



A Study of Conceptual Understanding, Science Process Skills, and Representational Coordination through Guided Inquiry with Integrated Physical and Virtual Laboratories

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Abstract

This study examines changes in prospective physics teachers' conceptual understanding, science process skills, and representational coordination in light refraction learning following a guided inquiry design integrating real and virtual laboratories. The study employed a one-group pretest–posttest design with a concurrent embedded mixed-methods approach involving 15 prospective physics teacher students. Quantitative data were analyzed using the Wilcoxon signed-rank test and N-gain analysis, while qualitative data were examined through representational coordination coding, including visual-graphical, symbolic-mathematical, and verbal-textual representations. The results showed an increase in students' conceptual understanding, with average scores rising from 10.07 on the pretest to 21.80 on the posttest, as indicated by the Wilcoxon test result ($p < 0.05$). The average N-gain score of 0.79 falls within the high category of improvement. Science process skills also increased from 3.93 to 8.33 ($p < 0.001$), with an average N-gain of 0.73, which falls within the high category. Qualitative findings indicated a shift from predominantly verbal and fragmented explanations toward more varied representations and relatively more coherent conceptual structures. Overall, the findings suggest that the integration of real and virtual laboratories within guided inquiry was associated with changes in conceptual understanding, science process skills, and representational coordination among prospective physics teachers.

Keywords: Guided inquiry; Physical laboratories; Virtual laboratories; Optics geometric; Representational coordination

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INTRODUCTION

Experiential learning is an important feature of physics education to increase conceptual understanding and scientific process skills (Idris et al., 2022). Consequently, students are not merely presented with concepts; they actively engage in knowledge building through interactions with scenarios where practical experience and theoretical representations converge. In this context, laboratories provide students with the chance to actively construct knowledge through scientific inquiry, link abstract ideas to empirical data and promote logical, critical and evidence-based reasoning (Kapici et al., 2019). Laboratories can be, thus, a significant environment for the development of scientific reasoning in physics learning (Gizaw & Sota, 2023).

Physical labs (PL) are vital but are generally limited by structural and operational constraints. These include limited access to equipment and materials (especially in low-resource institutions), high costs of purchase and maintenance, safety issues in experiments, and limited instructional time that limits opportunities for extended investigation (Caymaz,

2021; Ogunsola-bandele & Kennepohl, 2024). These limits often render laboratory activities procedural and verification-oriented, as students follow step-by-step instructions to validate known concepts (Pande & Chandrasekharan, 2017). Thus, success is generally measured by the extent to which desired results are attained, rather than by the quality of the reasoning or inquiry techniques employed to obtain them. This constrains the opportunity for students to question, create experiments, and critically analyze data (Dunnett et al., 2020). It also positions students more as procedural executors rather than as active knowledge producers. The mismatch between the desired goals of inquiry-based learning and the actual implementation of these concepts in laboratory practice exists.

PL limitations have led to the creation of virtual labs (VL) as an alternative. VL allows security-enhanced experimenting wherever and anytime and is repeatable without resource and equipment constraints, enabling iterative learning (Psillos, 2023). Furthermore, VLs are adept at visualizing abstract concepts (Usmonova, 2025). For example, in the topic of thin lenses, students may see the trajectories of rays, the formation of the peculiar rays, and the dynamic changes of the quality of the image. VL are generally considered a valuable tool to enhance physics learning but might not adequately imitate the hands-on experience of typical laboratory work, especially with the direct engagement with physical phenomena (El Kharki et al., 2021; Usmonova, 2025).

The discussion on the usefulness of VL and PL is still inconsistent. Various studies like those of Papalazarou et al. (2024) and Ratamun & Osman (2018) indicate that virtual inquiry-based experiments can reach comparable learning outcomes to physical experiments concerning conceptual understanding, particularly as they can offer dynamic visualizations of abstract phenomena. On the other hand, several studies demonstrate that PL still has major advantages, especially in the development of science process skills that need direct interaction with physical objects, for example, in Kapici et al. (2019) and Urbančič & Glažar (2012). The manipulative abilities, experience in real-world measurements, and ability to cope with variability and uncertainty in experiments are hard to accurately reproduce in a virtual context. At the same time, research by Husnaini & Chen (2019) shows that both VL and PL can be effective in enhancing students' conceptual comprehension and inquiry skills, each type having its own advantages. This means that the design of activities and the environment in which they are implemented affect the efficiency of VL and PL.

Thus, the pedagogical dimension plays a central role in laboratory learning, given that several studies suggest that instructional design is more impactful than the choice of the medium itself, either VL or PL (Wang et al., 2025; Wörner et al., 2022). In this regard, guided inquiry is considered an instructional strategy to optimize laboratory learning as it actively involves students throughout the inquiry process with structured support through guiding questions and scaffolding (Husnaini & Chen, 2019). Unlike open inquiry, guided inquiry provides systematic instructional support through guiding questions, worksheets, prompts, and lecturer facilitation that help students focus on relevant variables, observations, and emerging patterns while maintaining their active role in knowledge construction (Crawford, 2014; Husnaini & Chen, 2019). Properly designed scaffolding has been shown to promote higher-order thinking skills, conceptual understanding, metacognitive awareness, and science process skills (Alanazi et al., 2024; Peşman et al., 2025). It allows students to go beyond identifying "what" a concept is and understanding "how" and "why" it occurs through the inquiry process (Zhuang et al., 2024). Furthermore, guided inquiry has significant compatibility with laboratory learning (Hubber et al., 2017; Husnaini & Chen, 2019), involving explicit connections between actual phenomena and other representations, such as visual, verbal, and mathematical, to facilitate integrated conceptual understanding (Munfaridah et al., 2021; Volkwyn et al., 2020).

Although research on VL and PL has increased significantly, much of the existing work has primarily focused on comparing their overall effectiveness in terms of learning outcomes,

often positioning VL and PL as separate or even competing instructional environments. This comparative orientation appears to have limited attention to how both types of laboratories might be meaningfully integrated within a single pedagogical framework, particularly through guided inquiry. As a result, the interaction between guided inquiry and the complementary features of VL and PL is still not fully understood, especially in relation to how their integration may support conceptual understanding and science process skills. Moreover, relatively few studies have explicitly examined guided enquiry as a structured approach for integrating VL and PL, although such an approach may offer opportunities to systematically combine the affordances of both laboratory environments within a coherent instructional sequence.

In addition, much of the prior literature still tends to emphasize conceptual understanding as a final learning product measured mainly through test scores, with limited attention to the underlying cognitive processes that occur during the use of different laboratory environments. In particular, how guided inquiry supported by PL and VL facilitates the development of representational coordination, the ability to connect and translate among representations derived from physical experiments, virtual simulations, verbal explanations, diagrams, graphs, and mathematical models, has been relatively underexplored. This gap is especially relevant in prospective physics teacher education, where conceptual understanding includes not only the ability to solve problems but also the ability to explain phenomena and to coordinate various complementary representations (Volkwyn et al., 2020). However, this ability does not emerge automatically (Aregehagn et al., 2023; Opfermann et al., 2017); many students still experience difficulties in integrating representations due to cognitive load and limited prior knowledge, which results in fragmented and procedural understanding (Scheid et al., 2019).

This difficulty is more evident in sophisticated multi-representational physics topics like geometric optics, notably the refraction of light that is often taught using two or more representations (Kuo et al., 2017). In the notion of Snell's Law, students need to not only understand the mathematical relationship between the angle of incidence and the angle of refraction but also relate it to the geometric construction of the normal line and the physical meaning of the refractive index. This complexity is increased in refraction in thin lenses, which involves the coordinates of ray diagrams, the production of principal rays, the quantitative link between the position of the object and its image, and the interpretation of the features of the image. In practice, however, students tend to focus on a single representation (Klein et al., 2017), especially mathematical representations, making it difficult to obtain a complete and cohesive understanding. This highlights that the key challenge in learning physics is not just to learn formulas but to be able to connect representations in a meaningful way and underscores the need for research on the development of representational coordination in learning.

The description of this article aims to examine changes in conceptual understanding and science process skills of prospective physics teacher students on the topic of light refraction, specifically Snell's law and image formation in thin lenses, through the implementation of guided inquiry learning that integrates PL and VL. In addition, this study seeks to explore how students' representational coordination appears to develop within this learning context. This study may be viewed as a preliminary effort to explore the potential role of integrating PL and VL within guided enquiry in supporting representational coordination and conceptual understanding in physics learning.

