Serious Game Design and Evaluation: Light Propagation and Reflection in Elementary Education

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Abstract: The intangible nature of light is the primary reason why children develop misconceptions in their attempts to understand phenomena related to light and its properties. The most common misconceptions among children aged 11-13, are related to what happens when light strikes a mirror. This difficulty stems from their inability to perceive light as an entity in space. Therefore, the use of various representations and experiments is necessary for children to effectively construct light-related concepts. This study reports the design and evaluation of a logic-based digital game for fifth- and sixth-grade primary school students, named "*Fotogonies*". Ten levels were developed as a minimum viable, fully functional version of the game. The player guides a laser beam from a source to a target by rotating mirrors. The game becomes progressively more challenging, with the difficulty carefully calculated and gradually increased. The main goal is to create an appealing digital game that can deliver educational value. It is designed to accurately represent key concepts of light propagation and reflection, with specially defined mechanics and rules, aligning with the relevant scientific models. At the same time, the game meets the requirements of serious educational games, balancing simplicity and low-cost development. Additionally, emphasis was placed on designing a classroom-friendly game with an easy-to-use setup to support possible widespread adoption. Surprisingly, the first tests showed that the game can be equally challenging and appealing for adults. The resulted game was evaluated in terms of usability and user satisfaction, gathering both quantitative and qualitative data. The evaluation showed that the participating students had a positive experience engaging with it - an essential precondition for supporting conceptual change regarding children's misconceptions about light. Furthermore, the evaluation revealed that self-reporting questions addressing specific aspects of the game (consistency, learnability, difficulty), may not be as reliable as qualitative results when answered by young children.

Keywords: Digital game, Physics, Optics, Primary school, Game-Based learning

1. Introduction

Serious games can have a positive impact on cognition, as playful activities can evoke interest, commitment, and fun (Lopez et al., 2023). According to Ullah et al. (2022), there are significant gains in conceptual understanding and problem-solving when serious games in education are well aligned with the critical principles of the targeted scientific concepts. Utilising them in education, however, is primarily guided by defined learning goals, while fun is a secondary objective. Indeed, most primary school studies emphasise design and evaluation in terms of learning gains, with usability and overall player experience addressed secondarily (Kara, 2021; Juhari, Hani & Bakar 2020; Cheng et al., 2015).

At the same time, not many studies report on digital games related to concepts of light. One such study is that of Huei et al. (2014), which reports on the development and evaluation of Shimmer©, a three-dimensional digital educational game designed to teach basic optical phenomena such as reflection and refraction to students aged 12-13. In the game, students solve problems by guiding laser beams through the strategic placement of mirrors and lenses across levels of increasing difficulty. The study's findings highlight a significant improvement in conceptual understanding, emphasising the importance of game-based learning and the need for educationally grounded digital game design. Regarding the participants' experience, however, that study focuses more on assessing the flow construct of the game, rather than usability aspects or students' satisfaction. Another game includes light propagation as one of its main concepts. However, it is a Virtual Reality (VR) game in which the physics principles are quite advanced, targeting young adult students. Additionally, VR equipment is not designed for children under 13 years, while the game production itself seems complex and time consuming (Zhang, Zhang & Lee, 2025).

From a design perspective, hardware costs and technical complexities can require instructional and set-up time, which may limit adoption in classrooms (Ullah et al., 2022). Moreover, games addressing specific topics are generally used only to support certain curriculum chapters, not daily or year-round. Therefore, design should balance low production costs with high quality.

Under this scope, the main objective of this work is to propose a game that provides students with an environment where they can explore two fundamental concepts related to light: propagation and reflection. More specifically, the game aims to allow students to intuitively discover that light travels in a straight line and changes direction when it strikes smooth, reflective surfaces at predictable angles (angle of incidence equals the angle of reflection). The name of the game, "*Fotogonies*" (Greek: Φωτογωνίες = Light angles), indicates exactly that. The goal is to propose a simple, relatively low-cost, yet appealing and high-quality game that not only contributes to the educational objective, but also provides a positive experience for students.

This paper reports on the design decisions made, focusing on the *Fotogonies* player experience. Section 2 outlines the relevant requirements for serious educational games, while Section 3 describes the game design, covering the gameplay, navigation, mechanics, rules, level design and accessibility. Section 4 summarises the findings from initial formative evaluations and presents the results of a summative evaluation of usability and user satisfaction conducted with fifth-grade students. Additionally, to assess learning gains, a pretest-posttest evaluation and four metrics (e.g., level completion time) were used to analyse the students' behaviour. However, although the learning impact results were positive, they are beyond the scope of this work.

