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ORIGINAL ARTICLE

Developing an Augmented Reality-based Board Game for Teaching Atomic Models

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ABSTRACT

This study aims to develop an augmented reality (AR) board game for teaching atomic models and measure its effectiveness from the student's point of view. The Analysis, Design, Development, Implementation, and Evaluation model was used to create the AR board game to help achieve the study objectives. The study collected data from three focus groups, each one consisting of 8 students, as well as a questionnaire distributed to a sample of 30 specialists. Qualitative analysis was used on the reflective writing of a sample of 20 female students from Kferit's Secondary Girls' school upon experiencing the educational product to measure the study's effectiveness. The study findings revealed the great credibility of the educational product and its effectiveness in promoting creativity, innovation, communication and collaboration skills, and information literacy; as well as improving student motivation in a more entertaining learning environment.

KEY WORDS: Atomic models; augmented reality; board game

INTRODUCTION

For effective learning, knowledge should be uniquely constructed by individuals through play, exploration, and social discourse. This approach is rooted in constructivist learning theory, which emphasizes that learners should actively build their understanding through interacting with the world. In constructivist learning environments, objectives should be embedded in real-life contexts. Students are encouraged to take responsibility for their own learning and be motivated to explore new knowledge domains (Amory and Seagram, 2003).

The implementation of gamification in the teaching–learning process, which involves the integration of game-like elements in non-gaming contexts such as education, is one approach to achieving these constructivist goals. It can be defined as adding game elements into non-gaming contexts, "including that of education." Games are one of the most vital art forms and the most predominant platform of the 21st century. In education, gamification is used to increase engagement and motivate students to learn; not only receiving knowledge, but also other life aspects such as life skills, beliefs, and values (Kusuma et al., 2018; Pektaş and Kepceoğlu, 2019). Educational games – specifically serious games are mainly designed to teach specific subjects – align with the principles of gamification. One type of educational game is the board game which is still quite popular despite existing in a rapidly digitalizing world. They offer interpersonal and personal experiences that help learners develop psychological and social skills, self-regulation, cooperation, and strategic thinking (Johnson and Tiwari, 2021). These games also tend to strengthen personal bonds, allow learners to be more assertive, and increase their confidence whenever they outperform their peers. They also encourage cooperation, social affiliation, and rule-following as well as enhance student memory and strategical-logical thinking (Al Ghawalbi, 2012; Luliana and Juhasz, 2020).

There are many different kinds of board games including tangible and digital board games. The first refers to the stereotypical fully tactile games, and the second to fully digital board games played online in a browser, or through an application in a mobile device. Another kind is multimodal board games, which utilize a mixture of tangible and digital interaction for gameplay, such as Augmented Reality (AR) or Virtual Reality (VR) Board Games. These are one of the most remarkable technological advances that elevate the educational process by providing an interactive learning environment. They reinforce learners' physical environments with digital content, such as videos, holograms, and interactive tests. AR enriches the learning process by providing visually and auditorily engaging information that captivates learners' attention, caters to individual learning differences, and promotes collaboration (Johnson and Tiwari, 2021; Al Husamiyah, 2020).

The use of AR in education is not only a technological advancement but also a pedagogical tool aligned with constructivist principles. It enables learners to construct their knowledge through discovery rather than passive reception (Al Hajely, 2019). Research shows that AR supports creative thinking, collaborative learning, and social interaction, making it a valuable tool for 21st-century skills development (Abualrob, 2019). Implementing AR board games in the classroom improves the learning process by making it more interesting for the students. After all, board games have a huge social impact

on young individuals, and AR games provide players with a rich and potentially unlimited range of interaction possibilities (Rizov et al., 2019). Further, AR games can be motivating, fun, and captivating environments for learning 21st-century skills (Schrier, 2017). However, despite these benefits, AR's integration into educational games remains underexplored, with few instances of its application in board games (Kusuma et al., 2018).

Given the unique advantages of both board games and AR technology, this study aims to develop an AR board game to teach atomic models in a more engaging and entertaining manner. By combining the social and cognitive benefits of board games with the interactive potential of AR, this approach seeks to create a captivating learning environment that enhances student motivation and facilitates the mastery of scientific concepts.

