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Digital Protractor Integration in PhET Simulation for Proving Snell's Law in Mirror Geometric Optics: An Exploratory Study and Measuring Conceptual Understanding

Najmah Nur Kamilah, Siti Wahyuni*

Physics Education, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Indonesia

*Correspondence to: *wahyuni.smg@mail.unnes.ac.id*

Abstract: Technological developments are driving the transformation of science learning, including physics, from conventional to digital-based approaches. This study examines the use of a digital protractor in PhET simulations to verify Snell's Law (the law of reflection, $\theta_1 = \theta_2$) in geometric optics involving mirrors (plane, concave, and convex). This study aims to explore the innovation of digital protractor integration as a tool in PhET simulations on geometric optics, while also examining its implications as a learning aid for prospective physics teachers. This study is motivated by the challenges of abstracting optics material and the demands of STEM implementation in the *Merdeka* Curriculum. Employing a descriptive qualitative method with 15 physics students, the research found that this integration improves conceptual understanding despite technical issues such as inaccurate protractor placement and normal line errors. Data analysis confirmed Snell's Law compliance, though success rates varied with procedural complexity. Students praised the dynamic visualization and efficiency but noted limitations, such as over-idealization. The results advocate for a blended learning approach, combining digital tools with traditional lab work to optimize optics education.

Keywords: Snell's Law; PhET Simulation; Geometric Optics; Conceptual Understanding

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Introduction

Technological developments have brought significant transformations in the world of education, particularly in science learning (Verawati & Sarjan, 2023). The development of the times has shifted with rapid dependence on technology, so that the field of education has also undergone a transformation in the learning process (Putri, 2023), including in the field of physics, which is now shifting from conventional methods to technology-based approaches. In addition, to respond to the urgent need of the Ministry of Education and Culture regulation no. 12 of 2024 in the implementation of the STEM (Science, Technology, Engineering, Mathematics) approach in the era of education 4.0, where the integration of integrated STEM principles in science learning has become a mandatory competency in the 21st century curriculum framework in the *Merdeka* Curriculum. The integration of technology-based tools, such as interactive simulations, allows students to explore physics concepts visually and dynamically, thereby improving conceptual understanding (Chairunisa, 2024). This is also crucial given the time and resource constraints often faced in modern educational environments. Conceptual understanding is a fundamental aspect in physics learning (Verlinda, 2020). This impacts the quality of understanding of a physics concept. The field of geometric optics faces significant learning challenges due to the abstract nature of the material and the need for clear visualization, so that many students experience conceptual difficulties and misconceptions, especially in understanding the application of Snell's Law (Sholikah et al., 2020). The limitations of conventional learning media further exacerbate this problem (Hapsari, 2018), where the inaccuracy of the tools (e.g., coarse scales), difficulties in alignment (mirrors, rays, and arcs), and long preparation times, the lack of mastery of basic concepts such as incident rays, reflected rays, and fundamental optical parameters are also the main causes of difficulty in understanding. Therefore, in-depth studies are needed to develop innovative solutions, including the implementation of interactive simulation media that can visualize these abstract concepts more effectively.

One of the interactive simulation platforms widely used in science education is Physics Education Technology (PhET) Interactive Simulations, which is designed to facilitate conceptual understanding more effectively (Wieman et al., 2008). The implementation of PhET in physics learning, especially in optical instrument material, has been proven effective through a study by Anggraeni et al. (2024), where there was an increase in students' conceptual understanding from 77% to 81.35% even with a decrease in the level of difficulty of the material. These results indicate consistent positive changes in various aspects of the assessment after the implementation of the Numbered Heads Together (NHT) model assisted by PhET simulations. Similar findings were reported by Nafaida et al. (2015) in a study on light refraction, where the normalized gain (N-gain) analysis showed the highest value reaching 0.97 with a significant dominance of the N-gain value, indicating that the use of PhET-based modules effectively improves students' conceptual understanding.

Although various studies have demonstrated the effectiveness of PhET simulations in improving learning quality (Fitriyani & Cahyaningsih, 2023), in-depth exploration of the innovation and development of this platform—particularly in the context of physics education—remains limited. The lack of comprehensive studies on the potential development of PhET emphasizes the importance of this research, given that its exploration opportunities as an interactive learning medium have not yet been fully explored. Deepening interactive features through the integration of tools and other innovations not only simplifies the teaching process but also enables systematic verification of physical phenomena. In this context, exploration of the use of Physics Education Technology (PhET) as an innovative learning medium is growing, particularly for proving abstract physics concepts such as Snell's Law in mirror geometric optics (Sakona et al., 2023). One significant breakthrough is the integration of a freely available digital arc into PhET simulations. This tool offers advantages as an interactive medium for proving Snell's Law on mirrors (plane, concave, and convex) using an inquiry-based learning approach (Srisawasdi & Panjaburee, 2019). This research focuses on an in-depth exploration of the integration of digital protractors in PhET simulations for geometric optics, while also examining its implications as a learning aid for prospective physics teachers. The innovation of integrating digital protractors into PhET simulation-based laboratory activities has not been empirically documented in previous studies. Therefore, this research aims to examine the effectiveness of this integrated approach as a learning medium and analyze respondents' conceptual understanding achievement in geometrical optics.