2. Educational Requirements

The game should be embedded in the appropriate learning context and enriched with well-designed interactive artefacts, enabling teachers to teach and learners to learn, as with any other educational material (Dimitracopoulou, 2018). Through this lens, the game should address the key design requirements for serious educational games. Based on those defined by Al-Awadai (2024) and Asadzadeh et al. (2024), essential requirements were identified as relevant, necessary, and adequate for designing *Fotogonies* for fifth- and sixth-grade primary school classrooms. These are organised into eight axes:

- Scientific fidelity and misconceptions: graphics and rules representing scientific optics while addressing common children's misconceptions related to light (e.g., light shines but does not travel) (Driver, Guesne & Tiberghien, 1985).
- Story and goal: a game that is simple, engaging, age-appropriate, and free of cultural or gender bias.
- Mechanics: use of clear, intuitive, minimal mechanics that map directly onto the underlying physics.
- Interactivity: incorporate encouragement, provide feedback in text and audio, and allow social interaction.
- Challenge: gradually increasing difficulty with clear, attainable objectives and repetitive tasks.
- Rules: concise rules that limit player actions to support concentration and reasoning.
- User interface and usability: a visual representation that makes sense and is consistent and responsive.
- Accessibility and cost: a low-cost game, use of high-contrast colour combinations appropriate for most vision conditions.

3. Digital Game Design

3.1 Game Story, Goal and Navigation

A two-dimensional, logic-based puzzle game was designed and developed in Unity using C# for Android devices. When the application launches, the user is presented with a home page with "Play" and "Exit" options. The core gameplay is guiding a beam of light from a source (beam torch) to a target (candy) by rotating mirrors. After the player taps "Play", a brief introduction explains the objective: "Find the candy in the dark. Tap on the mirrors to turn them to the right angle and hit the candy". It is a story that most children can relate to, resembling a real-life scenario of searching for something in the dark. The player rotates mirrors by tapping them. Each tap rotates the mirror by 45 degrees clockwise and counts as a single move (Figure 1). It was intentional to exclude a "game over" tactic, which could be tiring and discourage a player after failure. Instead, if the player exhausts all available moves without hitting the target, a failure screen suggests a retry of the same level. The player can replay it until they solve it and continue to the next. Each level also includes a "Home" button for easy navigation back to the main menu. From there, the player can "Play" from the first level or "Exit" the game (Figure 2).

