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Enhancing Preservice Physics Teachers' Optics Understanding Through PEK-Supported 7E Inquiry Using Educational Design Research

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ABSTRACT

Purpose of the study: This study aimed to design, refine, and evaluate Photonics Explorer Kit (PEK)-supported inquiry activities for enhancing preservice physics teachers' conceptual understanding of optics, particularly in reflection, refraction, and diffraction.

Methodology: The study employed Educational Design Research (EDR) involving two iterative cycles with 89 level 200 preservice physics teachers at the University of Education, Winneba, Ghana. Cycle 1 involved 51 participants, while Cycle 2 involved 38 participants. Data were collected using a validated two-tier diagnostic test and analysed using descriptive statistics, paired-samples t-tests, effect sizes, and comparison of learners' correct conceptions, partial conceptions, misconceptions, and no-explanation responses.

Main Findings: The findings showed significant improvement in participants' conceptual understanding in both cycles. In Cycle 1, mean scores increased from 7.75 to 11.14, $t(50) = 25.78$, $p < .001$, $d = 1.95$. In Cycle 2, mean scores increased from 8.10 to 12.46, $t(37) = 29.84$, $p < .001$, $d = 2.34$. Cycle 2 also recorded higher correct conceptions and fewer misconceptions across the assessed optics concepts.

Novelty/Originality of this study: The study presents an Educational Design Research-based approach for refining PEK-supported 7E inquiry activities in optics. It shows how iterative refinement of instructional support, diagrams, inquiry questions, and multimedia can strengthen preservice physics teachers' conceptual understanding in optics, especially in resource-constrained physics teacher education contexts.

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1. INTRODUCTION

Optics is a fundamental branch of physics that explains the behaviour of light and its interactions with matter. Optics consist of concepts that underpin numerous scientific and technological applications. Therefore, having a correct conceptual understanding of optics is crucial for learners pursuing science education, especially for preservice physics teachers who will teach these optics concepts to their future students in schools [1], [2]. Studies have repeatedly demonstrated that despite the importance of optics, learners struggle to comprehend basic optics principles and frequently form false beliefs that last long even after teaching [3]-[5]. Concepts like image formation, reflection, refraction, diffraction, and interference are reportedly difficult for students to comprehend [3], [6], [7]. These difficulties are especially problematic for preservice physics teachers since a lack of conceptual knowledge may affect their future teaching strategies [8]. Findings show that learners consistently struggle to understand optical events and connect them to scientific explanations and physical facts [9]-[11]. Addressing these difficulties is urgent because preservice physics teachers with weak conceptual understanding may carry the same problems into their future classrooms.

The prevalence of conventional teaching methods that prioritise formula memorisation over conceptual thinking is one factor leading to these conceptual challenges [12]. In many physics classrooms, learners are introduced to optics through abstract diagrams and formulas with limited opportunities to investigate optical phenomena directly [1], [3]. Therefore, students often learn how to do things without really knowing the scientific principles behind them. This case shows how important it is to use teaching methods such as Inquiry-based learning which has been widely recommended as an effective approach for promoting conceptual understanding in science education [13], [14]. Inquiry-based learning encourages students to ask questions, make scientific guesses, plan investigations, gather evidence, investigate data, and come up with explanations based on what they have observed [12], [13]. Recent studies have reported positive effects of inquiry-based learning on students' conceptual understanding in science and physics education [15]-[19]. Therefore, inquiry-based learning has become an important pedagogical approach for addressing persistent conceptual difficulties in science classrooms.

The Photonics Explorer Kit (PEK) supports inquiry-based optics learning by providing materials and activities for investigating light phenomena [20], [21]. The PEK contains lenses, mirrors, lasers, optical fibres, diffraction gratings, and colour filters for exploring optics. Studies show that PEK activities improve conceptual understanding and scientific reasoning [22], [23]. The training of preservice physics educators offers a significant framework for the use of novel teaching methodologies [1]. Effective teacher education programmes must cultivate robust material knowledge while also familiarising potential educators with pedagogical strategies that facilitate meaningful learning [24]. Preservice teachers who experience inquiry-based learning are more likely to adopt similar approaches in their future classrooms and develop positive attitudes toward student-centred instruction [25]. However, few studies have looked at how preservice physics teachers might employ PEK-supported inquiry activities to improve their conceptual knowledge, especially in Ghana.