STUDY QUESTIONS

1. What is the AR board game that employs AR applications to teach atomic models?
2. How effective is the proposed AR board game for teaching atomic models according to the students?

BACKGROUND

Educational games create student-centered education, improving student's learning outcomes (Lutfi et al., 2021). Educational board games fall into the gamification category that consists of a set of activities and processes which utilize various game mechanics toward solving problems related to learning and education. One of its defining qualities is that it involves the use of game elements, such as incentive systems, to motivate players to engage in a task they otherwise would not find attractive. This is reflected in gamification's potential when it comes to increasing students' engagement, participation, and motivation during classes (Ilić Rajković et al., 2017).

Board Game Elements

Board games consist of tangible, conceptual, and social elements. The tangible elements include the board, made up of a flat piece of paper or cardboard with a distinct beginning and end, with a straight, circular, or spiral path which varies in length depending on the game. They also include game pieces which consist of any pieces or figures used when playing the game such as statues, tags, and small pieces that represent each player or team. Finally, the progress tools, consisting of number generators such as dice or a spinner, which determine player progress on the board, or game currency such as coins, statues, and cards, measure players' gains or losses in some games (k2games; Walk et al., 2017).

Conceptual elements are the rules of the game, which present a clear start and finish and clarify the means of progress, possible outcomes, and the rewards and penalties that make the game interesting. They also determine the competition type and whether the players compete against the game or one another, individually or in teams (Walk et al., 2017; Kusuma et al., 2018).

People are considered the main social element in board games, where the players can be friends, relatives, students, or family members. These players could be friends, family members, relatives, or students. The social elements extend beyond the players as individuals to include the interactions between players, in the same or the opposing teams. Such interactions involve turn-taking, slyness, and plotting to advance in the game, as well as players' live reactions as they play which include them laughing, touching their faces, moving their feet under the table, or smiling, all of which can be easily noticeable hints or giveaways to the other players (Kusuma et al., 2018).

Designing Educational Board Games

Several standards must be met when designing an educational board game. For starters, the game objectives should stem from the learning material and correspond with the required lesson objectives. The game choice should also meet the appropriate educational and psychological standards. Further, the game should be age appropriate, suit the students' cognitive development level, and include as many students as possible. It is also preferable for the teacher to participate in the game, provided that the students stay in control, corresponding with the constructivism learning theory by keeping the student at the center of the educational process. Students would actively construct their knowledge through organized group social interactions, as well as organized tasks targeted toward reinforcing various thinking skills. Meanwhile, the teacher would act as a mentor for the students; guiding them, intriguing them, and listening to their observations and feedback (Amory and Seagram, 2003).

AR Applications

AR is a type of VR that aims to stimulate elements of the real world and enhance them with the addition of virtual components; for instance, converting two-dimensional images into virtual images or 3D models, or linking them with different types of multimedia such as videos or audios (Al Zahrani, 2018; Kerawalla et al., 2006; Abu Sara et al., 2019; Abualrob, 2019).

There are many AR smartphone applications used in the educational field. The two applications chosen for this study are *QR reader* and *Halo AR*. *QR reader* is an application used for Quick Responses (QRs) to codes, particularly one-dimensional codes, also known as "universal product codes," where each product has its own unique code stored in the international database, as well as two-dimensional codes that link the real world with digital contents such as different websites or multimedia including audios, videos, or three-dimensional holograms (Hijazi, 2022; Wei Kan et al., 2011).

Halo AR is a free smartphone application that enables anyone to create their own AR by linking various digital content to the real world. It works on most devices and does not require any prior technical experience. This app can read any physical object, be it a picture, painting, book cover, postcard, etc., and

integrate it with virtual (digital) information, enriching the physical content with an array of useful digital information.

This study uses the QR feature to codes and objects from both of these applications which identify different pictures, drawings, or shapes that had been previously scanned and stored in the database. The applications then display pictures, videos, audios, or 3D holograms upon scanning pictures with the smartphone camera (Hijazi, 2022). Figure 1 demonstrates the QR to images.