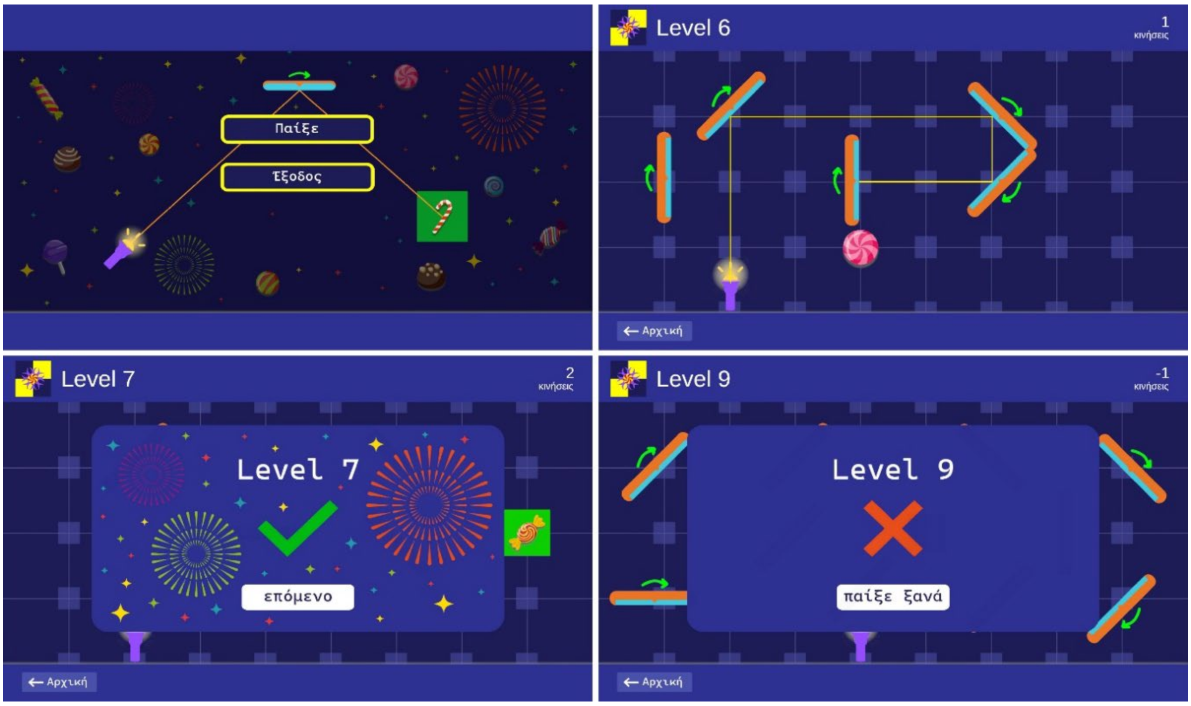

Figure 1: Screenshots – from top left to bottom right (a) home page, (b) gameplay, (c) success feedback, (d) fail feedback

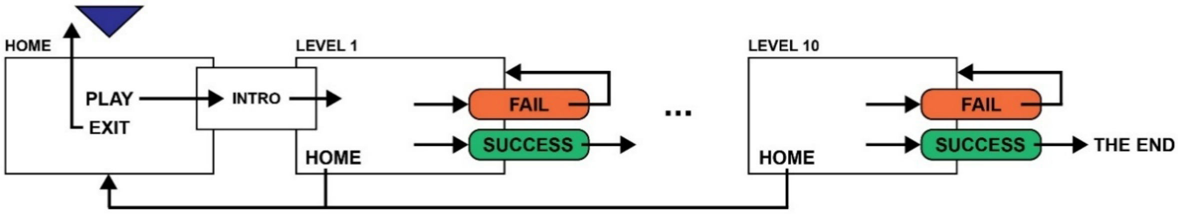

Figure 2: Navigation diagram

3.2 Game Mechanics and Rules

As the player advances, the game introduces rules by gradually providing prominent evidence of each rule. This evidence is also repeated in subsequent levels before introducing evidence of another rule. Core (CO) rules are introduced first so that the player can become familiar with the environment and the game's goal. These form the foundation of the game. Then, supplementary (SU) rules are introduced – rules that add variety and increase the difficulty. Ten levels have been built, with increasing difficulty. Table 1 outlines the game rules and the levels where the player is most likely to discover them.

As the levels progress, more mirrors are introduced, more moves are required, and fewer available moves are given. This creates more complex configurations, leaving less room for errors and requiring greater mental effort. This progression promotes strategic planning, critical thinking, and spatial reasoning, requiring the player to refine their control over their decisions and moves. The level difficulty can be expressed by the combination of three factors: the room for error between available and required moves, the number of mirrors given at each level, and the proportion of given mirrors that are required to successfully complete the level. Based on this, the difficulty of each level is defined by the following equation:

$$Level\ Difficulty\ (\%) = [0.4 * MoRM + 0.4 * \mathrm{RMC} + 0.2 * (1 - \mathrm{MiRM})] * 100, \text{ where:}$$

$$Moves\ Relative\ Margin\ (MorM) = \frac{Minimum\ Required\ Moves}{Available\ Moves}$$

$$Relative\ Mirror\ Count\ (RMC) = \frac{Level\ Given\ Mirrors}{Max\ Given\ Mirrors} = \frac{Given\ Mirrors}{10}, \text{ and}$$

$$Mirrors\ Relative\ Margin\ (MiRM) = \frac{Required\ Mirrors}{Given\ Mirrors}.$$

The smaller the MoRM, the more room the player has for errors, meaning they can make many unnecessary moves and still win the level. The larger this margin, the tougher the level becomes.

The larger the RMC, the more mirrors there are in a level, thus increasing the mental load and making the level tougher.

The smaller the MiRM, the greater the complexity of the level, meaning the player is more prone to mistakes as they need to identify the necessary mirrors to win the level. The smaller the margin, the harder it is to win.