To address this gap, this study adopted Educational Design Research (EDR) which involves designing, implementing, evaluating, and refining interventions within authentic learning environments [26], [27]. The novelty of this study lies in combining the PEK, the 7E inquiry model, and iterative EDR cycles within a Ghanaian preservice physics teacher education context.

This study was grounded in constructivist theory, which explains learning as an active process in which learners build understanding through experience, reflection, and interaction with learning materials [28]. The study focused the cognitive, social, and radical constructivism. Cognitive constructivism holds that learners use prior knowledge and experience to understand new ideas [29]. Social constructivism places emphasis on learning environment where learners share ideas, challenge one another's thinking, and negotiate meaning through social engagement [30], [31]. Radical constructivism also informed the study because it views knowledge as personally constructed through the learner's active engagement with the environment [32].

Within this constructivist theoretical position, the 7E inquiry model extends earlier inquiry cycles by arranging learning into seven connected phases: elicit, engage, explore, explain, elaborate, evaluate, and extend [33], [34]. These phases align with constructivist views of learning because they begin with learners' prior ideas, provide opportunities for active exploration, and support the development of more scientifically acceptable explanations [35], [36]. Figure 1 presents the conceptual link between constructivist learning theory, the 7E inquiry model, and the PEK-supported inquiry activities used to enhance preservice physics teachers' conceptual understanding of optics.