METHOD

Research design

This study employed a one-group pretest-posttest design (Creswell, 2012) and a concurrent embedded mixed-methods design (Chang & Chen, 2020). In this design, quantitative and qualitative data were collected simultaneously and were complementary to give a complete picture of the research results (Han et al., 2016). A quantitative analysis was conducted to compare pre- and post-intervention scores in order to describe differences observed after the learning activities. The analysis examined several aspects of science process

skills, including students' ability to evaluate data, recognize links between variables, and make conclusions. The embedded qualitative component was designed to analyze the representational coordination in students' answers, i.e., how much students integrated several representations (graphical, mathematical, and textual) in their explanations.

Sampling

The sampling technique utilized was total sampling. Total sampling is the sampling strategy where all members of the population are employed as study samples (Sugiyono, 2020). The reason for choosing this technique was that the population was rather small, that is, 15 prospective physics teacher students studying optics courses in the present semester with an average age of about 19 years, consisting of 4 male students and 11 female students.

Procedures and interventions

The learning intervention was designed based on the guided inquiry framework (Bell et al., 2005), in which the lecturer acted as a facilitator by providing structured scaffolding throughout the learning process. The implementation followed an inquiry cycle adapted from Pedaste et al. (2015) and Lee et al. (2023), consisting of orientation and conceptualization, investigation, and conclusion phases (Figure 1). Within this framework, PL and VL were integrated as complementary investigation environments, while scaffolding was embedded across the inquiry stages to support scientific reasoning and the translation of verbal, visual, and mathematical representations. Through these interconnected processes, the intervention was designed to facilitate students' representational coordination, conceptual understanding, and science process skills in learning Snell's law and thin lenses. To ensure consistency across meetings, all students received the same worksheets, scaffolding procedures, and lecturer facilitation throughout the intervention.

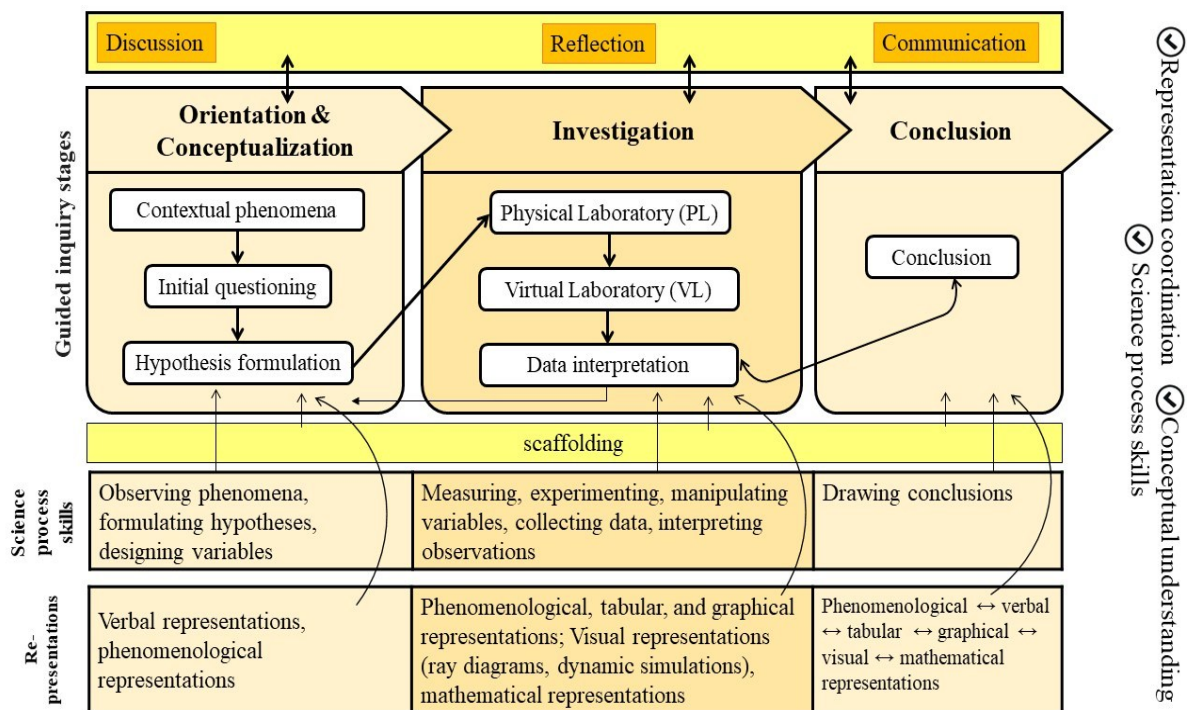


Figure 1. Conceptual framework of guided inquiry integrating physical and virtual laboratories

The research procedure began with a pre-test to identify the initial profile of students' conceptual understanding on the topics of Snell's Law and refraction and image formation in thin lenses (convex lenses and concave lenses). A pre-test was also given to measure students' science process skills, which include the ability to formulate hypotheses, design variables, design experiments, analyze data, and draw conclusions..

During the orientation and conceptualization phase, the lecturer demonstrates geometric optics phenomena via demonstrations in a PL, which are related to the refraction at the boundary between two media and to the production of pictures by a narrow lens. In the thin convex lens activity, the physical laboratory apparatus consisted of a convex lens, optical bench, light source, object screen, image screen, ruler, and lens holder. Students are expected to note the phenomena, identify the factors involved, and make initial hypotheses in the form of verbal descriptions and rudimentary ray diagram sketches. At this phase, the lecturer acted as a facilitator by introducing the problem context, demonstrating the phenomena, and guiding students through initial questioning, while students actively observed the demonstrations, identified relevant variables, formulated hypotheses, and constructed preliminary representations. Scaffolding is supplied by leading questions such as "What happens to the direction of light as it crosses the boundary between two media?" "What is the relationship between the angle of incidence and the angle of refraction that you predicted?" And in the case of a thin lens, "what is the nature of the image formed (real/virtual, upright/inverted)? and "What could affect the position and size of the image?". These questions lead students to explore links between variables and encourage the usage of initial representations to foster scientific reasoning.

During the exploration phase, activities are structured in a sequential way between PL and VL with adaptive scaffolding. At the investigation stage, students were guided using structured worksheets consisting of a physical laboratory worksheet and a virtual laboratory worksheet (Figure 2). In the PL phase, students plan and conduct experiments and gather data from direct observations. The lecturer monitored the experimental process, provided procedural guidance when necessary, and encouraged students to connect observations with conceptual explanations, while students collaboratively designed measurements, manipulated apparatus, recorded data, and interpreted experimental results. Scaffolding is supplied by queries like "How can I ensure just one variable is changing? What do you have to measure to test the link between the angle of incidence and the angle of refraction?" and for lenses: "What is the ratio between the object distance and the image distance that you measured? and "How can these results be shown in a ray diagram?" These questions assist students in relating the experimental activity with the visual representation and empirical facts.

Next, in the VL phase, the virtual laboratory utilized the specific PhET Interactive Simulations module "Geometric Optics: Lens." Scaffolding questions focus on translation between representations: "How does the refractive index change the path of the light beam?" "Is there a mathematical pattern in the data you collected?" and for lenses: "How does the focal length change the position of the image?" and "How does the graph or equation relate to the ray diagram that you saw?" What is your conceptual explanation of this phenomenon?" During the VL activities, the lecturer facilitated conceptual reflection and representational translation, while students manipulated variables independently, compared virtual and physical observations, and refined their conceptual understanding through multiple representations. The interactive visualization and direct manipulation of variables, as well as the facilitation of inquiry-based learning and multi-representational coordination, have been found to be helpful in improving conceptual understanding and student engagement in the PhET Interactive Simulations (Diab et al., 2024). The choice of progression from the PL to the VL is made because it allows for first concrete experiences that are then extended by a more representational virtual exploration (Flegr et al., 2023). Direct experience with physical phenomena builds an initial foundation of understanding, which is further consolidated through more flexible variable manipulation and representation-based analysis (Wörner et al., 2022).

EKSPERIMEN

LEMBAR KERJA
KEGIATAN PERCOBAAN LENS A CEMBU NG

AKTIVITAS 1

Inferensi: Jarak bayangan dipengaruhi oleh jarak benda.