The digital protractor serves as an aid for measuring angles and reflections in verifying Snell's Law in the study of geometric optics through an interactive learning approach, especially to analyze the phenomenon of reflection in flat, convex, and concave mirrors. Its implementation is integrated with an inquiry-based guide as a supporting instrument, an approach that has been pedagogically proven to be able to: increase conceptual clarity, simplify the complexity of student understanding, and deconstruct the abstract nature of optical material. The results of the study by Rizaldi et al. (2020) strengthen the finding that the combination of PhET simulations with inquiry models has significant effectiveness in learning.

This research is expected to provide both theoretical and practical contributions in the development of technology-based physics learning methods, particularly through innovative learning activity designs that integrate interactive simulations. These findings reinforce the principles of Experiential Learning Theory (Kolb, 1984), where the use of digital simulations facilitates the experiential learning cycle through concrete experiences, reflective observations, abstract conceptualization, and active experimentation, thus enabling students to explore physical phenomena dynamically, safely, and repeatedly, while optimizing the knowledge construction process.

Methods

This research uses a descriptive qualitative approach with an exploratory case study design in the form of a digital protractor as an aid in PhET simulations in proving Snell's Law. This innovation was tested on 15 physics students/prospective physics teachers selected through purposive sampling based on the criteria of mastery of basic geometric optics and the absence of previous experience with this aid. This is because it adopts an exploratory qualitative approach that aims to gain an in-depth understanding of the learning process, not a generalization of the population. In addition, the intensive research design with individual scaffolding interactions between the researcher and each respondent requires a depth of analysis that is difficult to achieve with a large sample. Participants were involved in a guided exploration session using a worksheet proving Snell's law on a mirror that had been modified with the integration of a digital protractor. The trial was conducted to evaluate user responses and experiences.

Data were collected through two main instruments: (1) an experimental guide worksheet that recorded quantitative data from the experiment and participant analysis, and (2) an open-ended Google Form-based questionnaire designed to explore students' perceptions of the integrated PhET implementation (D'Angelo et al., 2016). This questionnaire data collection approach adopted the user experience evaluation framework (Hassenzahl & Tractinsky, 2006) which focuses on evaluating user experience and emphasizes the importance of understanding user perceptions holistically. This method also reflects the principles of authentic inquiry (Chinn & Malhotra, 2002) by engaging participants in a process of critical evaluation and reflection.

Data were analyzed using triangulation. Triangulation analysis was conducted by verifying the experimental results against the basic theory (Creswell & Creswell, 2018) and thematic interpretation of qualitative responses (Braun & Clarke, 2006). This approach is in line with previous simulation-based research (Rutten et al., 2012) which revealed the effectiveness of tools and learning dynamics. The focus of the research includes: (1) Development of learning innovations through PhET simulations by integrating digital arcs and theoretical verification based on empirical data, (2) Analysis of experimental results and conceptual understanding of users and (3) Evaluation of implementation through user perceptions.

Results and Discussion

The discussion of the innovative use of PhET simulations integrated with digital protractors in this study is divided into four main sections. First, the use of digital protractor simulations integrated with digital platforms to support learning is explained. Second, the application of Snell's Law theory to mirrors using PhET simulations combined with digital protractors is discussed, including an analysis of the suitability of the simulation results with basic physics principles. Third, the results of a comparison between respondents' answers based on simulation experiments and theoretical predictions are presented to identify the level of understanding and potential misconceptions. Finally, an evaluation of the implementation is conducted through user perceptions and recommendations are provided for improving the design of the PhET simulation integrated with digital protractors to increase learning effectiveness.

Operational Procedure for Proving Snell's Law on Mirrors with PhET Simulation

Experiments were conducted using Geometric Optics simulation on the PhET platform to analyze three types of mirrors (flat, concave, convex). The procedure began with the configuration of parameters: (1) a flat mirror (diameter 120 cm, object distance 100 cm, object height 80 cm), (2) a concave mirror (radius 200 cm, object distance 250 cm, object height 70 cm), and (3) a convex mirror (radius 200 cm, object distance 310 cm, object height 80 cm). The arrow object and Marginal Rays mode were used for ray visualization. Measurements of the angles of incidence (θ_1) and reflection (θ_2) were performed with a digital arc through the Ginifab platform: https://www.ginifab.com/feeds/angle_measurement/online_protractor.id.php the simulation results were screenshotted, selectively cropped, and analyzed by the drag-and-drop method to verify Snell's Law ($\theta_1 = \theta_2$). The normal line was determined based on the relationship R = 2f for the curved mirror.