Previous Studies

A 2021 study by Bratitsis et al. presented the concept of an educational board game designed to teach informatics-related topics to kindergartners; it disclosed the game's concept, mechanics, and dynamics. Other studies demonstrated the positive impact AR and board games have on learners in numerous areas. For example, the 2021 study by Koong Lin et al. revealed the positive effect of the use of AR on student motivation and engagement during the educational process, resulting in profound learning. Another study by Dilmen and Atalay in 2021, as well as a study by Ahmed and Yunis in 2020, demonstrated that the use of AR educational programs enhanced students' creativity, innovation, critical thinking, problem-solving, cooperation, and communication skills. Another study in the same context by Papanastasiou et al. (2018) pointed out that AR applications create a three-dimensional environment with new ways of interaction between man and computer, increasing participation and self-learning rates, enabling multisensory learning, increasing spatial intelligence and student concentration, as well as boosting confidence and enjoyment. Further, the 2021 study by Zafeiropoulou et al. established AR game-based learning to be an easy-to-use educational tool for improving not only the teaching of physics experiments in primary school but also the learning process, by positively affecting the students' motivation and engagement. These findings were further supported by the 2019 study results by Rizov et al. which established that AR board games provide players with a rich and potentially unlimited range of interaction possibilities and that the implementation of AR creates added value to the game. In addition, board games are increasingly being recognized by educators as an effective educational resource to improve comprehension and encourage students to learn in a pleasurable manner (Pawaa et al., 2020). Finally, Schrier's 2017 study revealed that AR games can potentially teach 21st-century skills, such as problem-solving, information management, teamwork, and flexibility.

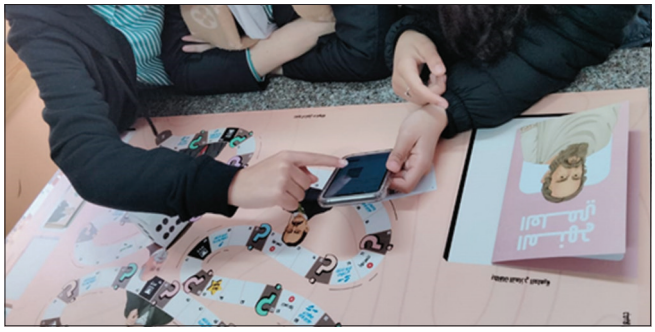

Figure 1: The use of quick response technology

METHODOLOGY

This study used developmental research to develop an AR board game for teaching atomic models using the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) model. Developmental research is a "research method used to produce certain products, and test the effectiveness of these products" (Arpan et al., 2018; Richey et al., 2004; Abualrob & Shah, 2012; Lutfi et al., 2023). The ADDIE model was chosen for this study upon examining the educational literature and previous studies on integrating AR technology into the educational process such as the studies by Johar and Abdullah (2018) and Ahmad and Younis (2020). This model was chosen for its flexibility, simplicity, and easy use (Hidayanto et al., 2018). Finally, to measure the effectiveness of the proposed AR board game for teaching atomic models, journal writing was used to determine students' behaviors, attitudes, reactions, and interactions with the developed educational product. The following Figure 2 shows the AR board game development steps.

Data Collection Instruments

Several tools were used during the stages of AR-based board game development and are explained according to the stages of their use as follows:

- Teacher's Guide titled Board Game Design by Shell Centre for Mathematical Education (2022): Some steps

