. The survey involved 169 students from the biology education program, providing a comprehensive understanding of the game's impact on the learning process. This structured approach ensured a comprehensive assessment of both the implementation process and the product's suitability as an effective educational tool.

Table 1. Analysis of questionnaire reliability

Construct	Value of Cronbach's alpha	Interpretation
Goals	0.834	Good
Design	0.839	Good
Components and organization	0.838	Good
Playability	0.905	Excellent
Usefulness	0.850	Good
Overall Cronbach's alpha value of the questionnaire instrument	0.954	Excellent

Table 2. Description of construct to evaluate GeneXpress card game

Construct	Evaluation description
Goals	The evaluation aimed to determine if the GeneXpress card game met its educational goals. Students were asked to rate the clarity of the game's purpose and objectives, its ability to promote interaction and enhance social skills, and its effectiveness in helping recall concepts and encouraging discussions on DNA transcription.
Design	The survey evaluated the design of the GeneXpress card game, including the appropriateness and engagement of the visuals and materials used, the clarity of the instructions, and the game's portability.
Components and organization	This aspect focused on the relevance and organization of the game's components, such as the DNA and RNA cards, instruction cards, flashcards, and dice. The evaluation assessed how well these components illustrated abstract concepts and their alignment with the learning objectives.
Playability	The playability construct was evaluated to understand the clarity of the game rules, the fairness of play conditions, the balance between competition and cooperation, and the overall enjoyment experienced by the students.
Usefulness	The usefulness of the GeneXPress card game was assessed by asking students to rate how well the game helped them explore the subtopic of DNA transcription, provided a productive way to spend study time, facilitated better social interactions, and its recommendation as a teaching aid.

3. RESULTS AND DISCUSSION

3.1. Validity and reliability of questionnaire and GeneXPress card game

The survey questionnaire and the GeneXPress card game developed in this study have demonstrated strong validity (κ=1.00, CVI=1.00) and a high level of reliability (Cronbach's alpha coefficient =0.954). Table 3 present the analysis of both face validity and content validity for the survey questionnaire and GeneXPress card games. Research instruments with a content validity index (CVI) of 0.80 or higher are deemed relevant and suitable [23]. Furthermore, an instrument's reliability is considered high when the Cronbach's alpha value exceeds 0.90, indicating consistent and appropriate use [24].

Table 3. Analysis of face and content validity of the survey questionnaire and GeneXPress card games

	Value of Kappa	Value of CVI
Expert 1	1.00	1.00
Expert 2	1.00	1.00
Interpretation	Almost perfect	Appropriate

3.2. Evaluation of GeneXPress card game

The efficacy and impact of GBL within educational settings forms a cornerstone of contemporary pedagogical research. At its core, GBL represents an innovative learning paradigm that not only integrates gaming within an educational framework but also fosters collaborative and active learning among students. This approach, as highlighted by Min and Maat [12], underscores the transformative potential of games in education, offering a method that not only augments the national education system through innovation but also actively engages students in the learning process. Such engagement is pivotal in consolidating knowledge and redefining the traditional perceptions of learning materials. Active learning, facilitated through GBL, emphasizes the importance of students' direct involvement and participation in their own learning journey, making the process not just informative but enjoyable. This harmonization of play and learning, as supported by the findings of Coleman and Money [13], significantly enhances motivation and engagement, creating a competitive yet collaborative environment that drives academic performance.

Furthermore, the positive impact of GBL extends beyond mere engagement; it plays a crucial role in conceptual understanding and academic success, as corroborated by Thomas and Mahmud [14]. Their work specifically illuminates how game-based learning environments can alleviate anxiety associated with challenging subjects like mathematics, simultaneously fostering a sense of self-competence and boosting academic achievements. Research on game-based learning indicates its effectiveness in facilitating students' development of 21st-century skills. The review found that games have been designed to promote a range of skills, including problem-solving and critical thinking, which are relevant to understanding complex subjects like DNA transcription [25]. Therefore, it is essential to explore the multifaceted benefits of GBL, not only as a tool for enhancing educational engagement and performance but also as a means to innovate learning strategies and improve student outcomes across various disciplines.