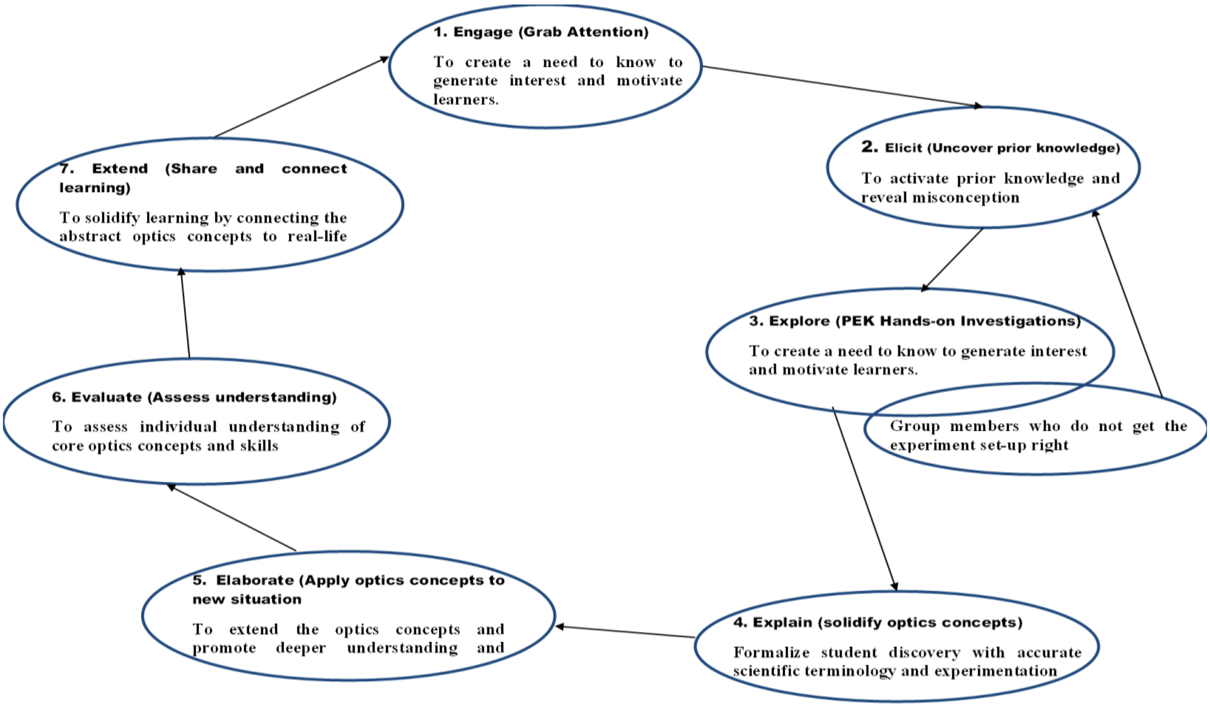

Figure 1. Instructional framework showing the implementation of the 7E inquiry model in PEK-supported optics inquiry activities.

In optics, the 7E model helped preservice physics teachers question prior ideas and rebuild understanding through inquiry. Constructivism guided the study, while the 7E model shaped the PEK-supported activities within the EDR process [37], [38].

Although previous studies have reported positive effects of inquiry-based learning and PEK-supported activities, limited evidence exists on how PEK-supported 7E inquiry activities can improve preservice physics teachers' conceptual understanding of optics in Ghanaian teacher-education contexts. Guided by EDR, this study developed, implemented, refined, and evaluated PEK-supported 7E inquiry activities to improve preservice physics teachers' understanding of reflection, refraction, and diffraction at the University of Education, Winneba. The study contributes to inquiry-based physics teaching, photonics education, preservice teacher preparation, and the iterative improvement of instructional practice.

This study aimed to develop and evaluate PEK-supported 7E inquiry activities for improving preservice physics teachers' conceptual understanding of optics. Specifically, it examined learning gains within each EDR cycle, compared participants' conceptions across the two cycles, and identified refinements from Cycle 1 that informed Cycle 2.

The study was guided by the following research questions:

1. To what extent did PEK-supported 7E inquiry activities improve preservice physics teachers' conceptual understanding of optics in each Educational Design Research cycle?
2. How did preservice physics teachers' conceptions of optics differ between Cycle 1 and Cycle 2 following refinement of the intervention?
3. What refinements to the PEK-supported 7E inquiry activities emerged from Cycle 1 and informed Cycle 2?

2. RESEARCH METHOD

2.1. Research Design

This study employed Educational Design Research (EDR) to design, implement, refine, and evaluate Photonics Explorer Kit (PEK)-supported inquiry activities for enhancing preservice physics teachers' conceptual understanding of optics. EDR is characterised by iterative cycles of analysis, design, implementation, evaluation, and refinement conducted in authentic educational settings to generate both practical solutions and theoretical insights [26], [39]. As illustrated in Figure 2, the study was conducted through two iterative implementation cycles. The analysis and exploration phase involved identifying conceptual difficulties in optics through literature review and diagnostic assessment of preservice physics teachers' understanding of reflection, refraction, and diffraction concepts. The findings informed the development of PEK-supported inquiry activities grounded in inquiry-based learning principles [27].

In Cycle 1, the initial version of the intervention was implemented and evaluated with a cohort of preservice physics teachers. Learning outcomes, classroom observations, and participant feedback were analysed to identify the strengths and limitations of the instructional design. Based on these findings, the intervention was refined through the incorporation of multimedia resources, clearer experimental diagrams, more structured inquiry questions, and additional time for hands-on investigations.

The revised intervention was subsequently implemented during Cycle 2 with a second cohort of preservice physics teachers. The second cycle served to evaluate the effectiveness of the refined design and examine whether the modifications contributed to improved conceptual understanding. Through this iterative process, the study generated both evidence of learning outcomes and practical design principles for implementing PEK-supported inquiry activities in optics instruction using EDR.