Masalah: Apakah jarak benda di depan lensa cembung mempengaruhi sifat bayangan yang terbentuk?

Hipotesis: Jika jarak benda bertambah, maka jarak bayangan berkurang.

Tujuan: (1) Untuk mempelajari hubungan antara jarak benda, (s) dan jarak bayangan, (s') untuk lensa cembung; (2) Untuk menentukan panjang fokus lensa tipis menggunakan rumus lensa; (3) Menggambar pembentukan bayangan pada lensa cembung menggunakan diagram sinar istimewa.

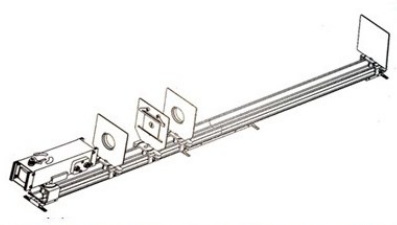
Variabel:

- Variabel yang dimanipulasi: Jarak benda (s)
- Variabel yang direspons: Jarak bayangan (s')
- Variabel konstan: Jarak fokus (f) dan jenis lensa

Alat: Lensa cembung bertangkai ($f = +10$ cm), catu daya, rel presisi, pemegang slide diafragma, diafragma anak panah, layer, sumber cahaya (kotak lampu dan lampu), penyambung rel, kaki rel, tumpukan berpenjepit.

Prosedur kerja:

- Siapkan peralatan seperti yang ditunjukkan pada gambar di bawah ini.



- Nyalakan lampu dan mulailah percobaan dengan jarak benda $s = 12$ cm. Atur posisi layar hingga terbentuk bayangan yang tajam.

- Ukur jarak bayangan s' dan catat hasil pembacaan pada Tabel Hasil Pengamatan.
- Ulangi langkah (2) dan (3) dengan jarak benda $s = 14$ cm, 16 cm, 20 cm, 22 cm, 24 cm, dan 25 cm. Catat hasil pengukuran pada Tabel Hasil Pengamatan.
- Coba untuk jarak benda $s = 8$ cm. Geserlah layar hingga terbentuk bayangan yang tajam. Jika tidak ditemukan bayangan, carilah bayangan dengan mengamatin ya ke dalam lensa dari arah "belakang" lensa.

Hasil Pengamatan

Tabel Hasil Pengamatan				
s (cm)	s' (cm)	$\frac{1}{s}$	$\frac{1}{s'}$	Sifat bayangan
12				
14				
16				
20				
22				
24				
25				

Analisis data:

- Apakah posisi benda terhadap lensa cembung memengaruhi bayangan yang terbentuk? Berikan penjelasan Anda.
- Apa saja ciri-ciri umum bayangan nyata yang dibentuk oleh lensa cembung?
- Gambarkan grafik $1/s$ terhadap $1/s'$.
- Tentukan gradien dari grafik yang Anda buat.
- Tentukan titik potong kedua sumbu.
- Dengan menggunakan rumus lensa dan grafik yang telah dibuat, tentukan panjang fokus lensa pada percobaan ini.

Kesimpulan:

Kesimpulan apa yang dapat diambil dari percobaan ini?

EKSPERIMEN

LEMBAR KERJA
KEGIATAN PERCOBAAN LENS A CEMBU NG

AKTIVITAS 2

Tujuan: Menggambar proses pembentukan bayangan pada lensa cembung menggunakan simulasi PHET.

Alat: Laptop atau telepon genggam, simulasi PHET, penggaris, kertas, dan pensil.

Prosedur Kerja:

- Buka simulasi PhET Geometric Optics. Selanjutnya, pilih menu *Convex Lens*, kemudian aktifkan fitur *Rays* dan *Labels* agar jalannya sinar serta titik-titik penting pada lensa dapat terlihat dengan jelas.



- Letakkan benda pada posisi lebih jauh dari $2F$. Geser benda hingga berada di luar titik $2F$, kemudian amati arah sinar dan posisi bayangan yang terbentuk. Setelah itu, gambarkan pembentukan bayangan menggunakan minimal dua sinar istimewa, serta beri tanda pada titik fokus (F), titik $2F$, benda, dan bayangan.
- Letakkan benda tepat pada posisi $2F$. Amati perubahan posisi dan sifat bayangan yang terbentuk, kemudian gambarkan diagram sinar nya.
- Letakkan benda di antara titik fokus (F) dan $2F$. Perhatikan ukuran, posisi, dan sifat bayangan yang dihasilkan. Selanjutnya, gambarkan diagram sinar pembentukan bayangan tersebut.
- Letakkan benda tepat di titik fokus (F). Amati arah sinar bias yang keluar dari lensa, kemudian gambarkan hasil pembentukan bayangannya.

6. Letakkan benda di antara lensa dan titik fokus (F). Amati posisi serta sifat bayangan yang terbentuk, kemudian gambarkan diagram sinar pembentukan bayangan tersebut.

Gambar Pembentukan Bayangan

Posisi Benda	Diagram Sinar
$s > 2F$	
$s = 2F$	
$F < s < 2F$	
$s = F$	
Benda antara lensa dan F	

Figure 2. Example worksheet on the topic of convex lenses

In the conclusion phase, students synthesize the results of their studies by creating data-based conclusions that include a variety of representations. At this phase, the lecturer guided classroom discussions, clarified conceptual inconsistencies, and reinforced relationships among verbal, visual, and mathematical representations, while students communicated findings, compared interpretations, defended conclusions using evidence, and reflected on representational consistency. At this stage, the scaffolding is based on the reflection and integration questions such as "Are your calculations consistent with the ray diagram you constructed?" "How do you physically explain the reason for the image having these properties?" and "What is the relationship between the experimental results, the graph, and the equation you obtained?" These questions inspire students to develop cohesive, evidence-based

explanations. The results are then shared in a class discussion. The instructor provides comments that help to spot discrepancies and reinforce the links between representations.

A posttest was given to students after the complete sequence of learning interventions to quantitatively assess conceptual comprehension. Furthermore, the posttest was also designed to examine students' science process skills. The students' replies on the posttest and the pretest were also qualitatively assessed in addition to being a measurement tool for learning outcomes in order to examine their competence in coordinating different representations. The intervention implementation followed a structured guided inquiry protocol consisting of four meetings, with each meeting conducted for 150 minutes. In addition, two separate sessions were allocated for the pretest and posttest, each with a duration of 120 minutes.

Instrument

The research instrument was a conceptual understanding test. The conceptual understanding test consisted of five open-ended items, with each item scored on a scale ranging from 0 to 5, in which students were asked to explain refraction phenomena using various interconnected representations, including verbal explanations, geometric ray constructions, quantitative relationships, and mathematical formulations. The rubric for giving scores is shown in Table 1.

Table 1. Scoring rubric for assessing students' conceptual understanding

Score	Criteria
0	– No response, irrelevant response, or answer unrelated to Snell's law and thin lens concepts.
1	– The response suggests inaccurate conceptual interpretation regarding light refraction, Snell's law, or thin lens image formation. Verbal explanations, ray diagrams, or equations are scientifically incorrect.
2	– The student demonstrates limited understanding of Snell's law or thin lens concepts. Some relevant representations are used, but explanations remain incomplete, inaccurate, or inconsistent.
3	– Student demonstrates partially correct understanding of refraction phenomena, including Snell's law or thin-lens image formation. Verbal explanations, ray constructions, or mathematical relations are generally appropriate, but some conceptual errors or incomplete connections among representations remain.
4	– Student provides mostly accurate explanations of Snell's law and thin lens concepts using appropriate verbal explanations, ray diagrams, quantitative relationships, and mathematical formulations with only minor inaccuracies.
5	– The student demonstrates scientifically accurate and comprehensive understanding of Snell's law and thin-lens concepts through coherent integration of verbal explanations, geometric ray constructions, quantitative relationships, and mathematical formulations. All representations consistently support the same conceptual interpretation.

The content of the conceptual understanding test is shown in Table 2. The conceptual understanding test used in this study was adapted and modified from classical physics textbook references, namely Tipler & Mosca (2022) and Halliday et al. (2014), and was in accordance with several reputable scientific articles discussing geometric optics (Aregehagn et al., 2023; Ceuppens et al., 2018; Grusche, 2017; Uwamahoro et al., 2021) and multi-representation analysis in physics learning (Kuo et al., 2017; Opfermann et al., 2017).