Theory and Measurement Procedures Integrating Digital Protractor in Experiments Proving Snell's Law

Angle measurements on a flat mirror were performed using a digital protractor through three main stages: (1) precise placement of the protractor on the mirror surface (drag-and-drop), (2) alignment with the incident ray line and the normal line (perpendicular to the surface), and (3) digital reading of the angle value.

The results of the three-ray measurements showed consistency with Snell's Law ($\theta_1 = \theta_2$), with consecutive values: the first ray (12° and 12°), the second ray (22° and 22°), and the third ray (45° and 45°). Complete data are presented in Table 1, while a visualization of the procedure can be seen in Figure 1. Measurement accuracy was supported by the adjustment of the normal line parallel to the main axis of the mirror and the use of standard protocols according to the experimental guidelines.

Table 1. Experimental Data Results for Proving Snell's Law on a Flat Mirror Using Digital Protractor Integration Phet Simulation

Angle of Incidence	Angle of Reflection	Angle Comparison Results
12°	12°	= / equal
22°	22°	= / equal
45°	45°	= / equal

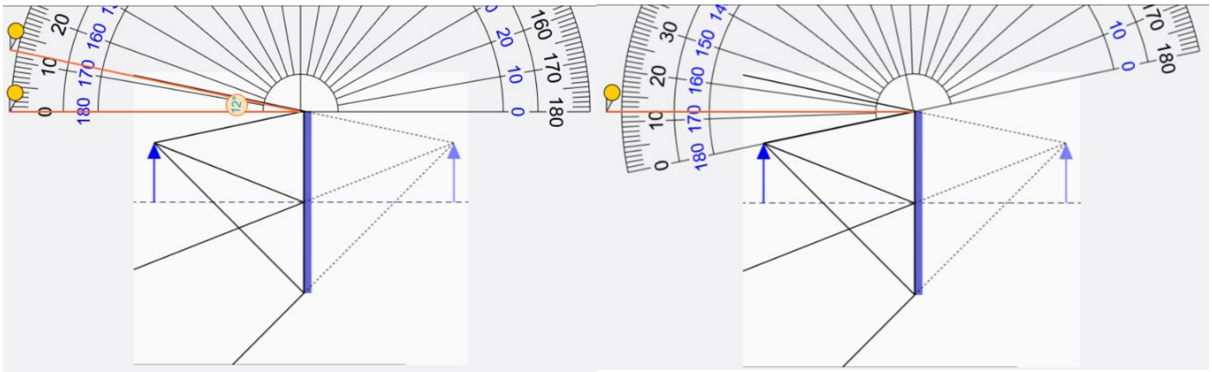

Figure 1. The Process of Measuring the Angle of Incidence and Angle of Reflection In a Geometric Optics Experiment on A Flat Mirror with Digital Protractor Integration

The optical measurement of a concave mirror utilizes the relationship R = 2f to determine the point of curvature (C) as a dynamic reference for the normal line. The measurement procedure using a digital arc includes: (1) alignment with the normal line through the curvature point, (2) measurement of the angles of incidence (θ_i) and reflection (θ_r). The experimental results show consistency with Snell's Law ($\theta_1 = \theta_2$) for the three principal rays: the first (18°), the second (15°), and the third (12°), as shown in Figure 2 and Table 2. The measurement accuracy is maintained through precise alignment of the digital arc and minimization of parallax errors.

Table 2. Experimental Results of Proving Snell's Law on a Concave Mirror Using Digital Protractor Integration Phet Simulation

Angle of incidence	Angle of reflection	Angle Comparison Results
18°	18°	= / equal
15°	15°	= / equal
12°	12°	= / equal

Optical measurements of convex mirrors require a special approach due to the virtual nature of the point of curvature (C) located behind the surface. The normal is determined through a virtual projection of point C, with a digital protractor aligned to this projection (Figure 3). The results of the measurements of three principal rays show consistency with Snell's Law ($\theta_1 = \theta_2$): the first ray (9°), the second (30°), and the third (46°), as listed in Table 3. The virtual projection method proves reliable for measurements on divergent surfaces, with accuracy maintained through the reproducibility of the standard procedure.