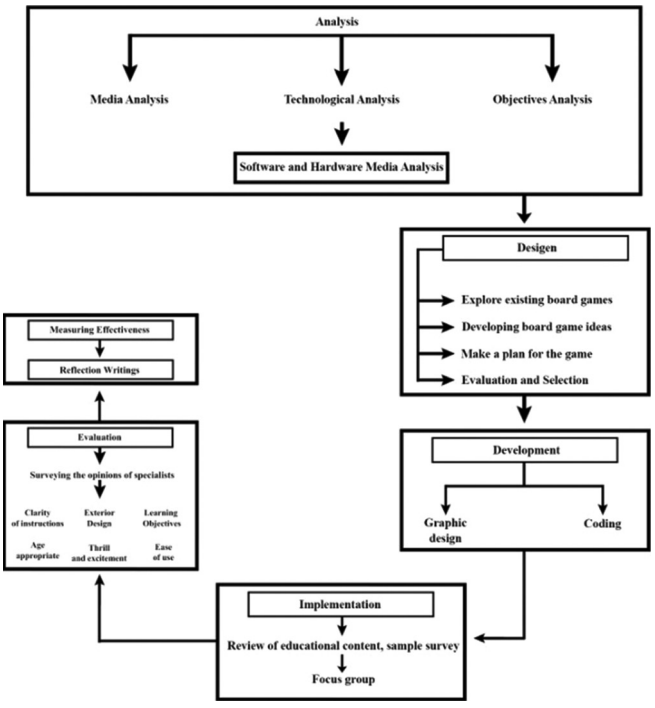

Figure 2: Augmented reality board game development steps

from this guide were used during the design phase to engage students in designing and producing the educational game and to create the initial working model
- Focus groups: Three focus groups were utilized during the implementation phase. Their characteristics are detailed in Table 1.

Questionnaire

Used during the evaluation phase, this questionnaire consists of 11 items, formulated based on the Learning Object Review Instrument outlined by Nesbit et al. (2004). It was designed to assess the board game, evaluate its appropriateness for the target group, ensure it meets board game design standards, and confirm that the educational objectives are achieved (Sari et al., 2022).

FINDINGS

First Study Question

To answer the question, "What is the AR board game that employs AR applications to teach atomic models?," students were involved in the designing stage of the ADDIE model, following steps inspired by a teacher's guide titled *Board Game Design* by Shell Centre (2022). Herein is a breakdown of the steps for developing an AR board game.

1. Analysis: analysis is the fundamental stage for developing an AR board game, thus the product is designed by its standards. This stage includes goal analysis, technology analysis, and media analysis.
   1.1. Goal analysis: The educational goals are what the learner is expected to comprehend after the learning process. These goals must be suitable for the target group, precise, non-dual, noticeable, and measurable (Arpan et al., 2018). A prototype list of these goals was established and presented to a group of judges experienced in chemistry education, science, curricula, and teaching methods. The list was then adjusted according to their feedback.
   1.2. Technology analysis: This analysis aims to determine the optimal technology for the product. Developing this AR board game requires *Android* or *Apple* smartphones, which are available to most parents, students, and teachers since the used applications work on both their operating systems.
   1.3. Media analysis: This aims to elect the media delivery strategy best suited for the target group in this digital age. The style of learning has evolved from verbal, to visual, then virtual. Thus, the learning media was made to adapt to this style by using AR technology (Sari et al., 2022).

Table 1: Characteristics of the three focus groups utilized during the implementation phase

Grade	Section	No. of students	Gender	Focus Group No.
10- grade	B	8	female	1
10- grade	B	8	female	2
10- grade	B	8	female	3

2. Design: Some design steps were inspired by a teacher's guide titled *Board Game Design* by Shell Centre (2022) to endorse the student's active role in designing and producing the educational game, as well as the proposed game concept. The student sample used in this step consisted of 29 tenth-grade female students from section "A" who were studying the chemistry curriculum at Kfirt Girls' Secondary School. These steps were:
   2.1. Discovering board game examples: For this step, the students play a number of standard board games, then detect flaws and shortcomings, and suggest improvements, as shown in Figure 3.
   2.2. Developing their own ideas: In this step, the students work together to brainstorm board game ideas using the worksheet for recording student ideas.
   2.3. Creating the layout: Each group presents a detailed layout of their own board game.
   2.4. Testing and evaluating: This non-competitive step involves receiving constructive feedback which helps evaluate the students' different prototypes. Each group presented their prototype models to the students who then elected the model best suited for the desired educational goals. The elected model is then further examined by all students who discuss the game description, rule comprehensibility, and how to make progress to win the game, then provide suggestions for improvement.
   2.5. Finalizing the prototype: A detailed outline of the board game was made and then presented along with the required videos, 3D models, and educational content to a number of judges made up of IT experts, as well as expert teachers and supervisors in the educational chemistry field. The judges' feedback and recommendations regarding the presented content were recorded to help with the initial verification of the game model.
   2.5.1. Educational experts' recommendations:
   - Gradually presenting the questions and curricular tasks from easiest to hardest.