Table 2. Conceptual understanding test grid

Topic	Conceptual Indicators	Representation Demands
Snell's Law	Analyze the relationship between the angle of incidence, angle of refraction, and refractive index of two media.	Verbal-textual, visual-graphical, symbolic-mathematical

Topic	Conceptual Indicators	Representation Demands
Thin convex lens	Analyze the concept of apparent depth based on the refraction of light.	
Thin concave lens	Analyze the characteristics of the image formed by a thin convex lens.	
Thin convex-concave lens system	Analyze the characteristics of the image in a thin concave lens.	
	Analyze the formation of the image in a system of two thin lenses.	

The content validity of the conceptual understanding test instrument was evaluated using Aiken's V based on assessments from two experts covering material relevance, construction, and language aspects. The analysis produced Aiken's V coefficients ranging from 0.63 to 1.00, based on Sabaruddin et al. (2022), the Aiken's V values obtained are in the moderate- to high-validity category. Prior to its implementation in the main study, the conceptual understanding test was piloted with prospective physics teacher students outside the research sample to examine its internal consistency reliability. The reliability analysis using Cronbach's Alpha yielded a coefficient of 0.78, indicating high internal consistency of the instrument (Trabelsi et al., 2024). Because the conceptual understanding test consisted of open-ended responses requiring rubric-based scoring, inter-rater reliability was also examined to ensure scoring consistency between raters. The inter-rater reliability analysis was conducted using the Intraclass Correlation Coefficient (ICC). The average-measures ICC reached 0.859, reflecting good reliability when scores were averaged across raters (Koo & Li, 2016). This result suggests that the scoring rubric was sufficiently clear and consistently applied across raters.

Science process skills of prospective physics teacher students were measured using a research instrument consisting of 10 test items representing various aspects of science process skills, referring to the study of Gultepe & Kilic (2015), which are formulating hypotheses, designing variables, designing experiments, analyzing data, and drawing conclusions. The grid of the science process skills test instrument is described in depth in Table 3. The content validity of the science process skills test instrument was analyzed using Aiken's V based on evaluations from two experts in terms of material, construction, and language appropriateness. The Aiken's V coefficients ranged from 0.63 to 1.00, indicating a moderate-to-high validity range (Sabaruddin et al., 2022). The science process skills test was also piloted with prospective physics teacher students outside the study participants to assess internal reliability. Since the instrument employed dichotomous scoring, reliability analysis was performed using the Kuder–Richardson Formula 20 (KR-20). The analysis resulted in a KR-20 coefficient of 0.79, indicating acceptable reliability and satisfactory internal consistency (Ntumi et al., 2023) for measuring science students' process skills.

Table 3. Science process skills test grid

Aspects of science process skills measured	Indicators	Question Number
Formulating a hypothesis	Formulate a hypothesis about the relationship between the angle of incidence and the angle of refraction.	1
	Formulate a hypothesis about the relationship between the object and image distances.	7
Designing variables	Design a dependent variable in an experiment.	2
	Design a control variable in an experiment.	3
Designing an experiment	Determine an experimental procedure to test the relationship between the variables.	4, 8
Analyzing data	Interpret the relationship from the experimental data table.	5

Aspects of science process skills measured	Indicators	Question Number
Drawing conclusions	Interpret the relationship between the object and image distances from the table.	6
	Draw conclusions from the experimental results (sin i/ sin r ratio).	9
	Draw conclusions about image formation in a lens.	10

Data Analysis

Data were analyzed quantitatively and qualitatively. Quantitatively, each conceptual-understanding question was scored 0–5 with a maximum total score of 25. Meanwhile, science process skills were analyzed using a dichotomous scoring system, where each correct answer was scored as 1 and each incorrect answer was scored as 0, resulting in a maximum score of 10. Pre-test and post-test scores, both on the conceptual understanding test and the science process skills test, were analyzed using SPSS version 27. A normality test was conducted first to determine the type of inferential test, namely a paired sample t-test for normally distributed data and a Wilcoxon signed-rank test for non-normal data (Afifah et al., 2022). In addition, improvements in conceptual understanding and science process skills were analyzed using *N-Gain*, which is calculated from the difference between pre-test and post-test scores normalized to the maximum score. The interpretation of *N-Gain* refers to Hartanto et al. (2023), namely high ($g \geq 0.70$), medium ($0.30 \leq g < 0.70$), and low ($g < 0.30$) improvement categories. The combination of the difference and *N-Gain* tests was used to provide a more comprehensive picture of the improvement in students' conceptual understanding.

In addition to statistical testing, effect size analysis was also conducted to complement the interpretation of the results by providing information on the magnitude of the changes that occurred. The obtained values were then interpreted using categories referring to the guidelines proposed by Wang & Fan (2025): very small (0.1), small (0.2), medium (0.5), large (0.8), very large (1.2), and huge (2.0) as a descriptive reference for assessing the magnitude of the changes.

Qualitative analysis focused on the use and coordination of representations in students' written responses in the pretest and posttest. Each written response was analyzed by identifying the occurrence of three types of representations, referring to Wu & Puntambekar (2012), that is visual-graphical, symbolic-mathematical, and verbal-textual. The first stage of analysis was carried out by calculating the frequency of occurrence of each representation in the pretest and posttest, which was then expressed as a percentage. This stage was adapted from a study conducted by (Dinçer, 2025).

The next stage, qualitative data analysis, focused on representational coordination to examine how various representations are interconnected in building conceptual explanations (Müller et al., 2017) in students' written answers. All answers in the pretest and posttest were analyzed using the descriptive coding method (Dinçer, 2025). Coding was carried out on the coordination patterns between representations with the following categories: isolated representation, unintegrated representations, partially coordinated, and integrated coordination. The four categories used in this study represent a continuum of understanding development, from a state of fragmented knowledge to the formation of an integrated and coherent knowledge structure, based on several studies, for example, Scheid et al. (2019) and Müller et al. (2017). To minimize subjectivity, each category was defined through explicit operational indicators and applied consistently throughout the analysis. The coding scheme used in this study is presented in Table 4. Based on these criteria, each response was coded through the decision-making process illustrated in Figure 3.

Table 4. Coding scheme for representational coordination categories

Category	Operational Definitions	Indicators
Isolated Representation	Students use only one form of representation	(1) There is only one representation (written, graphic, or mathematical); (2) Students can give

Category	Operational Definitions	Indicators
	without any connection to other representational forms.	scientifically valid or incorrect explanations, but there is no attempt to translate to another representation; (3) Diagrams, equations, or verbal explanations are independent of the other forms.
Unintegrated Representations	Students use more than one form of representation, but these representations are not connected.	(1) Multiple representations are present; (2) Representations exist separately and are not explicitly connected; (3) One or more representations may be scientifically valid, yet they work separately.
Partially Coordinated Representation	Students connect some representations, but the relationships between them are incomplete, inconsistent, or partially developed.	(1) At least two representations are explicitly linked; (2) Students translate representations; (3) Students may correctly connect two representations while the third contradicts the reasoning; (4) Despite connected representations, coordination may incorporate scientific mistakes, misunderstandings, or inconsistent reasoning.
Integrated Coordination	Students coherently integrate multiple representations into a consistent explanatory structure.	(1) All the representations are available and openly related; (2) Representations help one another to explain the same phenomenon; (3) Translation between representations is theoretically correct; (4) Explanations show coherent scientific reasoning across all representations; (5) Representations do not have any significant conceptual contradictions.