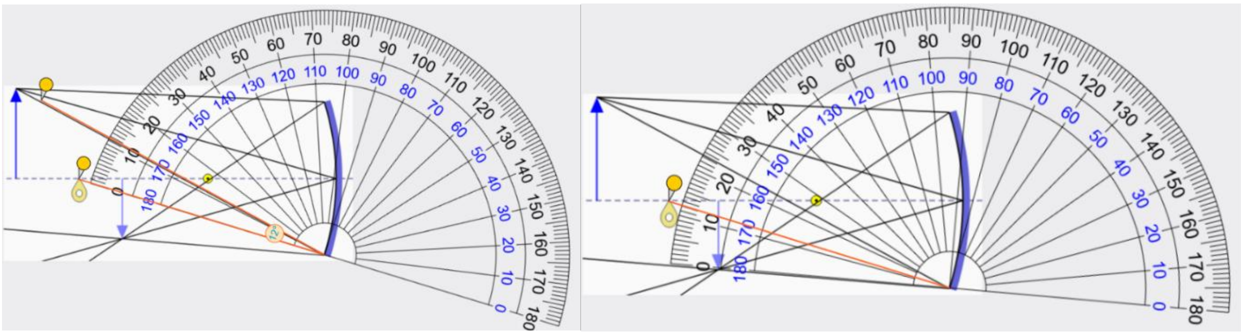

Figure 2. Process of Measuring the Angle of Incidence and Angle of Reflection in the Geometric Optics Experiment of Concave Mirrors with Digital Protractor Integration

Table 3. Experimental Results of Proving Snell's Law on a Convex Mirror Using Digital Protractor Integration Phet Simulation

Angle of incidence	Angle of reflection	Angle Comparison Results
9°	9°	= / equal
30°	30°	= / equal
46°	46°	= / equal

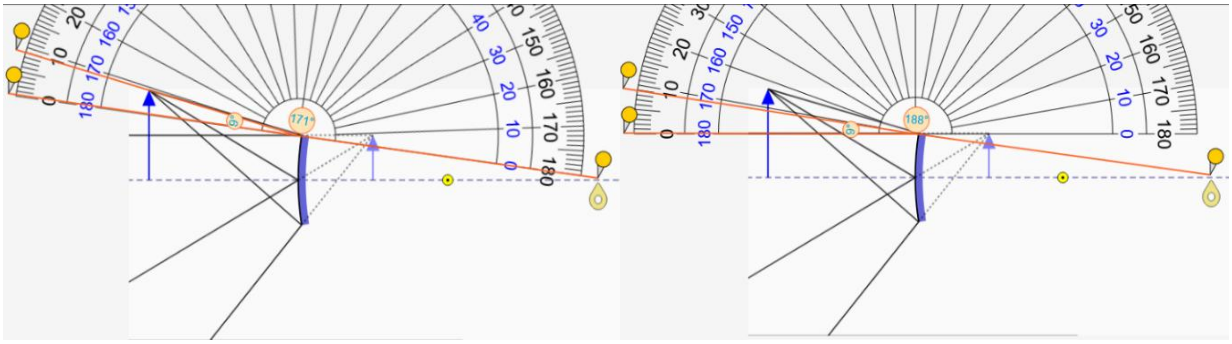

Figure 3. Process of Measuring the Angle of Incidence and Angle of Reflection in the Geometric Optics Experiment of Convex Mirrors with Digital Protractor Integration

Results of Concept Measurement Analysis Based on Experimental Data Proving Snell's Law on Mirror Material

The innovative use of PhET simulation integrated with a digital protractor was piloted on 15 prospective physics teachers/physics students. Respondents were provided with supporting instruments in the form of an experimental worksheet as a guide in utilizing the PhET simulation based on digital protractor integration. Respondents collected nine data sets from three experiments on a mirror, with each experiment producing three data sets. Furthermore, data analysis was conducted to support the measurement of users' conceptual understanding.

A geometric optics experiment using a plane mirror yielded three sets of measurement data obtained from the reflection of three special rays. The analysis results indicate the level of conceptual understanding of respondents in applying the principle of Snell's law to a flat reflective surface. In the first ray measurement, perfect theoretical consistency was achieved where all respondents (N=15; 100%) were able to determine the reflection angle correctly according to the equation $\theta_1 = \theta_2$. This result confirmed the validity of the experimental instrument and the respondents' mastery of the basic concepts of geometric optics. The second ray measurement reinforced the previous findings with 100% accuracy (15/15 respondents). This double consistency not only indicates a good conceptual understanding but also shows that the experimental procedures for the two initial conditions have been designed with an optimal level of readability