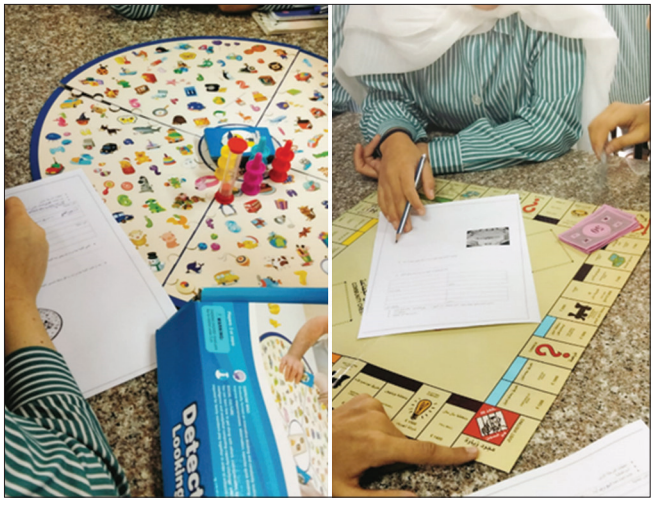

Figure 3: Discovering board games like monopoly

- Including all the required educational goals in the game's educational content.

2.5.2. IT experts' recommendations:

- Choosing clear images that captivate students' attention.
- Diversifying the language of the displayed videos, employing YouTube's auto-translation feature.
- Adding more thrill to the game rules.
- Utilizing some online test makers for creating curricular tasks.

3. Development: This stage involved the researchers performing a number of steps.
   3.1. Preparing the educational content using a Microsoft Word, drawing the board layout by hand, writing the curricular questions on Google Forms, and organizing the links to them in tables, before handing them over to the technicians.
   3.2. Designing educational content cards, question cards, and the game board with the help of a few graphic designers.
   3.3. Linking the educational and curricular question cards digitally with the *Halo AR* and *Sketch fab* mobile applications.
4. Implementation: The researchers met with a reconnaissance sample consisted of 24 tenth-grade female students from section "B" studying the chemistry curriculum at Kfirt Girls' Secondary School as shown in figure 4. The game rules and progress methods were explained to the sample, which was then trained on how to use AR technology. The sample was later provided with smart devices with the required applications installed. The sample tested the educational content, making sure the content and question cards worked properly, and that the game rules were coherent and easy to play by. Finally, three focus groups, each consisting of 8 female students, helped evaluate the board game content through discussions using worksheets from Youth Scotland. Youth Scotland provides resources and guidance for designing board games, including tools and support for youth engagement in game design.
5. Evaluation: The focus group's notes were recorded and then implemented. The notes included creating a game guide containing everything the players need to know about the board game, as well as adjusting the placement of some of the icons on the board to better correspond with the game rules. Figure 5 shows the finalized board game model. Finally, the product was presented to a group of 30 specialists in curricula and teaching methods, educational technology, and e-learning. The results showed that all the experts involved in the study were female, with 10 specializing in curricula and teaching methods, 10 in educational technology, and 10 in e-learning.

The sample's responses show the arithmetic mean for all questionnaire parts to be between (4.33 and 4.66), revealing a high value for all questionnaire parts (Table 2).

Survey Correction

To interpret the sample's responses to the study tool and evaluate the educational product, the following relative assessment criteria were used: According to Pimentel (2019), the survey correction criteria are as follows: A response score of 1.0–1.79 indicates "Strongly Disagree," 1.8–2.59 represents "Disagree," 2.6–3.39 is "Neutral," 3.4–4.19 signifies "Agree," and 4.2–5.0 denotes "Strongly Agree."

Second Study Question

To answer the second question, "How effective is the proposed AR board game for teaching atomic models according to the students?," the researchers met with a sample of (20) female 10th-grade students of Kferit's Secondary Girls' School section (C). The sample played the board game and then was tasked with writing a reflective paper answering the following guiding questions (Klimova, 2014, p122):

- What have I achieved by playing the board game?
- Which tasks were the most difficult for me and why?
- Which tasks were the clearest? Why did I find them easy?
- How did the game improve my skills and knowledge?
- Which were the top 3 hardest challenges I faced while