Hence, this study is anchored in the integration of three foundational educational theories-constructivism, cognitive load theory, and experiential learning-which collectively inform the design and development of the GeneXPress card games. Drawing from Piaget's constructivist theory, this study suggests that learning is a dynamic and interactive process in which individuals construct new knowledge by integrating it into their existing cognitive frameworks. This perspective challenges the traditional view of learners as passive recipients of information, instead portraying them as active participants in their own learning journey. Within the framework of this study, teachers or instructors are reimagined as facilitators who guide students in navigating the complex subject of DNA transcription through the innovative medium of card games. This method transcends conventional educational constraints, such as fixed schedules and physical classroom settings, thereby broadening the horizons of comprehension and sparking heightened interest in genetic studies.

The GeneXPress card game is meticulously designed to consider the cognitive load theory, ensuring that the educational content delivered through the game is both engaging and digestible, without taxing the students' mental capacity excessively. This aligns with the findings [26], which emphasize the criticality of aligning educational game design with the cognitive capacities of learners to avert cognitive overload. The interplay between the game's design and cognitive load is crucial, as it directly impacts the effectiveness of learning by managing the amount of information processed by the working memory during gameplay. Moreover, the card game embodies the principles of experiential learning by offering students a hands-on opportunity to apply theoretical knowledge to practical scenarios. This immersive approach not only enhances engagement and enjoyment but also significantly improves the retention and application of genetic concepts. As highlighted by Li [27], GeneXPress serves as an exemplary educational tool, custom-designed

to meet the unique learning needs and preferences of students. It presents an engaging and interactive platform for undergraduate biology students to deeply engage with the transcription subtopics of genetics. Through direct involvement in gameplay, students can unravel and internalize complex genetic principles, cultivating a profound understanding and appreciation for the discipline.

Bridging the theoretical underpinnings and practical application of the GeneXPress card games, the empirical evaluation of this innovative educational tool provides quantitative evidence of its effectiveness and suitability in enhancing the teaching and learning experience of DNA transcription. In its evaluation, the developed GeneXPress card game received an average score of 3.79, with a standard deviation of 0.41. According to Riduwan [28], this mean score falls within the high range, specifically between 3.50 and 4.00. This indicates that the GeneXPress card game is well-suited for use in teaching and learning processes related to the DNA transcription subtopic. The detailed analysis presented in Table 4, which evaluate the perceptions of Biology students regarding various aspects of the game-such as its goals, design, components and organization, playability, and usefulness.