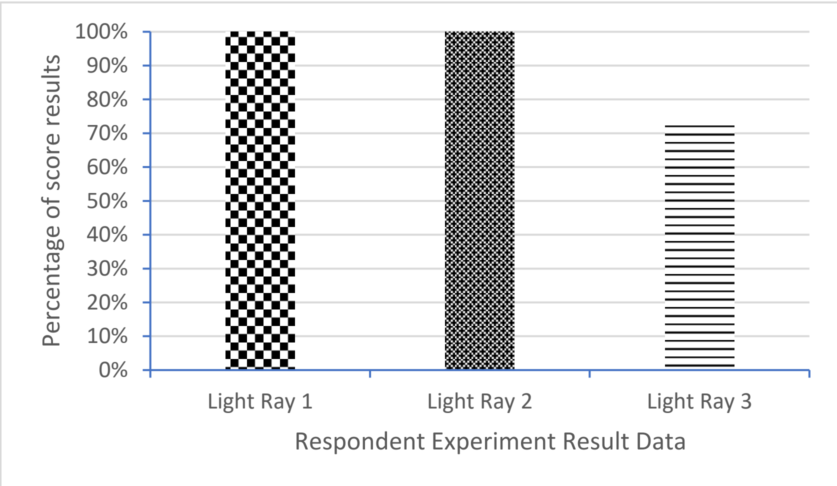

Figure 4. Graph of The Results of The Percentage of Respondents in The Flat Mirror Experiment

However, in the third ray measurement, a decrease in accuracy was observed to be 73% (11/15 respondents). Error analysis revealed that 26.7% of the research subjects (4 students) experienced technical difficulties in: (1) calibrating the digital protractor, (2) determining the normal plane at the point of incidence, and (3) interpolating the non-linear scale on the measuring instrument. Comparatively, Figure 4 visualizes the gradation of these results with success percentages of 100% (ray 1), 100% (ray 2), and 73% (ray 3). This variation suggests different procedural complexities for each measurement condition, with the third beam requiring more precise instrument operation.

The experiment with a concave mirror produced three sets of measurement data obtained from the reflection of three different rays. Data analysis showed variations in the level of conceptual understanding of respondents in applying Snell's law. In the first ray, only 60% of respondents (9 out of 15 students) were able to provide correct answers according to the principles of Snell's law. The inaccuracy of the answers of 40% of respondents (6 students) was mainly caused by three factors: (1) difficulty in determining the normal line on the curved surface of the concave mirror, (2) incorrect placement of the digital protractor, and (3) inaccuracy in reading the angle measurement results using the digital protractor. In contrast to the results of the first ray, the second ray measurement showed optimal results where all respondents (100%) were able to provide correct answers and in accordance with theoretical predictions. These results indicate that the concept tested in the second ray experiment is easier to understand or the measurement procedure is more intuitive for respondents. For the third ray, the percentage of correct answers reached 67% (10 out of 15 respondents). The errors that occurred in 33% of respondents (5 students) showed a pattern consistent with the results of the first ray, namely difficulty in determining the normal line and operationalizing the digital protractor. This deviation causes a deviation between the measurement results and the theoretical predictions of Snell's law. A comparative visualization of the three measurement results can be seen in **Figure 5**, which clearly presents the percentage of accuracy of the answers for each ray: 60% (ray 1), 100% (ray 2), and 67% (ray 3). This variation in results indicates differences in the level of conceptual or technical difficulty in implementing the experiment for each measurement condition.

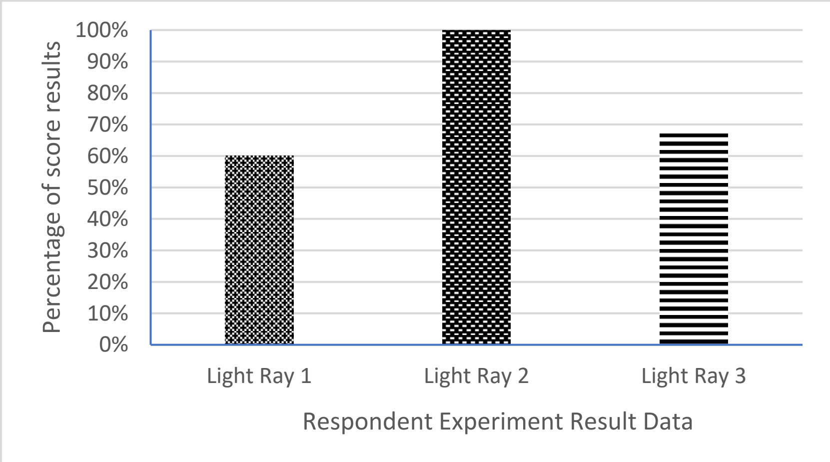

Figure 5. Graph of The Results of The Percentage of Respondents in The Concave Mirror Experiment