Figure 4: A reconnaissance sample for constructive evaluation

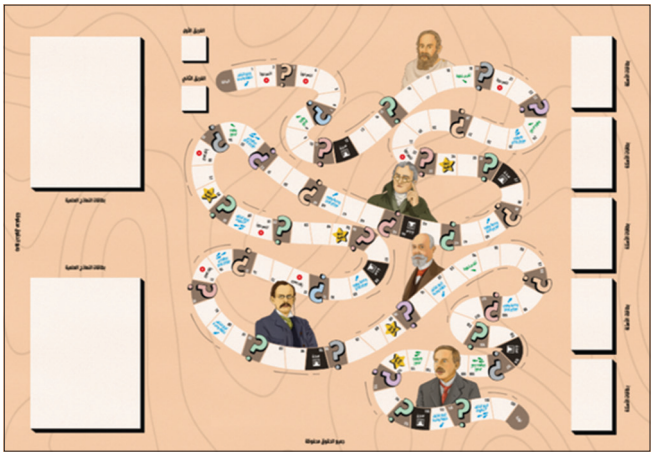

Figure 5: Finalized board game model

Table 2: The arithmetic means and standard deviations for the different parts of the questionnaire evaluating the board game

Number	Question	Arithmetic mean	Standard deviation	Value
1	The game seems professionally made with an appealing design.	4.6667	0.47946	High
2	The board game, its designs, and drawings correspond with the course contents.	4.5333	0.62881	High
3	The game is engaging and exciting.	4.5667	0.50401	High
4	The game includes all its requirements such as game pieces, cards, and dice.	4.5000	0.57235	High
5	The board game comes with a special guide explaining what the game is.	4.6333	0.49013	High
6	The board game guide is linguistically coherent and understandable.	4.5000	0.68229	High
7	The game guide clearly illustrates how to advance through the stages and win the game.	4.4000	0.85501	High
8	The game goals accord with the course contents.	4.5667	0.72793	High
9	The board game tasks are suitable for the target age group.	4.3333	0.60648	High
10	The board game utilizes augmented reality technology in a user-friendly manner.	4.4667	0.73030	High
11	The augmented reality applications required for the board game are easy to download and operate.	4.5333	0.62881	High

playing this educational game?

- Which part of the game was the most boring? What do you suggest to improve it?
- In what way can this educational game be beneficial for my future?
- What would I advise my schoolmates who are studying this educational game next year?
- What have I learned about myself after completing the educational game tasks?

The researchers used the six steps from the (Caulfield, 2022; Kiger and Varpio, 2020; and Creswell, 2012) studies as a guide for interpreting and analyzing the qualitative data (the reflective papers). These steps include preparing and organizing the data, discovering and coding primary data, forming and categorizing the themes, reporting analysis results through tables or figures, interpreting the results, and, finally, verifying their accuracy.

Themes

Analyzing the students' reflective writing revealed positive indicators toward the effectiveness of the board game across five themes as shown in Figure 6. The researchers provide examples from the students' writings indicating the board game's effectiveness when it comes to improving students' creativity, innovation, communication, and collaboration skills, along with their information literacy, as well as enforcing healthy competition and increasing fun, pleasure, and student motivation while learning.

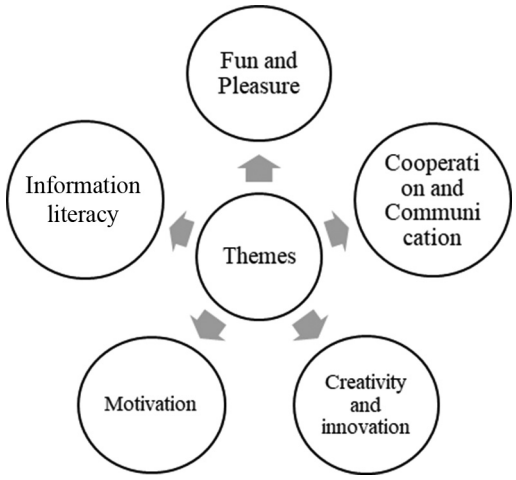

Figure 6: Themes are drawn from students' opinions around the board game

Creativity and innovation

Analyzing students' reflective essays revealed that the positive effect the board game had on the students' innovation skills by getting them to use innovative methods such as brainstorming and aiming to come up with unique new ideas, whether they were fully or partially valuable. The writings also reflected an increase in student curiosity and enthusiasm for developing and implementing their own creative ideas. These effects can be seen in the following reflective writings of some of the students:

- R.J.: "I have come up with a new idea. I was merely asked to suggest a video game. However, my passion for programming urged me to program the game myself. I designed the game logo and stages, using an app called *Struckd*, and named it *Atomic Models Gates*. The idea did not come to me easily, I thought hard about it before bed, on my way to school, and all the time. I would talk to my friends about it, explaining my idea and taking some of their suggestions. I discovered new talents and skills I never knew I had, I'm very proud of myself."
- S.A.: "Forming the 3D figures for the atomic models motivated me to create my own 3D model as a project for the study unit and submit it in the science fair of this year."
- R.A.: "I chose "designing a video game embodying the role of a designer at *Apple* company" from the available tasks because of my great love for video games. I thought long and hard about the game concept, mechanics, and logo; spent long hours searching the internet for design ideas; and designed four different game logos before finally choosing one. I tried, as much as I could, to think outside of the box. Finally, I named my game *The helper* to correspond with the player's role of helping the scientists."
- D.N.: "I used an app dedicated for graphic novels to create the timeline."
- B.A.: "Combining the printed game with digital content astonished me. It got me thinking about how to present

the teacher with a project utilizing AR for the next unit."

- S.F.: "I used graphic novel programs to create my own novel and was very pleased with the outcome!"
- R.M.: "I thought of something new to stand out amongst my classmates and made an effort to add my own twist to it. The required tasks helped me put my weekend leisure time to good use, making me more open-minded."
- W.Y.: "The organization process was fun. It allowed me to add my own style to the game through various features of the used applications."
- L.S.: "I learned how to think harder, and use my cognitive skills to produce something like a journal and a timeline."
- B.H.: "I had thought of yet another idea, but I did not have the time to execute it."
- N.A.: "I chose the task of "writing a scientific article on the history of discovering atomic models in Al-Quds newspaper". I used an application called *InDesign* to complete the task which turned out to be rather hard and demanding. I aimed for my design to resemble a proper newspaper one would buy from a conventional newsstand. I worked hard on the design of the front page and various page headlines. Moreover, I used unconventional headlines such as "The other half?" for the article about Marie Curie, and "Where are we today?" for another article about the modern atomic model."

Information literacy

The reflective writings' analysis reported the board game's positive impact on students' abilities to effectively and efficiently finding the necessary resources through the internet; as well as its impact on their ability to critically evaluate information and manage the information flow from various resources. Further, the writings reflected the students' core understanding of the legal ethics of information gathering, evident in their strive to verify the gathered information. This impact can be seen in the following reflective writings of some of the students:

- N.A.: "I didn't use Wikipedia as the tasks instructed. Instead, I searched through different websites, blogs, books, and magazines. I also researched various verification methods using different search engines."
- A.A.: "I compared information by visiting numerous websites and using search engines other than Google, as well as using apps like *Pinterest*. I did not use Wikipedia since it allows its users to edit articles."
- S.A.: "I researched methods of assessing websites and magazines' credibility and reliability, as well as proper verification methods, which was not easy."
- W.Y.: "I used YouTube to learn some skills, as well as the *Canva* and *The Arab designer* apps, both of which I found while browsing different search engines."
- J.J.: "Having internet access satisfied my curiosity to learn more. I searched through various websites, comparing information, and ensuring its accuracy."

Cooperation and communication

Experiencing the developed educational product positively impacted the students' effective communication both inside and outside the classroom. The experience also enhanced their collaboration skills and sense of responsibility. These can be seen through the following reflective writings:

- T.N.: "I was very happy to have my classmate on the same team as me, especially because we had never worked as a team before."
- B.A.: "Being around new classmates I didn't use to interact with made me learn more about their lovely personalities."
- T.G.: "I made sure to contact my teammates after school hours to prepare well and discuss the required tasks so that we would win."