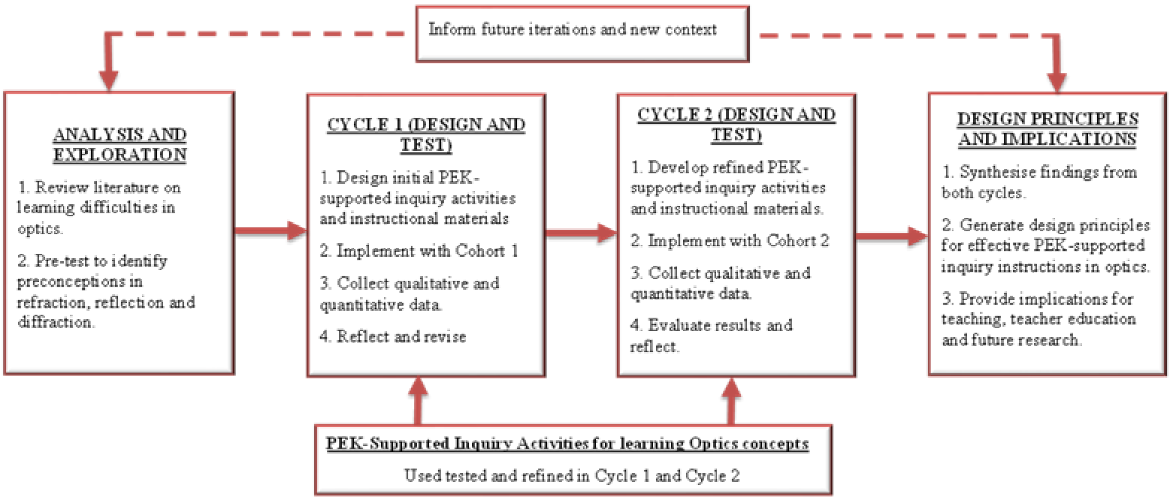

Figure 2. The EDR Cycle for Cohort 1 and Cohort 2.

2.2. Participants

The study involved two cohorts of Level 200 preservice physics teachers enrolled in the Bachelor of Science Education (Physics) programme at the University of Education, Winneba. Cohort 1 consisted of 51 participants, while Cohort 2 consisted of 38 participants. The participants were selected purposefully because they were studying optics as part of their programme and had completed introductory physics courses relevant to participating in the intervention. Participation in the study was voluntary, and all ethical requirements regarding informed consent and confidentiality were observed. Approval was sought from the Head of Department prior to the commencement of the study.

2.3. Instructional Intervention

The intervention consisted of PEK-supported inquiry activities designed around three major optics domains: reflection, refraction, and diffraction. The activities were implemented during regular instructional sessions and focused on learner-centred inquiry, experimentation, collaborative problem-solving, and evidence-based reasoning. The reflection in optics activities focused on concepts such as rectilinear propagation of light, laws of reflection, image formation in mirrors, magnification, and the mirror equation. Refraction activities addressed Snell’s law, refractive index, image formation by lenses, the thin lens equation, and total internal reflection. Diffraction activities explored wave behaviour, interference patterns, constructive and destructive interference, and the effects of wavelengths on diffraction phenomena. Throughout the intervention, participants worked in small groups to investigate optical phenomena, make observations, formulate explanations, test predictions, and communicate their findings. The PEK materials provided opportunities for direct interaction with optical concepts that were often difficult to visualise through traditional instruction strategies.

2.4. Instrumentation

Data were collected using a two-tier diagnostic test designed to assess preservice physics teachers’ conceptual understanding of reflection, refraction, diffraction, and optics concepts. The instrument consisted of multiple-choice items (first tier) and second tier that required participants to justify their responses. This structure helped the study to distinguish between correct conceptions, partial conceptions, misconceptions, and no-explanation responses. The researcher-developed instrument was subjected to expert review by specialists in physics education and educational measurement to establish content validity. Reliability was established through pilot testing before the main study, yielding a Cronbach's alpha coefficient of 0.89, indicating high internal consistency [40].

2.5. Data Collection Procedure

Data collection occurred across the two Educational Design Research cycles. For each cycle, participants completed the two-tier optics diagnostic test prior to the intervention and a post-test following completion of the PEK-supported inquiry activities. In addition to test data, observations involving small-group investigation, experimentation, discussion, explanation and presentation of findings were made during implementation and participant feedback were used to inform the refinement process between the two field-test cycles.