Table 1: Game rules and possible levels of rule discovery by the user

No.	Rule	Level(s) of discovery	Rule Evidence
1	CO - The goal is to guide the beam to the candy by rotating mirrors.	1, 2	Torch and candy are stable. Mirrors rotate. Level 1 is impossible to lose. Level 2 has many moves available.
2	CO - The beam always reflects on 90-degree angle.	3, 4 or any of the next levels	Mirrors are positioned based on a grid. They rotate 45 degrees clockwise with each tap.
3	CO - Available moves are limited. Their number is different at each level.	3, 4	Level 3 is the first level where the player might continue taping rapidly and lose. In Level 4 the available moves are equal to the required moves. In both levels, it is quite possible for a player to lose if they are not paying attention.
4	CO - If the player exhausts all available moves, they can retry the level until they succeed.		
5	SU - Not all mirrors given in a level are necessary to complete it successfully.	5, 6 or any of the next levels	Level 5 and Level 6 each have an extra mirror placed close to the beam's path. In level 5, there are four unused mirrors for the second possible solution.
6	SU - A level may have two possible solutions.	5, 9, 10	Each of Levels 5, 9, 10 have two possible solutions.

Table 2 presents the gradual difficulty progression by level.

Table 2: Difficulty progression by level

<table>
<tr><th>Level</th><th>Av. Moves</th><th colspan="2">Req. Moves</th><th colspan="2">MoRM</th><th>Giv. Mirr.</th><th colspan="2">Req. Mirr.</th><th colspan="2">MiRM</th><th>RMC</th><th colspan="2">Difficulty (%)</th></tr>
<tr><td>1</td><td>20</td><td colspan="2">7</td><td colspan="2">0.35</td><td>1</td><td colspan="2">1</td><td colspan="2">1.00</td><td>0.1</td><td colspan="2">18</td></tr>
<tr><td>2</td><td>20</td><td colspan="2">8</td><td colspan="2">0.40</td><td>2</td><td colspan="2">2</td><td colspan="2">1.00</td><td>0.2</td><td colspan="2">24</td></tr>
<tr><td>3</td><td>16</td><td colspan="2">11</td><td colspan="2">0.68</td><td>3</td><td colspan="2">3</td><td colspan="2">1.00</td><td>0.3</td><td colspan="2">39</td></tr>
<tr><td>4</td><td>4</td><td colspan="2">4</td><td colspan="2">1.00</td><td>2</td><td colspan="2">2</td><td colspan="2">1.00</td><td>0.2</td><td colspan="2">48</td></tr>
<tr><td>5</td><td>13</td><td>7</td><td>12</td><td>0.53</td><td>0.92</td><td>5</td><td>1</td><td>4</td><td>0.20</td><td>0.80</td><td>0.5</td><td>57</td><td>60</td></tr>
<tr><td>6</td><td>4</td><td colspan="2">4</td><td colspan="2">1.00</td><td>5</td><td colspan="2">4</td><td colspan="2">0.80</td><td>0.5</td><td colspan="2">64</td></tr>
<tr><td>7</td><td>15</td><td colspan="2">13</td><td colspan="2">0.86</td><td>4</td><td colspan="2">3</td><td colspan="2">0.75</td><td>0.4</td><td colspan="2">55</td></tr>
<tr><td>8</td><td>5</td><td colspan="2">5</td><td colspan="2">1.00</td><td>6</td><td colspan="2">4</td><td colspan="2">0.66</td><td>0.6</td><td colspan="2">70</td></tr>
<tr><td>9</td><td>24</td><td>21</td><td>16</td><td>0.87</td><td>0.66</td><td>10</td><td>5</td><td>5</td><td>0.50</td><td>0.50</td><td>1.0</td><td>84</td><td>76</td></tr>
<tr><td>10</td><td>16</td><td>12</td><td>10</td><td>0.75</td><td>0.62</td><td>9</td><td>5</td><td>5</td><td>0.55</td><td>0.55</td><td>0.9</td><td>75</td><td>69</td></tr>
</table>

3.3 Expected User Experience and Accessibility Requirements

The game is designed primarily for tablet screens, even though it is responsive for all mobile devices. Larger on-screen objects with adequate spacing improve visibility and accessibility, allowing users to interact with precision. Additionally, tablets can offer flexibility in classroom settings and can accommodate collaboration between players. By allowing collaboration, no particular emphasis is placed on high competition between students, which can be a source of anxiety for some (Lopez et al., 2023; Ullah et al., 2022). Notably, this is also the reason why a time constraint was excluded from the game mechanics, so that the player does not play against time. On the contrary, the constraint of a limited number of available moves allows the player to develop their strategy at their own pace.