Fun and pleasure

Playing the proposed board game, with all its challenges, point collection, stage progression, instant feedback, and missions achieving the educational goals in an engaging, competitive atmosphere with students at the center of the educational process, created a boredom-free, entertaining educational environment. This is evident in the following reflective writings:

- T.M.: "I wish all our books were interactive and used AR technology. I think it would be really fun if it was used in Geography or the geometry unit in Mathematics."
- B.H.: "The competition between the teams created a particularly fun atmosphere filled with laughter."
- M.A.: "I don't mind spending my break time playing this kind of game."
- G.A.: "I would feel extremely happy whenever I advanced through the game path. However, luck wouldn't always be on my side; sometimes, I'd advance only to end up on a penalty square. That's when me and my teammate would scream, "Oh nooooo!"

Motivation

The following reflective writings showed evident indications of an inner desire amongst the students to do specific tasks toward achieving the board game's goals."

- R.A.: "I would eagerly wait for Chemistry classes so we could play the game, unlike the other boring classes."
- R.J.: "We made sure to advance through the game stages so that we would win. I had to prepare really well to quickly answer the questions."
- R.T.: "I would read up on the history of atoms so I could easily answer the task questions and advance through the game stages faster than the opposing team, without letting my teammates down."

DISCUSSION

The constructivism learning theory places the student at the center of the educational process, with the teacher guiding them, intriguing them, and receiving their feedback (Amory and Seagram, 2003). This theory stresses the importance of students actively acquiring knowledge and new concepts through their own experiences, accentuating student-centered education. The theory also suggests that the educational content

be derived from content students are interested in and would easily accept (Shed Sazly et al., 2021). Board games and AR technology allow learners to be the center of the teaching–learning process by assigning them various interactive, competitive, and cognitive tasks, aimed toward developing important skills such as collaboration and communication (Al Husamiyah, 2020; Al Hajely, 2019; Rizov et al., 2019; Iatsyshyn et al., 2020; Schrier, 2017). This, in turn, highlights AR's ability to transform the learning material from being intangible to a fun, excitement-filled interactive subject.

In this study, the researchers applied the scientific steps of the ADDIE model to create an AR-enhanced board game that engagingly teaches atomic models, leveraging the strengths of both board games and AR. As previously mentioned, the selection of board games and AR was justified based on their alignment with constructivist learning theory. Thus, from a theoretical perspective, this study offers a methodological framework for designing board games and incorporating modern technologies like AR.

Practically, the AR board game developed in this study offers several significant benefits that enhance learning and skill development. It sparks creativity by encouraging players to think innovatively through interaction with virtual elements embedded in the physical game, promotes teamwork, and enhances communication and collaboration skills crucial for both academic and professional environments. In addition, it helps students gain a deeper understanding of the subject matter, fosters a competitive spirit by adding excitement and encouraging friendly competition that supports personal growth while upholding teamwork and fair play, and makes learning more engaging and effective through an immersive, visually interactive experience.

The study findings coincide with Koong Lin et al. (2021) and Zafeiropoulou et al. (2021) studies by confirming the positive impact of educational games on student motivation and engagement in the educational process, which results in profound learning. The findings also agree with Dilmen and Atalay's (2021) and Schrier's (2017) studies when it comes to educational games' enhancement of creativity, innovation, cooperation, and communication skills. Finally, the findings correspond with Papanastasiou et al. (2018) study where educational games promote feelings of fun and pleasure among the students.

CONCLUSION

The study findings highlight the necessity of creating educational games that utilize AR. Such games have been proven to increase student motivation, which is a vital factor for better engaging students in the educational process. These games also enhance students' communication and collaboration skills; the two social skills necessary for building a more interactive, positive learning environment. Further, AR games are valuable tools for developing students' creativity and innovation skills, as well as their information literacy, which represents their ability to effectively and efficiently understand and utilize information. Moreover, with the increasing involvement of modern technology in students' everyday lives, this study stresses the need for more research to be conducted in this field to develop more technologically advanced educational games, specifically those using AR. It is crucial to investigate how these digital innovations such as AR might impact traditional methods of learning with board games. Furthermore, as games become increasingly prevalent in educational settings, evaluating their potential as assessment tools will be beneficial. Finally, the study emphasizes the importance of integrating AR technology into Science and Chemistry curricula, since this technology enhances the teaching of both subjects, as it extends students' learning experience. This integration would better prepare the students to face an ever-advancing technological world throughout their professional and personal lives.

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