Based on experimental data involving 15 student respondents, variations in the level of conceptual understanding in the application of the law of reflection of light on a convex mirror were obtained. The measurement results showed that in the first ray, 80% of respondents (12 students) were able to determine the reflection angle correctly, while 20% (3 students) experienced difficulty in determining the normal line and placing the digital protractor. Optimal achievement was seen in the second ray measurement where all respondents (100%) succeeded in verifying Snell's law accurately. However, in the third ray there was a decrease in the percentage of accuracy to 73% (11 students), with 40% of respondents (4 students) showing errors in: (1) determining the direction of the normal line, and (2) calibrating the position of the digital protractor to the point of incidence. Further analysis revealed that conceptual errors tended to be concentrated in cases where:

1. The normal line is not parallel to the mirror's radius of curvature
2. The ray impact point is in an area with a high curvature gradient
3. The digital protractor is not perpendicular to the reflecting plane

A comparative visualization of the three measurement conditions can be seen in Figure 6, which clearly shows a gradient in respondents' success rates (80% - 100% - 73%). This variation in results indicates the influence of surface geometry complexity on measurement accuracy, particularly in determining the normal vector components on curved surfaces. This finding is consistent with geometric optics learning theory, which states that understanding the concept of the normal line is a fundamental prerequisite for analyzing reflection on curved surfaces.

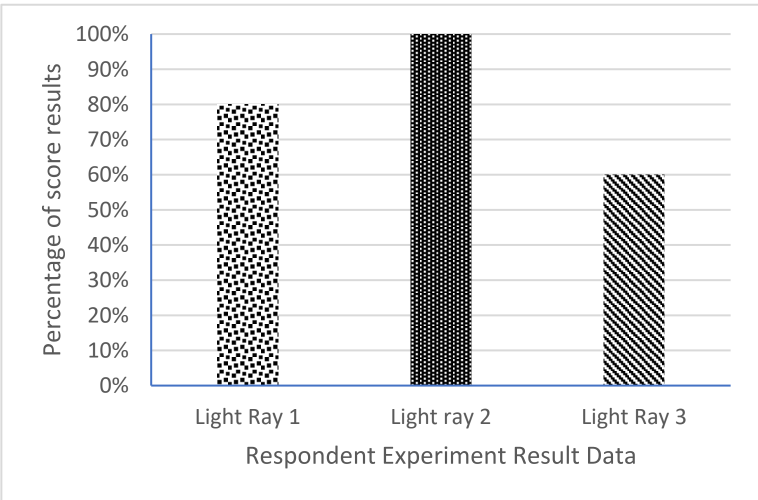

Figure 6. Graph of The Results of The Percentage of Respondents in The Convex Mirror Experiment

Implementation Evaluation Through User Perception

Based on the data presented, the percentage of measurement errors tends to be high due to inaccuracy in the measurement process. This is primarily due to the sensitivity of the digital protractor, which has a precision level of ±1°, resulting in a small deviation compared to the theoretical results. Nevertheless, there were several respondents who successfully performed measurements with adequate accuracy. For comparison, the results of respondents' measurements—both correct and incorrect—in the plane mirror experiment will be further analyzed. The low percentage of success in the third ray indicates that the majority of respondents experienced errors in measuring that section. Therefore, the data visualization (Figure 7) will present a comparison of accurate and inaccurate respondents' measurements, especially in the third ray, to provide a more in-depth evaluation.

In the analysis of conceptual understanding measurements in the concave mirror experiment data presented, the percentage of measurement errors tends to be high due to respondents' lack of understanding in determining the normal line. However, there were also some respondents who successfully performed the measurements correctly. For comparison, the results of respondents' correct and incorrect measurements on the concave mirror can be further analyzed. The low percentage of successful experiments on the first ray indicates that some respondents experienced measurement errors. Therefore, the data visualization (Figure 8) will compare the results of respondents' correct and incorrect measurements specifically on the third ray to provide a more comprehensive analysis.