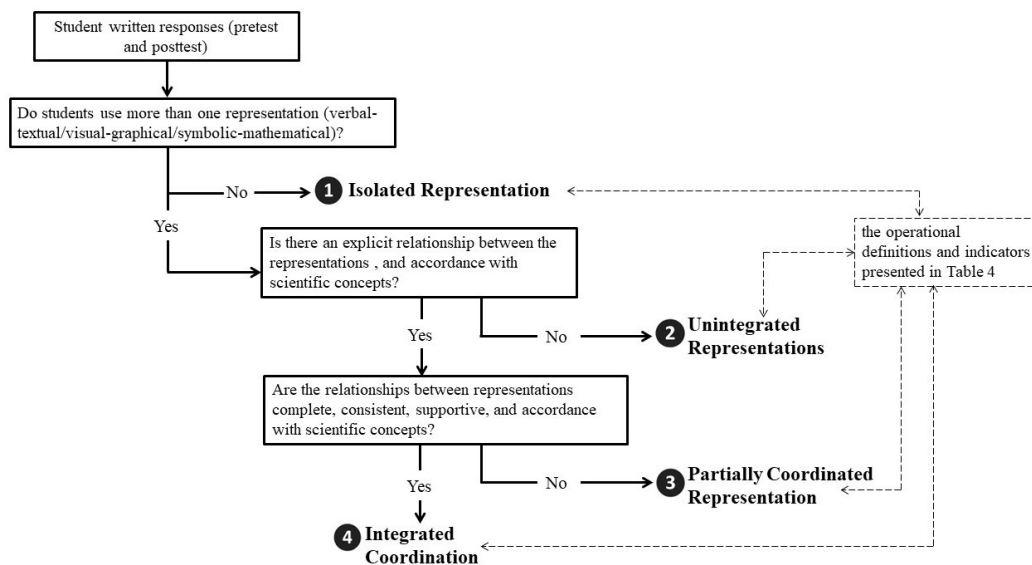


Figure 3. Coding procedure for classifying students' representational coordination

To ensure coding reliability, two independent experts separately analyzed all students' written responses from the pretest and posttest. Each written response was first carefully examined in terms of its verbal-textual, visual-graphical, and symbolic-mathematical then independently coded into one of four categories based on the coding scheme for representational coordination categories presented in Table 4, which considers the consistency and level of integration among these representations. Interrater agreement was calculated using Cohen's kappa coefficient, and the obtained kappa values were interpreted according to commonly accepted criteria for reliability. Any discrepancies between the two coders were

subsequently discussed in detail until consensus was achieved. This process was carried out to maintain the consistency and validity of the qualitative analysis results (Li & Yu, 2022; McHugh, 2012).

RESULTS AND DISCUSSION

The results of the quantitative analysis showed an increase in the conceptual understanding of prospective physics teacher students after the implementation of guided inquiry learning assisted by PL and VL (Table 5). The average pre-test score was recorded at 10.07, which indicates that before the intervention, prospective teacher students still had a relatively low level of understanding of explaining Snell's Law, the mechanism of refraction, and image formation in thin lenses. After the intervention, the average post-test score increased to 21.80.

Table 5. Descriptive statistics and normality test results for pre-test and post-test scores

Variable	N	Mean	SD	Median	Shapiro–Wilk		Distribution
					Statistic (<i>W</i>)	Sig. (<i>p</i>)	
Pre-test	15	10.07	1.335	10.00	0.897	0.086	Normal
Post-test	15	21.80	2.111	23.00	0.852	0.019	Non-normal

The normality test using Shapiro–Wilk showed that the pre-test data were normally distributed ($p > 0.05$), while the post-test data were not normally distributed ($p < 0.05$). Based on the results of the assumption test, a difference analysis was conducted using the non-parametric Wilcoxon Signed Ranks Test. The Wilcoxon test results showed an Asymp. Sig. (2-tailed) value of 0.001 (< 0.05), which means there was a difference between the pretest and posttest scores (Table 6). The large effect size ($r = 0.887$) indicates that the intervention was associated with a substantial improvement in students' conceptual understanding. The findings provide preliminary evidence that guided inquiry learning integrating PL and VL may facilitate more coherent conceptual understanding among prospective physics teachers.

Table 6. Results of the Wilcoxon Signed-Rank Test and N-Gain analysis of students' conceptual understanding

Analysis	Result	Interpretation
Wilcoxon Signed-Rank Test (Pretest–Posttest, $\alpha = 0.05$)	$Z = -3.436; p < 0.001$	There was a difference between pretest and posttest scores ($p < 0.05$)
Effect size	$r = 0.887$	Large effect
N-Gain	0.79	High improvement category

The results of the N-Gain analysis indicate an increase in the learning outcomes of prospective physics teacher students following the implemented learning activities. Based on the N-Gain calculation with a maximum score of 25, the average N-Gain was 0.79, which falls within the high category (Table 6). The distribution of N-Gain categories also showed that 60% of students (9 students) were in the high category, while 40% (6 students) were in the medium category, with no students categorized as low (Figure 4).

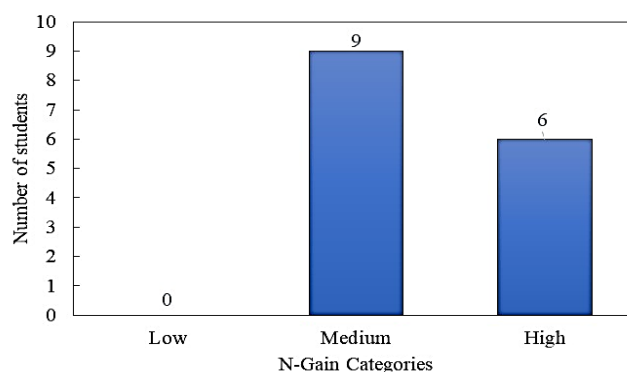


Figure 4. Distribution of N-Gain categories (high–medium–low) for conceptual understanding

The quantitative analysis further showed an increase in the science process skills of prospective physics teacher students after the implementation of guided inquiry learning assisted by PL and VL (Table 7). The average pre-test score was recorded at 3.93, indicating that before the intervention, prospective teacher students still had a relatively low level of science process skills related to formulating hypotheses, designing variables, designing experiments, analyzing data, and drawing conclusions. After the intervention, the average post-test score increased to 8.33.

Table 7. Descriptive statistics and normality test results for pre-test and post-test scores of science process skills

Variable	N	Mean	SD	Median	Shapiro–Wilk		Distribution
					Statistic (<i>W</i>)	Sig. (<i>p</i>)	
Pre-test	15	3.93	1.10	4.00	0.924	0.218	Normal
Post-test	15	8.33	0.72	8.00	0.817	0.006	Non-normal

The results of the Wilcoxon Signed Ranks Test indicate that there is a difference between the pretest and posttest scores of science process skills (Table 6). This is indicated by a *Z* value of -3.487 with a value of Asymp. Sig. (2-tailed) of $p < 0.001$. The *p*-value is smaller than the significance limit of 0.05, indicating a statistically detectable difference based on the chosen significance level (Table 8). A negative *Z* value, which is based on negative ranks, indicates that most of the posttest scores are higher than the pretest scores. The large effect size ($r = 0.90$) indicates that the intervention was associated with a substantial improvement in students' science process skills. Thus, the findings suggest a tendency toward increased science process skills among student teachers following the learning intervention.

Table 8. Results of the Wilcoxon Signed-Rank Test and N-Gain analysis of students' science process skills

Analysis	Result	Interpretation
Wilcoxon Signed-Rank Test (Pretest–Posttest, $\alpha = 0.05$)	$Z = -3.487$; $p < 0.001$	There was a difference between pretest and posttest scores ($p < 0.05$)
Effect size	$r = 0.90$	Large effect
N-Gain	0.73	High improvement category

The results of the N-Gain analysis indicate an increase in the science process skills of prospective physics teacher students following the implemented learning activities. Based on calculations with a maximum score of 10, the average N-Gain is 0.73, which is included in the high category. The distribution of N-Gain categories also shows a consistent pattern of improvement, where 33.33% of students (5 students) are in the high category, while 66.67% of students (10 students) are in the medium category, and there are no students in the low category (Figure 5).

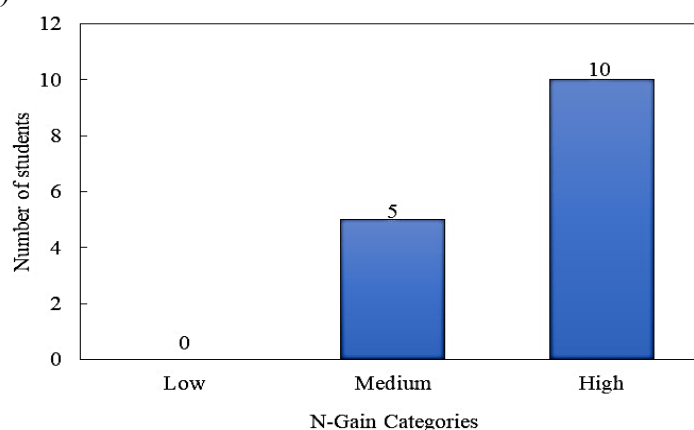


Figure 5. Distribution of N-Gain categories (high–medium–low) for science process skills

The observed improvement in conceptual understanding and science process skills may reflect the possible contribution of the guided inquiry learning design implemented in this study. Within this design, students were encouraged to engage actively in constructing knowledge through a series of scientific activities rather than functioning solely as recipients of information. This structure aligns with findings in inquiry learning studies, such as Lee et al. (2023) and Pedaste et al. (2015), which show that active engagement in the scientific cycle significantly contributes to the reconstruction of deeper conceptual understanding, as students not only know the “what” but also the “why” and “how” of a concept. This result also aligns with Aktamiş et al. (2016), who stated that by using the inquiry-based approach, students can build their potential by strengthening their scientific ideas through enquiry investigations.