Table 4. Descriptive evaluation of the GeneXPress card game

	Items	Mean score	Standard deviation	Mean score level
Goals	1. The purpose and rationale of the GeneXPress card game are fully explained.	3.81	0.39	
	2. The goals and objectives of the GeneXPress card game are clearly defined.	3.80	0.40	
	3. The card game encourages interaction among students while enhancing their social skills.*	3.79	0.40	
	4. The card game helps in recalling concepts or terms related to the transcription subtopic.	3.81	0.39	
	5. The card game promotes discussions among students regarding the transcription subtopic.	3.81	0.39	
	Average mean	3.80	0.40	High
Designs	1. The size of the card game used in the game is appropriate (6 cm x 9 cm).	3.82	0.38	
	2. The picture printed on the card game is suitable, visually appealing, and represents the transcription subtopic.	3.78	0.41	
	3. The material used (ivory paper) in the production process of the card game is durable and easy to shuffle.	3.82	0.38	
	4. The font size (font size: 14) used in the card game is clear.	3.77	0.46	
	5. The type of font (VF-Umbrage) used is easy to read and understand.	3.81	0.39	
	6. The card game is portable and can be easily carried around.	3.81	0.40	
	7. The number of cards in the card game was appropriate.	3.81	0.41	
	Average mean	3.80	0.41	High
Components and organization	1. The instructions provided in the GeneXPress card game are clear, concise, and easy to understand.	3.73	0.48	
	2. The learning materials used in the card game help illustrate abstract concepts.**	3.78	0.41	
	3. The GeneXPress card game is suitable for the level of understanding and mastery of Bachelor of Education (B.Ed.) students majoring in Biology.	3.82	0.38	
	4. The length of time required to play the card game is reasonable.	3.73	0.47	
	Average mean	3.77	0.44	High
Playability	1. The rules of the card game provide players with equal conditions for a fair play.	3.77	0.42	
	2. The card game provides opportunity for healthy competition and cooperation.	3.82	0.38	
	3. The rules of the card game provide flexibility for students in making decisions when playing the game.	3.79	0.40	
	4. Playing the card game was fun.	3.79	0.40	
	Average mean	3.79	0.41	High
Usefulness	1. The card game encourages players to explore deeper into the subtopic of transcription.	3.79	0.40	
	2. Playing the card game is one of the ways for students to spend their time productively.	3.83	0.37	
	3. The card game helps students establish better social relationships with other students.***	3.79	0.40	
	4. The GeneXPress card game is suitable for use as a teaching aid during the teaching and learning process related to the field of Gene Expression.	3.81	0.39	
	5. I recommend the game card to teacher trainees for teaching purposes related to the transcription subtopic.	3.80	0.40	
	Average mean	3.80	0.40	High
	Overall mean	3.79	0.41	High

*Social skills refer to behaviors that express ideas, feelings, opinions, affection, and maintain or improve relationships with others.
**Abstract concepts are difficult to visualize and involve complex ideas that are challenging to explain.
***Social relationships refer to the reciprocal connections between individuals, where they influence each other based on awareness and mutual assistance.

The analysis of the goal construct within the GeneXPress card game reveals compelling evidence of its strategic complexity and educational value. With a mean score of 3.80 and a standard deviation of 0.40, the game not only demonstrates a high level of engagement among players but also a consistent effectiveness in highlighting its educational objectives. This consistency aligns with Gutierrez study [18] involving eight

biology teachers (subject matter experts), focusing on the game's objectives, design, and components. Emphasizing well-defined goals and objectives is crucial in educational card games. These goals offer direction and a sense of purpose, aligning closely with educational objectives to ensure that gameplay is not only fun but also informative. By requiring players to engage in strategic thinking and decision making, games foster valuable educational development skills such as problem-solving and critical thinking.

With regard to the card game design aspect, the mean score obtained was 3.80 (SD=0.41). It is evident that the design of this card game is suitable and relevant for the DNA transcription subtopic and is easily manageable by students. By incorporating images in various shapes and colors, the learning environment becomes more engaging and less monotonous. The GeneXPress card game was designed with diverse pictures and attractive colors, stimulating student interest and enhancing the learning experience. The design also significantly impacts how players interact with the cards during the game, influencing their ability to manage them effectively. The design phase is helpful in aligning the game with educational objectives, translating theoretical goals into practical gameplay that reinforces subject matter understanding [20]. This underscores the importance of design in creating educational games that are not only enjoyable but also effective in achieving learning goals, particularly in teaching complex scientific concepts.

In this study, both the components and organization constructs yielded high mean scores, recorded at 3.77 (SD=0.44). These values indicate positive agreement from respondents regarding the learning materials provided by the researcher. These findings align with a previous study by Cosme *et al.* [29], which also reported a high percentage of agreement for similar constructs. Based on the mean scores obtained, respondents concurred that the learning materials are well-suited for the subtopic of DNA transcription, consistent with the Genetics subject curriculum. Additionally, respondents acknowledged that the instructions on the card game are clear, concise, and easily comprehensible. Consequently, this construct is rated at a high level, where the content of the GeneXPress card game is relevant and aligned with the understanding level of Biology students. These results underscore the effectiveness of the learning materials within this game in enhancing students' understanding and mastery of the topic of DNA transcription.