Visual and audio elements aim to invite engagement and sustain it. The graphics are simple yet aesthetically pleasing, minimising distractions and aiding concentration. A blue colour scheme dominates the design, chosen for maintaining focus and promoting a calm environment (AL-Ayash et al. 2016). Visual elements adhere to accessibility guidelines (WCAG 2.1 Success Criteria), ensuring proper contrast and readability, with the aim of meeting Level AA compliance. Figure 3 depicts the colour contrast levels between elements and their background (adjacent) colour for the most used combinations. TPGi Color Contrast Analyser (CCA) version 3.5.4 was used to confirm that all colour combinations pass the 3:1 ratio for graphics (criterion 1.4.11) and the 4.5:1 ratio for text (criterion 1.4.3), while real text is used instead of image (criterion 1.4.5). All screens of the game were also checked with a colour blindness simulator (Coblis) for all colour vision conditions (protanopia, achromatopsia, etc.). The graphics are complemented by sound effects that provide immediate feedback for player actions, and are present but not overwhelming, supporting a multi-sensory experience.

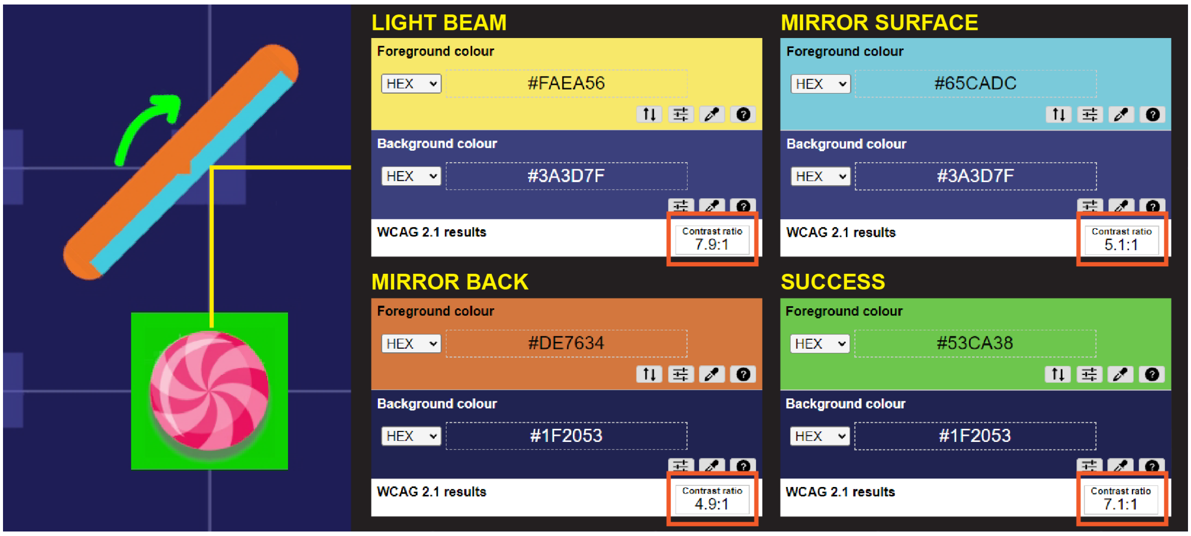

Figure 3: Main colour combinations checked for appropriate contrast in CCA

4. Evaluation, Results and Findings

4.1 Formative Evaluation

Formative evaluations are essential for refinement (Koutsabasis, 2015). Two of the first functional versions of the game were used to conduct two formative evaluations with four adults (aged 35 to 50) and four children (aged 11 to 12). These were carried out using the think-aloud protocol, direct observation, and open-ended questions to gather feedback on what was easy or confusing, as well as preferences and suggestions.

Based on the feedback, mainly visual changes (sizes, colours, shapes) were made to various elements to make them more distinguishable and to indicate their functions more intuitively. For instance, the back of the mirror was not clearly distinguishable from the front, which represents the reflective area. Additionally, level configurations and mirror placements were also adjusted, and the background was updated to a square-based grid to ensure that the light beam would always hit the centre of each mirror. This ensured that the beam's path is predictable and the gameplay is solvable in the same way across all levels, helping the player make safer assumptions about which mirror is the last to reflect the beam to the candy.

Another notable finding was that some adults tried to tap and drag a mirror to rotate it and had to try several gestures before discovering the correct one. Children, on the other hand, directly used a single tap to rotate the mirror. Moreover, although the game is designed prioritising children, feedback from adults showed that it can also be suitable and challenging for older audiences.

4.2 Research Methodology and Tools

This study adopted a mixed methodological approach, combining quantitative and qualitative data to explore the learning outcomes and usability of *Fotogonies*. The main study sample consisted of 44 students, approximately 11 years old, from two sixth-grade classes at the 4th Experimental Primary School of Ermoupolis, Syros. The sample included students from diverse socio-economic and academic backgrounds, a diversity attributed to the lottery-based admission system of Experimental Schools.