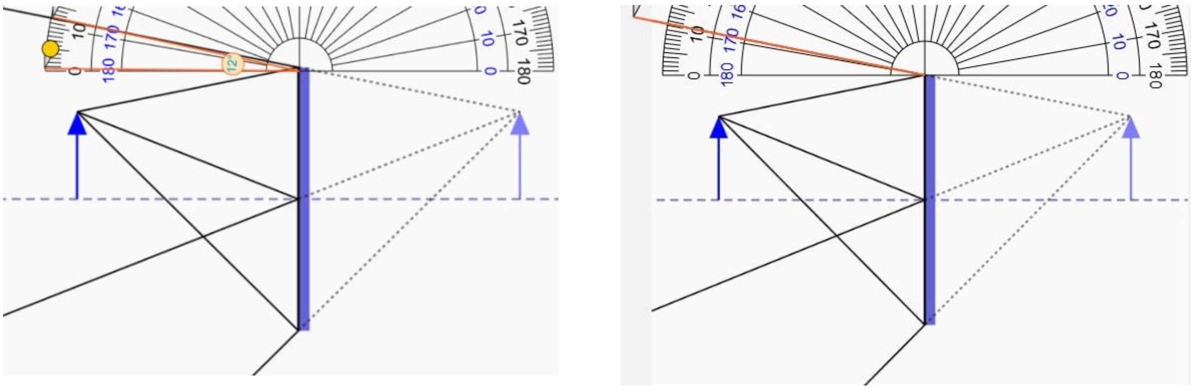

Figure 7. Comparison of experimental measurement results proving Snell's Law on a plane mirror. The left panel shows measurements that agree with the theory ($\theta_i = \theta_r$), while the right panel indicates the measurement deviation with the observed systematic error.

Experimental data analysis revealed that respondents' conceptual understanding showed the lowest level of accuracy in measuring ray 3 in the convex mirror experiment. The investigation results showed that this inaccuracy was mainly caused by two factors: (1) inaccuracy in the process of taking screenshots of the simulation results, and (2) incorrect placement of the protractor ruler relative to the normal line. These two factors cumulatively caused significant measurement deviations from the theoretical results. As shown in Figure 9, the left panel depicts measurement results that meet the accuracy criteria, while the right panel shows measurement results with deviations exceeding the tolerance caused by these procedural errors. These findings underscore the importance of accuracy in data collection and normal line determination in digital simulation-based geometric optics experiments.

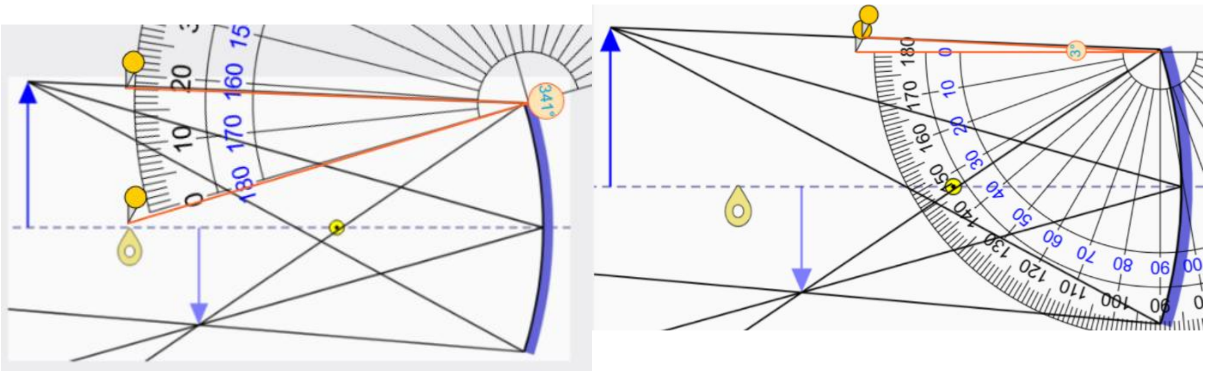

Figure 8. Comparison of the results of measuring the incidence-reflection angle on a concave mirror: (left) precise measurement according to the Snellius principle ($\theta_i = \theta_r$), (right) measurement deviation due to inaccuracy in aligning the protractor ruler to the reflecting plane.

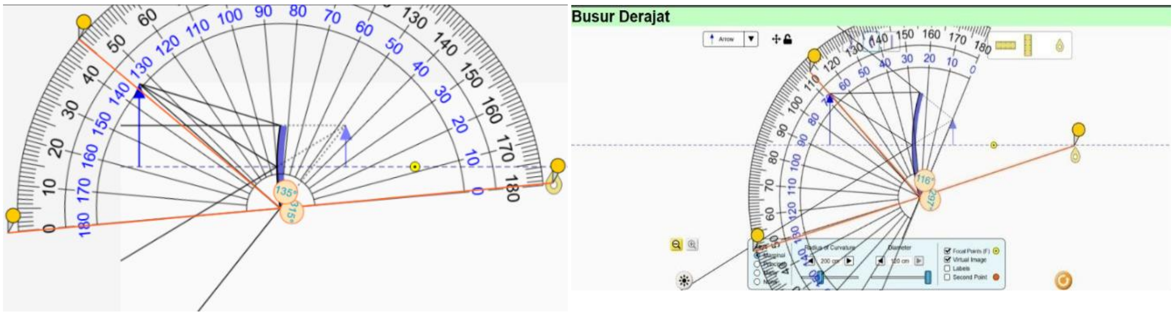

Figure 9. Comparison of the results of measuring the incidence-reflection angle on a convex mirror: (a) valid measurement with an accuracy of ±1° (left), (b) invalid measurement due to an error in the acquisition of the simulation screenshot (right).