Furthermore, the observed improvements may be associated with the integration of PL and VL within the guided inquiry framework. Through guided inquiry, students engaged in structured scientific activities such as formulating hypotheses, conducting investigations, interpreting evidence, and drawing conclusions, while PL and VL provided complementary learning experiences (Flegr et al., 2023). Physical laboratories enabled direct observation, measurement, and interaction with real optical phenomena, whereas virtual laboratories supported visualization, variable manipulation, and exploration of relationships that may be difficult to watch directly (Ouahi et al., 2024). Together, these complementary environments may help students connect concrete experiences with abstract representations while engaging in authentic scientific practices, which could contribute to the development of both conceptual understanding and science process skills (Aktaş & Karamustafaoğlu, 2025; Arantika et al., 2019; Husnaini & Chen, 2019; Wang et al., 2025).

In addition to the quantitative analysis described in the previous section, this article also describes the results of the qualitative analysis. The qualitative analysis began by examining the frequency of various forms of representation in students' answers, including visual-graphical representations (ray diagrams), symbolic-mathematical (equations and calculation procedures), and verbal-textual (text explanations). The results, as presented in Table 9, indicate a quite striking shift in representation patterns. In the pretest phase, student responses were completely dominated by verbal representations (100%), while the use of graphical (40.0%) and mathematical (53.3%) representations was still relatively limited and prone to error. This condition suggests that students' initial understanding tended to be descriptive, with limited use of visualization and quantitative modeling. Similarly, Hill & Sharma (2015) found that students were generally more comfortable with verbal explanations than with connecting mathematical and visual representations. After the learning intervention, there was a substantial increase in the use of graphical (86.7%) and mathematical (93.3%) representations.

Table 9. Frequency of appearance of representation in student responses ($N = 15$)

Types of Representation	Pretest (f)	Pretest (%)	Posttest (f)	Posttest (%)
Visual-graphical representations	6	40.0%	13	86.7%
Symbolic-mathematical	8	53.3%	14	93.3%
Verbal-textual	15	100%	15	100%

In addition to the frequency of occurrence, the pattern of representation combinations also experienced change, as shown in Table 10. In the pretest stage, student responses were dominated by the use of a single representation (verbal-textual, $f = 6$) as well as simple combinations of two representations, such as verbal-textual & symbolic-mathematical ($f = 5$) and verbal-textual & visual-graphical ($f = 3$), while combinations involving more complex integration were almost absent (visual-graphical & symbolic-mathematical, $f = 0$; three representations, $f = 1$). In contrast, the posttest responses showed a shift towards the use of more multi-representation combinations. The number of responses involving the integration of three representations (visual-graphical, symbolic-mathematical, and verbal-textual) increased ($f = 8$), becoming the most dominant pattern. Meanwhile, the use of single representations

decreased ($f = 1$), and the combination of two representations showed a more balanced distribution, including the emergence of a previously unseen combination of visual-graphical & symbolic-mathematical ($f = 1$).

Table 10. Distribution of representation combinations in student responses

Combination of Representations	Pretest (f)	Posttest (f)
Verbal-textual only	6	1
Verbal-textual + symbolic-mathematical	5	3
Verbal-textual + visual-graphical	3	2
Visual-graphical + symbolic-mathematical	0	1
Visual-graphical + symbolic-mathematical + verbal-textual	1	8

To strengthen this interpretation, the analysis continued at the representation coordination type. The coding results are presented in Table 11. To ensure the reliability of this analysis, the coding process was carried out by two independent raters with a high level of agreement. Cohen's Kappa values of $\kappa = 0.78$ (pretest) and $\kappa = 0.84$ (posttest) indicated substantial and almost perfect agreement, respectively, according to (McHugh (2012)). These results suggest that the coding scheme could be applied consistently across raters.

Table 11. Distribution of representation coordination types

Representation Coordination Type	Pretest (f)	Pretest (%)	Posttest (f)	Posttest (%)
Isolated representation	6	40.0%	1	6.7%
Unintegrated representations	5	33.3%	2	13.3%
Partially Coordinated	3	20.0%	5	33.3%
Integrated Coordination	1	6.7%	7	46.7%
Total	15	100%	15	100%

Table 11 shows a clear shift in the coordination of student representations between the pretest and posttest. In the pretest, the distribution of abilities was still dominated by low-level categories, namely isolated (40%) and unintegrated representations (33.3%). This condition indicates that most students are not yet able to integrate various representations meaningfully. At the isolated level, students tend to only use one type of representation without connecting it to other representations, while in the unintegrated representations category, even though more than one representation is used, the relationship between the representations has not yet been formed conceptually. This condition is in line with the findings of Bica et al. (2018), who showed that the initial learning process is often dominated by local information processing without integration, as well as the representational competence framework that emphasizes limited coordination between representations in the early stages (Scheid et al., 2019). Furthermore, Müller et al. (2017) also showed that in the early stages, students' knowledge tends to be fragmented and has not yet formed a coherent conceptual structure between contexts and representations.

After the intervention, the distribution of students' representational coordination tended to shift toward higher coordination levels. The proportion of students with isolated and unintegrated representations decreased substantially from 40% to 6.7% and from 33.3% to 13.3%, respectively, indicating a reduction in fragmented and disconnected thinking patterns. Meanwhile, partially coordinated representations increased from 20% to 33.3%, suggesting that students had begun to establish relationships between representations, although these connections were not yet fully consistent or complete, consistent with the incomplete integration stage described by Bica et al. (2018). The most notable change occurred in the integrated coordination category, which increased from 6.7% in the pretest to 46.7% in the posttest, indicating that nearly half of the students were able to coherently coordinate visual, mathematical, and verbal representations in explaining physics concepts. This pattern reflects the development of representational coherence, where multiple representations are integrated

into a more complete and consistent conceptual understanding (Scheid et al., 2019; Tytler & Hubber, 2016).

The qualitative findings suggest a tendency toward differences in students' representational coordination before and after the intervention. This development was evident, among other things, in the responses of Student Code 01 (Figure 6). In the pretest, the student used only one form of representation, namely a verbal-textual explanation, to explain the formation of an image by a thin convex lens. The student was able to identify the lens as a convex lens and stated that the resulting image is real and inverted. However, the response remained descriptive and relied solely on verbal statements without incorporating other forms of representation, such as ray diagrams (visual-graphical) or mathematical relationships (symbolic-mathematical), that could support or clarify the explanation. In addition, the student did not demonstrate any explicit connection between conceptual statements and optical principles governing image formation. There was no explanation of the light refraction process through the lens, no illustration of ray paths, and no indication of the relationship between object position and image characteristics relative to the focal point. Because the response involved only a single representational mode without evidence of coordination with other representations, it was categorized as an isolated representation. Similar findings were also reported by (Müller et al., 2017), which showed that students' understanding in the early stages is often tied to a particular domain or representational context.



GAMBAR 3

Dalam suatu percobaan optik di laboratorium, seorang siswa menggunakan sebuah lensa tipis dan meletakkan sebuah benda di depan lensa tersebut (Gambar 3). Pada layar yang diletakkan di belakang lensa tampak bayangan yang jelas, terbalik, dan berukuran dua kali lebih besar daripada benda aslinya. Diketahui jarak fokus lensa tersebut adalah 10 cm.
PERTANYAAN: (a) Analisislah jenis lensa yang digunakan dalam percobaan tersebut! (b) Jelaskan mekanisme pembentukan bayangan pada lensa tersebut; (c) Tentukan jarak benda terhadap lensa dan sertakan langkah perhitungan secara sistematis.