Moreover, the study revealed that playability achieved average scores and standard deviations, significantly interpreted as 3.79 and 0.41. This data is consistent with previous studies [29]–[31]. In this research, playability includes aspects such as the usage of card games, their significance, and their effectiveness in engaging players. The mean scores clearly indicate that the GeneXPress card game ranks highly in terms of playability, fostering an environment conducive to both competitive and collaborative interactions. These games also enhance the learning experience for students in an enjoyable manner. The importance of fun learning experiences cannot be overstated, as they play a pivotal role in sustaining long-term interest and participation. The combination of enjoyment and competition in educational games engages students comprehensively, significantly influencing their learning achievements and motivation [32], [33].

Finally, this study produced mean scores that was highly interpretable, with values of 3.80 (SD=0.40) for the construct of usefulness. Such outcomes align with previous findings [34]. Moreover, research by Zhou *et al.* [35] highlighted the benefits of non-traditional learning approaches, including the integration of gaming elements enhances learning by making the process more engaging and less monotonous compared to traditional methods. The mean scores suggest that the GeneXPress card game demonstrates considerable usability for educational sessions, making it an effective teaching tool for the DNA transcription topic.

While the study provides valuable insights into the evaluation of the GeneXPress card game as an educational tool for DNA transcription, several limitations should be acknowledged. First, the study involved 169 students from a single institution, Universiti Pendidikan Sultan Idris. Although the sample size is adequate for preliminary analysis, the findings may not be generalizable to other populations or educational settings. Future research should include a larger and more diverse sample to enhance the generalizability of the results. Second, the evaluation of the GeneXPress card game was conducted over a relatively short period, limiting the ability to assess the long-term impact of the game on students' understanding and retention of DNA transcription concepts. Longitudinal studies are needed to evaluate the lasting effects of using the game in educational settings. Finally, the GeneXPress card game was designed specifically for teaching DNA transcription. While this focus allowed for a detailed evaluation, it limits the scope of the study. Future research should explore the development and evaluation of similar educational tools for other complex topics in genetics and biology. By acknowledging these limitations, the study provides a more balanced view of its findings and highlights areas for future research to build on and improve the evaluation of educational tools like the GeneXPress card game.

4. CONCLUSION

In conclusion, the findings from this study underscore the significant potential and practicality of the GeneXPress card game as a novel educational tool within contemporary teaching methodologies. It offers an

engaging alternative to traditional teaching methods, having successfully met its educational goals by fostering student involvement in the learning process, deepening their understanding of DNA transcription, and enhancing both their social interactions and academic experience.

Based on the limitations identified in this research, several recommendations can be made for future researchers. Future studies should aim to include a larger and more diverse sample of students from various institutions and educational settings to improve the generalizability of the findings, making them applicable to a broader population. Researchers should consider involving participants from different geographic locations, educational levels, and socio-economic backgrounds to capture a wide range of perspectives and learning environments. Additionally, researchers should consider conducting longitudinal studies to assess the long-term impact of the GeneXpress card game on students' understanding and retention of DNA transcription concepts. This method will provide valuable insights into whether the educational benefits observed in the short term are sustained over time. Future research should also explore the development and evaluation of similar educational tools for other complex topics in genetics and biology, such as DNA replication, meiosis, mutations, and protein synthesis, to determine whether the success of the GeneXpress card game can be replicated. Furthermore, researchers should investigate how the GeneXpress card game performs in different implementation contexts, such as various classroom environments and teaching styles, to identify best practices for integrating game-based learning tools into diverse educational settings. By addressing these recommendations, future research can build on the current study's findings and contribute to the ongoing improvement and validation of innovative educational tools like the GeneXpress card game.

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