During the Cycle 1, classroom observations and participant feedback were used to identify challenges related to the use of PEK materials, interpretation of diagrams, inquiry questions, and the visualization of optics concepts. These findings informed the refinements introduced in Cycle 2, including an orientation session on the PEK materials, clearer diagrams, streamlined inquiry questions, additional time for experimentation, and video-based instructional resources.

2.6. Data Analysis

Data analysis was guided by the research questions. For Research Question 1, descriptive statistics, including means and standard deviations, were used to summarise pre-test and post-test performance in each cycle. Paired-samples t-tests were conducted to determine whether the differences between pre-test and post-test scores were statistically significant, while Cohen's d was calculated to determine the magnitude of the learning gains. For Research Question 2, participants' responses to the two-tier diagnostic test were categorised as Correct Conceptions, Partial Conceptions, Misconceptions, No Explanation. The distributions of these categories were compared across Cycle 1 and Cycle 2 to examine changes in participants' conceptual understanding. With respect to Research Question 3, classroom observations and participants feedback from Cycle 1 were reviewed to identify challenges in the implementation of the PEK-supported 7E inquiry activities. These findings were used to explain the refinements introduced in Cycle 2 and interpret the Educational Design Research process.

3. RESULTS AND DISCUSSION

3.1. Demographic Data of Participants

A total of 89 preservice physics teachers participated in the study across the two Educational Design Research (EDR) cycles. Cycle 1 involved 51 preservice physics teachers from Level 200, while Cycle 2 involved 38 participants from the same programme. Figure 2 presents the age and sex distribution of participants in Cycle 1. The majority of participants were male and within the age range of 21–30 years. This demographic profile reflects the typical composition of preservice physics teacher cohorts within the implantation institution.

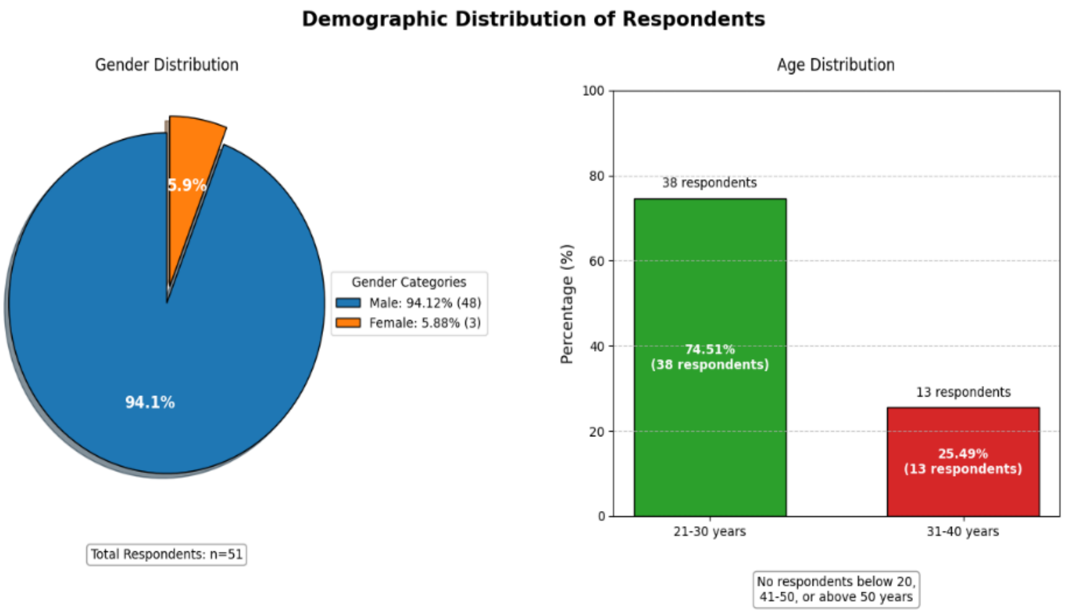

Figure 3. Demographic Distribution of Respondents in First Cohort.

3.2. Research Question 1: To What Extent Did PEK-Supported 7E Inquiry Activities Improve Preservice Physics Teachers' Conceptual Understanding of Optics?