Lensa yang digunakan adalah lensa cembung, karena bayangan yang terbentuk terbalik dan bisa ditangkap pada layar. Lensa cembung biasanya menghasilkan bayangan nyata dan terbalik, karena bayangan lebih besar dari benda, berarti lensanya membesar bayangan.

Figure 6. One example of a student's pretest answer (Code 01)

In contrast, the same student's posttest responses suggested a shift toward more integrated multi-representational coordination (Figure 7). The student identified the lens as converging and justified it using the image characteristics (real, inverted, and magnified), while connecting observations, ray diagrams, and conceptual understanding of refraction, showing how refracted rays intersect to form the image. In addition, the student interpreted "twice as large and inverted" as $M = -2$, derived the relation $s' = 2s$, and applied the thin lens equation to determine the object position quantitatively. Unlike the pretest response, the posttest response demonstrated coordinated relationships among verbal, graphical, conceptual, and mathematical representations, in which each representation supported a coherent explanation of the same optical phenomenon. Therefore, the response was categorized as an integrated representation. These findings are consistent with the representational coherence framework developed by (Scheid et al., 2019), which characterizes advanced representational competence by the ability to interpret, translate, and coherently coordinate multiple forms of representation in constructing conceptual understanding.

Jenis lensa yang digunakan :

- Bayangan yang terbentuk memiliki sifat
- Terlihat jelas dilayar → bayangan nyata
- Terbalik → Ciri bayangan nyata Pada lensa tertentu
- Lebih besar (2 kali benda)
- Bayangan nyata, terbalik, dan diperbesar hanya dapat dihasilkan oleh lensa Cembung (lensa konvergen) maka Posisi benda berada di antara F dan $2F$ dibelakang lensa.

Jadi : lensa yang digunakan adalah lensa Cembung (konvergen).

Sinar datang sejajar Sumbu Utama dibiaskan melalui titik fokus dibelakang lensa Cembung. Sinar melalui titik fokus didepan lensa dibiaskan sejajar Sumbu Utama. kedua Sinar tersebut dibiaskan oleh lensa akan berpotongan dibelakang lensa sehingga membentuk bayangan nyata, terbalik, dan diperbesar.

Jarak benda dari lensa

Diketahui : Fokus (f) = 10 cm

Perbesaran (M) = 2

Bayangan nyata dan terbalik → $M = -2$

Dari rumus Perbesaran bayangan :

$$M = \frac{s'}{s}$$

$$-2 = \frac{s'}{s}$$

$$s' = 2s$$

Rumus lensa tipis :

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{2s}$$

$$\frac{1}{f} = \frac{2+1}{2s}$$

$$\frac{1}{10} = \frac{3}{2s} \rightarrow 2s = 30 \rightarrow s = \frac{30}{2} = 15 \text{ cm}$$

Jadi benda diletakkan pada jarak 15 cm didepan lensa Cembung.

Figure 7. One example of a student's posttest answer (Code 01)

Another pattern was observed in the pretest responses of Student Code 12 (Figure 8), which reflected an interaction between intuitive understanding and an initial attempt to construct causal representations regarding apparent depth. Verbally, the student stated that “objects in water usually appear closer to the surface,” reflecting reasoning based on everyday visual experience (Ranney & Thagard, 2019). The student also included a simple diagram showing an eye, a rock, and the apparent position of the rock connected by a straight-line arrow. However, the verbal and visual representations were not conceptually connected through an explanation of light refraction or Snell’s law. Instead, the diagram mainly functioned as a perceptual illustration based on a naïve straight-line view of vision (Sebald et al., 2022), what is visually visible is prioritized over invisible physical mechanisms (Pinna et al., 2026). Because multiple representations were present but not coherently integrated, the response was categorized as an unintegrated representation.

Sebuah batu berada di dasar kolam berisi air jernih dengan indeks bias $\frac{4}{3}$. Kedalaman sebenarnya kolam adalah 2 meter. Seorang pengamat berada di atas permukaan air dan melihat batu tersebut dengan garis pandang yang membentuk sudut 30° terhadap garis normal permukaan air. **PERTANYAAN:** Berdasarkan kondisi tersebut, tentukan kedalaman semu batu yang terlihat oleh pengamat.

Kalau dilihat dari pengalaman sehari-hari benda di dalam air terlihat lebih dekat ke permukaan. Jadi batu terlihat dekat ke permukaan air

Pretest answers

$h = 2 \text{ m}$ $r = 30^\circ$

$n_{\text{air}} = \frac{4}{3}$

$n_{\text{udara}} \cdot \sin 30^\circ = n_{\text{air}} \cdot \sin i$

$1 \cdot 0,5 = \frac{4}{3} \cdot \sin i$

$0,5 = \frac{4}{3} \cdot \sin i \rightarrow \sin i = 0,375$

$i = 22,02^\circ$

menggunakan rumus :

$$\frac{h'}{h} = \frac{\tan i}{\tan r} \rightarrow h' = h \cdot \frac{\tan i}{\tan r}$$

$$= 2 \cdot \frac{\tan 22,02^\circ}{\tan 30^\circ}$$

$$h' = 1,4 \text{ m}$$

Jadi batu berada 1,4 m dari permukaan air atau kelihatan lebih dekat ke permukaan air. soalnya ada peristiwa pembiasan dari air ke udara menuju mata

Posttest answers

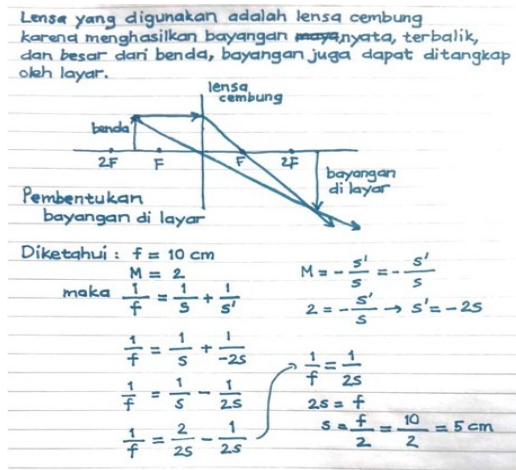
Figure 8. Example of one student's answer (Code 12)

In contrast, the posttest responses categorized as integrated representation (Figure 8) suggested greater representational coherence, in which students appeared more capable of coordinating verbal explanations, diagrams, and mathematical representations to explain the apparent depth phenomenon. Rather than relying on isolated representations, students demonstrated relationships among refraction concepts, ray trajectories, and symbolic expressions within a more connected explanatory structure. This pattern may indicate a developing ability to translate and coordinate different forms of representation more coherently, consistent with (Scheid et al., 2019), who argued that stronger conceptual understanding is often associated with the coordination of multiple representations.

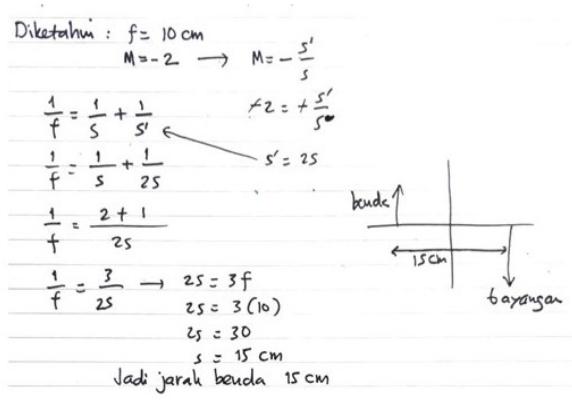
Initially, students relied primarily on verbal and phenomenological explanations, but after the intervention, they increasingly used more connected graphical and mathematical representations. This change may be related to the guided inquiry-based learning design that combined PL and VL, which supported the transition from experimental observations to visual and symbolic representations. In this process, VL served as cognitive support by visualizing unseen processes and enabling systematic manipulation of variables, thus helping students build connections between experimental, visual, and mathematical representations (Efstathiou et al., 2018; Gutierrez et al., 2022). This process aligns with the theory of multiple representations, which suggests that conceptual understanding develops through students' ability to translate and integrate experimental, visual, and mathematical representations into a coherent knowledge structure (Kuo et al., 2017). In this framework, each representation complements the others in building understanding (Ainsworth, 2008), where PL experiments provide empirical experiences, VL visualizations clarify unseen processes, and mathematical representations express quantitative relationships between variables.