The students were introduced to the game and played in pairs using tablets, while the think-aloud protocol was applied to capture their thinking. Data were collected via screen recording applications, written notes, and audio recordings. After completing the game, students individually filled out:

- a SUS (System Usability Scale) questionnaire to evaluate usability,
- a QUIS (Questionnaire for User Interaction Satisfaction) questionnaire to assess user satisfaction, and
- open-ended questions regarding positive or negative aspects of the game.

Both SUS and QUIS were adapted for the game and translated into Greek, with their English versions provided in the Appendix. The answers were collected manually and later digitised for analysis. The SUS questionnaire can reveal whether participants are "cheating" by answering randomly, making it reliable for insights at an individual level. The QUIS questionnaire, on the other hand, can offer an overall impression across five aspects of the system being assessed. Both questionnaires are subjective as they are self-answered, reflecting opinions. Nevertheless, they can provide valuable insights when combined with qualitative data.

Importantly, before all this, students completed a pre-test to assess their prior knowledge of light propagation and reflection concepts. A final post-test, identical to the pre-test, was used at the end to detect any cognitive improvement.

4.3 Summative Evaluation

The students played the game, reaching the tenth level without requiring any support from the facilitator. As the game became more challenging, all students collaboratively overcame difficulties within their teams. They employed a variety of problem-solving strategies that evolved as the difficulty increased. In the initial levels, students primarily used a trial-and-error approach, rotating the mirrors randomly. At intermediate levels, they began to formulate action plans before adjusting the mirrors. At advanced levels, students demonstrated the ability to analyse the light's trajectory and anticipate multiple sequential reflections across several mirrors. They articulated hypotheses regarding the light's path and evaluated possible outcomes before taking action, reflecting a gradual refinement of their strategic thinking.

After playing the game, the children shared feedback. Most were unfamiliar with the SUS and QUIS instruments. Nevertheless, about half of them completed the questionnaires independently, with little or no support from the facilitator. Eighteen children completed the questionnaire with the facilitator, who read each item aloud and rephrased it to help children understand the questions and context in a short, conversational manner. Five children struggled and gave random answers. Although these children offered positive comments in the open-ended questions, it is unclear whether their enthusiasm was genuine or merely a reaction to the positive remarks of their peers. Consequently, their answers were excluded from the calculation of both the SUS and QUIS scores.

Table 3 presents the SUS results of the 39 participants. The vast majority (about 92%) achieved a total score above 68, indicating good usability. Only three children scored lower (65–67.5). All three also displayed relative indifference towards the game, as revealed by think-aloud observations and open-ended responses. One of them found the game easy, yet still needed help from teammates. The second child found the game difficult. The third could not decide how often they would play and whether the game was complicated, and was confused over the "consistency" items, which contributed to a 67.5 score. Overall, about 36% of participants scored 72.5–80, 31% scored 82.5–90, and 23% scored 92.5–100. The mean SUS score across all 39 responses was 83.53.

Table 3: Summary of the SUS Questionnaire results

SUS Score	**65 – 70**	**72.5 – 80**	**82.5 – 90**	**92.5 – 100**	**83.53**
Number of participants	4 (10.2%)	14 (35.9%)	12 (30.8%)	9 (23.1%)	Overall SUS Score

Figure 4 presents ten pie charts, showing the distribution of responses per question. Most children (32, 82%) said they would like to play the game frequently. Six (15%) were unsure about the game's complexity, and only three were uncertain whether it was easy to use (Q3), consistent with observations that most children comprehended the gameplay quite easily after experimenting with the first two or three levels. Uncertainty was likewise low regarding whether they would need help: only two students were unsure whether they would require assistance from a more experienced player (Q4). About one-third (12) could not judge the game's consistency (Q5, Q6), and 23% (9) hesitated when rating its difficulty (Q7, Q8). However, most of those participants played the game with little to no significant support from their peers. About 30% of the participants (13) were not sure how confident they felt when making their moves in the game and how much they needed to learn before playing confidently (Q9, Q10). Even though the questions referred to learning the gameplay, many seemed to initially interpret them as relating to learning about light. In retrospect, those questions could be simplified further to make communication with children more effective. Nevertheless, with the support of the facilitator, 69% of the participants grasped the intended meaning and reported feeling that they knew what they were doing when playing the game, a finding also reflected in the qualitative results.