The effectiveness of the Photonics Explorer Kit (PEK)-supported inquiry activities was evaluated using pre-test and post-test scores obtained from the two-tier diagnostic test. Table 1 presents the performance of preservice physics teachers across the two Educational Design Research (EDR) implementation cycles.

Table 1. Pre-test and post-test performance across the two EDR cycles

Cohort	N	Pre-test Mean (SD)	Post-test Mean (SD)	Mean Gain	t	p	Cohen's d
Cohort 1	51	7.75 (1.65)	11.14 (1.81)	3.39	25.78	< .001	1.95
Cohort 2	38	8.10 (1.58)	12.46 (1.72)	4.36	29.84	< .001	2.34

The results indicate substantial improvements in conceptual understanding following participation in the PEK-supported inquiry activities in both implementation cycles. In Cycle 1, participants' mean score increased from 7.75 (SD = 1.65) to 11.14 (SD = 1.81), representing a mean gain of 3.39 points. The paired-samples t-test revealed that the improvement was statistically significant, $t(50) = 25.78$, $p < .001$, with a large effect size ($d = 1.95$).

Similarly, participants in Cycle 2 demonstrated significant conceptual gains. The mean score increased from 8.10 (SD = 1.58) on the pre-test to 12.46 (SD = 1.72) on the post-test, yielding a mean gain of 4.36 points. The difference was statistically significant, $t(37) = 29.84$, $p < .001$, with an even larger effect size ($d = 2.34$).

These findings suggest that the PEK-supported inquiry activities were effective in enhancing preservice physics teachers' conceptual understanding of optics. The substantial effect sizes obtained in both cycles indicate that the intervention produced educationally meaningful learning gains. The results support previous studies that have reported positive effects of inquiry-based learning environments on students' conceptual understanding, scientific reasoning, and engagement in science education [39], [40]. By allowing participants to actively investigate optical phenomena through experimentation and observation, the PEK activities enabled learners to connect theoretical principles with observable evidence, thereby promoting meaningful conceptual learning. Photonics education studies have reported similar improvements, where hands-on inquiry activities facilitated a deeper understanding of abstract optics concepts [23].

The learning gains observed in both cycles can be interpreted through the constructivist and 7E inquiry perspectives underpinning the intervention. The elicit and engage phases enabled participants' prior conceptions to be known, while the explore phase helped them to investigate optical phenomena directly using the PEK materials. Through explanation, elaboration, evaluations, and extension, participants were supported to compare their initial ideas with experimental evidence and develop more scientifically acceptable conceptions. This is consistent with constructivist views that conceptual understanding develops when learners actively interact with materials, reflect on evidence, and reconstruct prior knowledge [41]-[43]. The findings also support previous studies showing that guided inquiry and hands-on optics activities can improve learners' conceptual understanding of abstract science concepts [44], [45].

3.3. Research Question 2: How Did Preservice Physics Teachers' Conceptions of Optics Differ Between Cycle 1 and Cycle 2?

To evaluate the effectiveness of the iterative Educational Design Research process, participants' conceptual understanding of optics concepts was compared across Cycle 1 and Cycle 2. Figure 4 presents the distribution of Correct Conceptions (CC), Partial Conceptions (PC), Misconceptions (MC), and No Explanations (NE) for the major optics concepts assessed in both cycles.