Guided inquiry-based learning designs that integrate PL and VL appear to be able to help support conceptual understanding through scaffolding that facilitates representational coordination. In this process, the transition from experimental observation to visualization and mathematical representation does not occur spontaneously but is gradually guided through targeted pedagogical support (Rokhmat & Putrie, 2019). During learning about refraction and image formation in thin convex lenses, scaffolding helps students connect observations in the PL with ray diagrams in VL and symbolic representations such as Snell's law and the thin lens equation. While guided inquiry provides opportunities for interaction between PL and VL, scaffolding helps students meaningfully connect these representations, thereby supporting a more structured concept-construction process. Similar findings were reported by Hartanto et al. (2025) and Alanazi et al. (2024) who found that scaffolding can support conceptual explanation and conceptual restructuring in physics learning.

Although the distribution of representational coordination tended to shift toward higher categories after the intervention, not all students achieved integrated coordination. Several students still demonstrated partially coordinated, unintegrated, or isolated representations. This finding suggests that coordinating multiple representations in physics learning is a complex process (Yakob et al., 2026) that may develop gradually rather than simultaneously across all students. One example was observed in the posttest response of Student Code 08 (Figure 9a), who demonstrated partially coordinated representation. The student correctly constructed a ray diagram and verbally explained the formation of a real and inverted image through the intersection of refracted rays, indicating coordination between visual and verbal representations. The student also wrote the thin lens equation; however, the mathematical representation was not developed into a correct solution and was not yet fully connected to the conceptual explanation of image formation. According to Redish (2021), the ability to write physics equations but failing to manipulate symbols indicates that students are not yet fully capable of using mathematics meaningfully in physics, because using equations requires not only formula recognition but also a simultaneous understanding of the meaning of symbols and their physical interpretation.



(a) Participant Code 8 answer



(b) Participant Code 5 answer

Figure 9. Example of one student's answer

In some other cases, students successfully obtained correct numerical results but did not relate these results to the physical meaning of image formation. For example, student Code 5 (Figure 9b) did not explain that the value of $s = 15 \text{ cm}$ indicates the position of the object between the focal point (F) and twice the focal length ($2F$) in front of the lens, which is related to the formation of a real, inverted, and magnified image behind the convex lens. This response was categorized as unintegrated representation because the mathematical result was not conceptually connected to the visual and phenomenological interpretation of image formation. This is in line with Airey et al. (2019) and Lusiyana et al. (2019), who explained that the difficulty in integrating multiple representations is related to students' tendency to use representations procedurally, especially through the use of formulas and mathematical solutions, without understanding their relationship to physical phenomena or conceptual visual representations. Khatin-Zadeh et al. (2025) stated that mathematical symbols do not directly represent physical phenomena, so students must undertake an additional interpretation process to connect the symbols with the conceptual meaning and the physical situation they represent.

Although guided inquiry has provided opportunities for students to actively observe, explore, and investigate through PL and VL, some students still experience difficulties in connecting visual, verbal, and mathematical representations. This finding indicates that the presence of PL and VL alone does not automatically result in integrated representation coordination. This finding is in line with Kuo et al. (2017) and Lucas & Lewis (2019), who stated that students actually have the ability to use each representation separately but have not been able to connect them into a complete and mutually supportive conceptual understanding. In addition, this finding is also consistent with DiSessa (2018), which explains that students can demonstrate correct reasoning at the phenomenological level, but the elements of their knowledge are still not systematically integrated into a coherent conceptual structure. Munfaridah et al. (2021) explain that each representation in physics has different epistemic functions and cognitive characteristics; difficulties arise when students have to connect the three forms of representation simultaneously because this process requires complex representational fluency and translation abilities, which result in understanding the representations separately. This shows that challenges in representational coordination are not merely connected to the availability of various representations but also to how instructional support aids the translation and integration among those representations during learning.

The presence of isolated, unintegrated, and partially coordinated representations in some students indicates that scaffolding in guided inquiry-based PL and VL likely still favors the use of individual representations over coordination between representations. Although students have been guided to build understanding through experiments in PL and VL, the scaffolding provided does not appear to fully emphasize the translation processes between representations,

particularly between mathematical, visual, and conceptual representations. This condition can also be explained through the perspective of Lin & Singh (2015), who stated that the effectiveness of scaffolding is determined not only by the scaffolding design itself but also by its suitability with students' prior knowledge and initial skills. In the context of this study, some students may not have sufficiently strong representation translation skills, so the scaffolding provided does not fully help them coordinate visual, verbal, and mathematical representations conceptually. This condition is in line with Lucas & Lewis (2019), who showed that students still need explicit scaffolding to connect visual, verbal, and mathematical representations during physics problem-solving, because the use of various representations does not automatically result in integrated representational coordination. In this context, scaffolding between representations is crucial to facilitate the coordinated transformation of understanding from phenomenological observation to visual models to symbolic formulations. These findings suggest that the integration of PL and VL in guided inquiry still requires strengthening of representational scaffolding, for example, through explicit mapping between ray diagrams and mathematical equations and step-by-step guidance in translating visual reasoning into meaningful mathematical forms.

Furthermore, having more representations does not necessarily mean students understand concepts better if the relationships between these representations are not conceptually integrated. In several cases observed in this study, students were able to produce verbal explanations, ray diagrams, and mathematical formulations, but the relationships between these representations remained partial, fragmented, or scientifically inconsistent. This suggests that the use of multiple representations alone is insufficient to reflect integrated conceptual understanding when students are still unable to translate and coordinate meaning across different forms of representation. A similar trend was also reported by Dinçer (2025) in his study that students were able to move between experiments, simulations, schematic drawings, and mathematical expressions, but these representations were not always fully integrated conceptually. These findings suggest that representational learning in physics involves not only the use of multiple representations but also the ability to establish accurate conceptual relationships among them. In line with this, Pande & Chandrasekharan (2017) argue that representational competence involves not only the use of multiple representations but also the ability to coordinate and translate meaning across representations within scientific reasoning processes. Therefore, in several students may produce verbal, graphical, and mathematical representations simultaneously while still experiencing difficulties in integrating them into a coherent conceptual structure.

CONCLUSION

This study indicates that the guided inquiry learning design integrating PL and VL was followed by increases in prospective physics teachers' conceptual understanding and science process skills on the topics of Snell's law and thin lenses. These changes were reflected not only in quantitative results, such as higher posttest scores and N-gain categories, but also in qualitative patterns observed in students' responses. Several students demonstrated a transition from more descriptive and fragmented explanations toward more integrated forms of understanding. In addition, students showed a greater tendency to use graphical, mathematical, and verbal-conceptual representations together in their explanations, although the degree of coordination among these representations varied across students and was not always conceptually coherent.

Despite these observed tendencies, several limitations of this study should be acknowledged. First, the relatively small sample size (15 participants) limits the generalizability of the findings. Second, the use of a one-group pretest–posttest design restricts the ability to make strong causal inferences, as the observed changes may also be influenced by factors other than the intervention. Third, the data sources were limited to students' written responses, which may not fully capture the complexity of students' conceptual understanding

and representational coordination processes. Future studies are therefore recommended to involve larger samples, comparative research designs, and richer qualitative data sources such as interviews or classroom observations.

RECOMMENDATION

Based on the findings and limitations of this study, several recommendations can be proposed for future research and instructional practice. Future studies are encouraged to employ quasi-experimental or comparative designs with control groups in order to strengthen causal claims regarding the effectiveness of guided inquiry integrating physical and virtual laboratories. In addition, research with larger and more diverse samples is needed to improve the generalizability of the findings. To obtain a more comprehensive understanding of students' conceptual development and representational coordination, future studies are also recommended to incorporate richer qualitative data sources such as interviews, think-aloud protocols, and classroom observations, in addition to written test responses. From an instructional perspective, greater attention should be given to scaffolding strategies that explicitly support the translation and mapping among different representations, particularly in connecting mathematical formulations with visual and conceptual representations in physics learning.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Theo Jhoni Hartanto	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓
Pri Ariadi C. Dinata		✓			✓	✓		✓	✓	✓	✓	✓		✓
Suhartono				✓		✓		✓		✓		✓		✓

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy considerations of research participants.

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