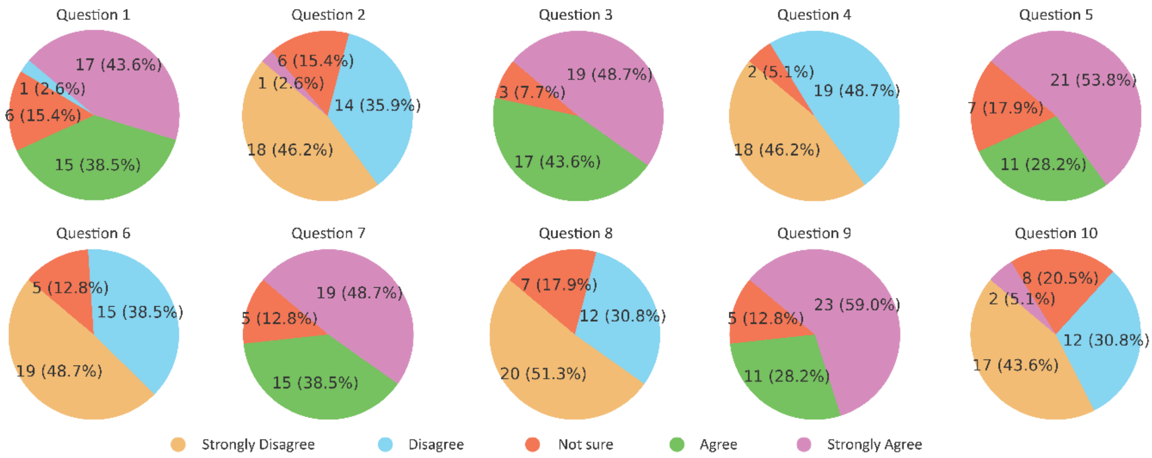

Figure 4: Participants' responses per SUS question

Table 4 summarises the QUIS questionnaire results: the mean score of all participants per question, the mean of question scores for each category, and the mean of all questions as an overall QUIS score. Category B (screen), which mainly addresses readability, indications, navigation, and layout, earned the highest mean score of 7.92, closely followed by Category C (terminology and information regarding the state of the game – terms, positions, actions, progress) with 7.88. Category A (overall reaction to the game), which addresses key aspects such as ease of use and user control, scored 7.84. Categories D (learning the game) and E (game capabilities) scored 7.81 and 7.66 respectively, largely because several participants chose the neutral midpoint (5) when unsure. Misinterpretation of learnability related items, which were largely understood as referring to physics content rather than interface mastery, also affected Category D scores. The overall mean score across all 27 questions was 7.82.

Table 4: QUIS questionnaire results per question, category and overall score

Category	**A**		**B**		**C**		**D**		**E**		
Question Score	Q1	7.77	Q7	7.87	Q11	8.00	Q17	7.87	Q23	7.69	Overall
	Q2	7.62	Q8	8.03	Q12	7.82	Q18	7.97	Q24	7.51	QUIS
	Q3	8.03	Q9	8.00	Q13	7.82	Q19	7.95	Q25	7.74	Score
	Q4	7.74	Q10	7.77	Q14	7.87	Q20	7.67	Q26	7.56	
	Q5	7.92			Q15	7.79	Q21	7.82	Q27	7.79	
	Q6	7.97			Q16	7.95	Q22	7.59			7.82
Category Score		7.84		7.92		7.88		7.81		7.66	

The responses to the open-ended questions regarding students' perceptions of the positive and negative aspects of the game were documented and compiled in Table **5**, highlighting the most frequently mentioned points.

Table 5: Open-ended questions replies

Open-ended questions	**Mentions**
1. Which feature of the game, in your opinion, is the best (liked or found most impressive)? why?	
Colors and music	21
That our goal was the candies	9
The fact that there were "traps"	7
2. Which element of the game, in your opinion, could be improved (did not like or found confusing)? why?	

Open-ended questions	Mentions
There are not many moves at some levels	6
That level 9 was difficult for us to solve	5
The fact that mirrors would rotate only to one direction	4
3. More thoughts and comments?	
There could be time limit	3
There could be bigger consequences when you lose. For example, to have less moves	2

Qualitative insights enriched the questionnaire data and exposed specific issues in how children interpreted some items. Children's self-reports on interface consistency, learnability, and difficulty proved less reliable than observational evidence: several students did not grasp the idea of consistency, and some confused the game's learnability with learning the underlying lesson or interface difficulty with gameplay difficulty. Additionally, technical aspects such as system speed and reliability are likewise better assessed by adult testers than by children.