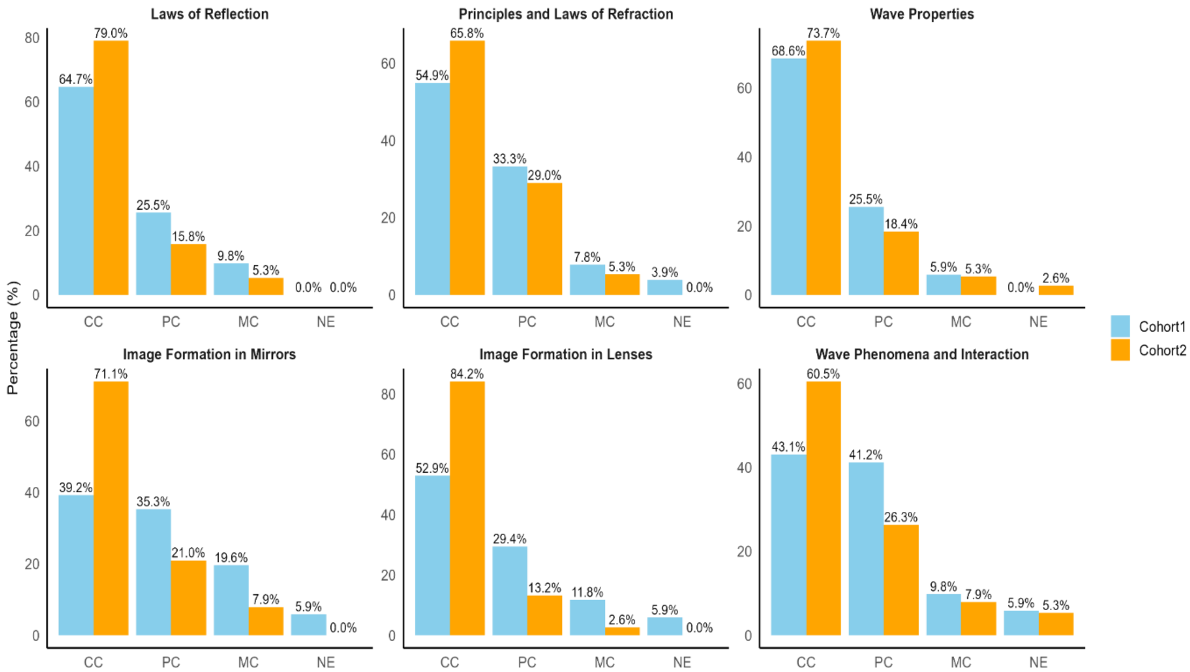

Figure 4. Comparison of Preservice physics teachers' Conceptions across Optics Concepts in Cohort 1 and 2 Field Test

The findings indicate that Cycle 2 consistently produced better learning outcomes than Cycle 1. Across all optics concepts, higher proportions of preservice physics teachers demonstrated correct conceptions, while misconceptions and incomplete explanations decreased. Cycle 2 marked a significant increase in correct conceptions regarding image formation by mirrors and lenses. Improvements were also evident in the understanding of reflection laws, refraction principles, and interference phenomena.

The enhanced performance observed in Cycle 2 may be attributed to refinements made following the evaluation of Cycle 1. Analysis of participants' responses and observations from the first implementation revealed difficulties in interpreting experimental setups, connecting observations to scientific explanations, and navigating some of the inquiry activities. In response, several modifications were introduced before the second implementation. These included the incorporation of the Photonics Explorer Kit's (PEK) multimedia resources to familiarise participants with the equipment, the provision of clearer diagrams and instructions, the use of more structured guiding questions, and additional time for experimentation and discussion.

The improvements recorded during Cycle 2 suggest that these iterative refinements enhanced participants' engagement with the inquiry activities and supported deeper conceptual understanding of optics concepts. The changes introduced after Cycle 1 provided additional instructional scaffolding while preserving opportunities for active inquiry [46], [47]. The orientation session increased familiarity with the PEK components, clearer diagrams supported interpretation of optical setups, streamlined questions reduced unnecessary cognitive load, and video-based resources improved visualization of abstract phenomena [48], [49]. These refinements reflects a central principle of Educational Design Research, where successive cycles of design, implementation, evaluation, and refinement contribute to the optimisation of educational interventions [26]. Similar studies have reported that iterative improvements to inquiry-based learning environments can enhance learners' conceptual understanding by providing greater instructional support while maintaining opportunities for active investigation and knowledge construction [50]-[52]. The finding therefore contributes to the literature by showing how PEK-supported inquiry activities can be refined for preservice physics teacher education in a Ghanaian context.

3.4. Research Question 3: What Refinements to the PEK-Supported 7E Inquiry Activities Emerged from Cycle 1 and Informed Cycle 2?