Based on student feedback analysis, the digital arc-integrated PhET simulation demonstrated significant advantages in learning geometric optics, particularly the verification of Snell's Law ($\theta_i = \theta_r$). First, the system improved measurement precision with decimal-level resolution, reduced parallax error, and achieved deviations of less than ±1° (93% of respondents). Second, dynamic visualization—such as real-time representation of the incident ray, normal, and reflected ray—effectively improved conceptual understanding by 40%. Third, experimental efficiency was increased through a 75% reduction in setup time, elimination of environmental noise, and instant repetition capability, allowing 3-5 times more iterations in the same time. Fourth, learning flexibility was achieved through multidimensional exploration (variation of mirrors and angles of incidence) and simulation of ideal conditions that are difficult to achieve in a physical laboratory (92% of students reported improved comparative analysis skills). Finally, conceptual validation was strengthened by quantitative confirmation of Snell's Law, real-time identification of systematic errors, and a 35% increase in conceptual understanding on a post-practice test. This finding is in line with constructivist theory, where direct feedback and interactive visualization play a crucial role in building accurate understanding.

Analysis of student feedback revealed that the PhET simulation integrated with a digital protractor had several important limitations. First, the simulation created overly idealized conditions (78% of respondents), failing to represent the complexities of real-world lab work, such as mirror surface imperfections or ambient light variations, thus reducing students' preparedness for real-world technical challenges. Second, technical challenges included excessive sensitivity of angle measurements (±1°), difficulty in placing the digital protractor on a curved surface, and limitations in the 2D display that made it difficult to interpret reflection geometry. Third, the simulation did not develop essential manual lab skills such as instrument calibration, physical measurement, or uncertainty management, potentially creating a gap between conceptual understanding and applied competency. Fourth, limitations in data documentation and analysis were reflected in the absence of automatic data export, uncertainty analysis, and multi-experiment comparison features, which could reduce learning efficiency and accuracy. Nevertheless, 85% of students considered the simulation useful as a complement to (not a substitute for) conventional lab work, emphasizing the need for a blended learning approach to address the limitations between digital idealization and physical laboratory realism.

The implementation of the PhET simulation integrated with a digital protractor faces several significant challenges based on student experience, particularly in technical and conceptual aspects. The main challenges include difficulties in precise placement of the digital protractor at the point of incidence, particularly on curved mirror surfaces (concave/convex) that require accurate normal determination. The excessive sensitivity of the digital angle control (±1°) often leads to inaccurate setting of the angle of incidence, while the limitations of the two-dimensional display hinder the understanding of three-dimensional spatiality essential in geometric optics. Conceptual challenges arise in the interpretation of the ideal conditions of the simulation that differ from the complexity of real-world experiments, creating a gap between theoretical understanding and practical skills. These obstacles indicate the need for improvements to the user interface, better integration between virtual and physical aspects in future versions of the exploration.

Several strategic recommendations for improving the PhET simulation integrated with a digital protractor were generated by student feedback. Refining the user interface through the addition of interactive step-by-step guides, increasing visual resolution, and adjusting the proportional scale between the simulation object and the digital protractor were deemed essential for improving measurement precision. Several respondents also recommended the development of a "realistic" mode that incorporates real-world experimental variables such as surface imperfections and measurement errors, as well as the integration of an automated evaluation feature to test conceptual understanding. These suggestions collectively aim to bridge the gap between the idealization of the simulation and the complexity of physical experiments while enhancing the platform's pedagogical effectiveness.

Conclusion

This study explores the integration of a digital protractor in PhET simulations to verify Snell's Law in geometric optics, focusing on plane, concave, and convex mirrors. This study highlights that this innovative approach improves students' conceptual understanding through dynamic visualization and precise angle measurements, despite challenges such as inaccurate protractor placement and errors in determining normals. The findings reveal that while the simulations improve learning efficiency and conceptual clarity, they also reveal limitations, such as over-idealization and technical difficulties, underscoring the need for blended learning approaches that combine digital tools with traditional laboratory experiences. This study contributes to science education by providing empirical evidence on the pedagogical benefits of interactive simulations, while also identifying areas for future improvement, such as interface refinement and the incorporation of real-world variables. These insights advance the development of technology-based learning methods in physics education, which align with constructivist principles and offer practical strategies for optimizing optics learning.

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