An additional remark is that the children found level 9 to be the most difficult, exactly as intended (Table 2). Nine pairs discovered two solutions at least once, especially after sharing their experience with other children. Sixteen students asked for additional levels.

Last but not least, the comparison of the pre-test and post-test results revealed a shift in the students' cognitive performance regarding basic concepts of light propagation and reflection (Baziakou, Tsita & Dimitracopoulou, 2025, in press), confirming that the game strengthened students' conceptual understanding.

5. Conclusion

Unlike most educational game studies that mainly focus on learning outcomes, this work reports on a game design approach that equally values the anticipated experience. Based on requirements for serious educational games, it presents the game design decisions and the evaluation results in terms of usability and user satisfaction, linking the anticipated cognitive gains with the user experience.

By transforming abstract physics concepts into tangible, interactive elements, the proposed game can support learning while acknowledging children's pre-existing misconceptions about light propagation and reflection. Its puzzle format encourages players to formulate hypotheses and test them, while the gradual introduction of rules and increasing difficulty supports problem-solving. The game has a simple and engaging story and goal. The mechanics and feedback are clear and intuitive. The game is low-cost and accessible, and it allows social interaction through collaboration.

The results indicate that the game offered a high-quality experience and proved to be appealing and engaging to its main audience, validating the initial design decisions. All children understood the gameplay while collaborating in pairs without adult assistance. The game was well received in the school setting, and no feature posed any issues for classroom use.

Combining the think-aloud protocol with the SUS and QUIS questionnaires yielded insights not only into the game itself but also into how children perceived the evaluation process, revealing that nearly half of them needed support to provide their feedback. At the same time, items related to the consistency, learnability and difficulty of the game as an interface should be better communicated to children to provide more reliable feedback.

Because of its simplicity, the game can be used as educational material to introduce fundamental physics concepts, spark interest and engagement, probe prior knowledge, or reinforce previously learned material.

Ethics declaration: Consent was obtained from all adult participants and the parents of students according to the University of the Aegean procedures for informed consent.

AI declaration: ChatGPT was used for grammar and spelling check

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Appendix 1: SUS Questionnaire

SUS Questionnaire adapted for the game, based on SurveyLab version. (Figure 5)

No.	Question	1-Strongly Disagree, 2-Disagree, 3-Not sure, 4-Agree, 5-Strongly Agree				
		1	2	3	4	5
1	I think that I would like to play this game frequently.					
2	I found the game unnecessarily complex.					
3	I thought the game was easy to use.					
4	I think that I would need the support of a more experienced player to be able to play this game.					
5	I found the various functions in this game were well integrated.					
6	I thought there was too much inconsistency in this game.					
7	I would imagine that most people would learn to play this game very quickly.					
8	I found the game very cumbersome to use.					
9	I felt very confident playing the game.					
10	I needed to learn a lot of things before I could get going with this game.					

Figure 5: SUS Questionnaire

Appendix 2: QUIS Questionnaire

QUIS Questionnaire adapted for the game (Chin et al., 1988) (Figure 6)

A. Overall reaction to the game			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
1		terrible										wonderful
2		difficult										easy
3		annoying										satisfying
4		inadequate control										adequate control
5		dull										stimulating
6		rigid										flexible
B. Screen			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
7	Reading text on the screen	hard										easy
8	Highlighting simplifies the game	not at all										very much
9	Organization of information	confusing										very clear
10	Sequence of screens	confusing										very clear
C. Terminology and information regarding the state of the game			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
11	Same terms throughout system	inconsistent										consistent
12	Words used describe gameplay clearly	never										always
13	Position of messages on screen	inconsistent										consistent
14	The interactive objects and buttons	confusing										clear
15	The player's progress	not evident										evident
16	Failure messages	unhelpful										helpful
D. Learning the game			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
17	Learning how to play the game	difficult										easy
18	Exploring the game by trial and error is	difficult										easy
19	Remembering what the objects and buttons of the game do	difficult										easy
20	The goal of the game is clear	never										always
21	Informing messages on the screen	unhelpful										helpful
22	Supplemental explanatory materials	necessary										unnecessary
E. Game capabilities			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
23	Speed – of application using tablet	slow										smooth
24	Reliability – how the game response to my actions	unreliable										unreliable
25	The game tends to cause	anxiety										calm
26	Continue playing after a mistake	difficult										easy
27	Game felt designed for both experienced and inexperienced students	never										always

Figure 6: QUIS Questionnaire