The first implementation cycle provided important insights that informed refinement of the intervention. Participants experienced difficulties using some PEK components, interpreting certain diagrams, and completing the large number of inquiry questions. In response, four modifications were introduced in Cycle 2: (i) an orientation session was conducted to familiarise participants with the PEK materials before the intervention, (ii) diagrams used in instructional and assessment materials were redesigned by the researcher to improve clarity, (iii) inquiry questions were streamlined to reduce cognitive load, and (iv) video-based instructional resources were incorporated to support the visualisation of abstract optics concepts as can be seen in Table 2. These refinements contributed to improved engagement and conceptual understanding in Cycle 2, highlighting the value of iterative design and refinement in Educational Design Research.

Table 2. Challenges identify in cycle 1 and their refinement in cycle 2

Challenge Identified in Cycle 1	Refinement Introduced in Cycle 2	Intended Benefit
Participants unfamiliar with PEK components	Orientation session on PEK equipment	Improved confidence and effective equipment use
Unclear diagrams in instructional and assessment materials	Researcher-developed diagrams	Improved interpretation of optical phenomena
Excessive inquiry questions	Streamlined and reduced questions	Reduced cognitive load and increased focus
Difficulty visualising abstract concepts	Integration of video lessons	Enhanced conceptual visualisation and understanding

Table 2 illustrates how the EDR process generated practical design principles for PEK-supported optics instruction where learners require early familiarization with unfamiliar equipment, clear visual representations of experimental arrangements, manageable inquiry prompts, and sufficient time to connect observations with scientific explanations [53]-[55].

Beyond confirming that PEK-supported inquiry activities improved preservice physics teachers' conceptual understanding of optics, the novelty of this study lies in showing how the intervention was progressively refined across two EDR cycles. The findings indicate that the value of the study was not limited to improved learning outcomes; the iterative process also strengthened the design of the activities, the sequencing of tasks, the clarity of instructions, and the support provided to learners. This demonstrates how EDR can be used not only to evaluate an instructional intervention but also to improve it systematically within an authentic teacher-education setting.

The findings from this study have practical implications for physics teacher education. Teacher educators can use the PEK-supported 7E inquiry activities to help preservice physics teachers move beyond formula-based learning towards observation, experimentation, explanations, and evidence-based reasoning in optics. The refinements identified and made in this study also provide practical guidance for implementing similar activities. That is learners should be oriented to unfamiliar equipment, supported with clear diagrams and manageable inquiry questions, and given sufficient time to connect experimental observations with theory or scientific explanations.

The findings should, however, be interpreted within the context of the study. The research was conducted with two cohorts of preservice physics teachers from one institution. Therefore, the findings were interpreted within this context. The study also used a pre-test-post-test without a control group, and conceptual understanding of the preservice physics teachers were measured a week after the intervention. Future studies could involve participants from multiple teacher-education institutions, including comparison groups where feasible. It can also examine long-term retention of optics concepts and investigate whether preservice teachers transfer PEK-supported inquiry approaches into their future classroom practices..

4. CONCLUSION

This study employed an Educational Design Research (EDR) approach to design, implement, refine, and evaluate Photonics Explorer Kit (PEK)-supported inquiry activities for enhancing preservice physics teachers' conceptual understanding of optics.. The findings revealed that the intervention significantly improved participants' understanding of concepts related to reflection, refraction, diffraction, and interference. The increase in post-test scores and the large effect size indicate that the instructional design was effective in promoting conceptual learning in optics. Analysis of individual concepts further demonstrated substantial gains in understanding of the law of reflection, image formation by mirrors and lenses, refractive index, Snell's law, total internal reflection, and interference phenomena. These improvements suggest that the PEK-supported inquiry activities provided opportunities for learners to engage meaningfully with optical phenomena through observation, experimentation, discussion, and evidence-based reasoning. From an Educational Design Research perspective, the comparison across the two cycles showed that the refinements introduced after Cycle 1 strengthened the instructional process and participants' conceptual understanding in Cycle 2. The findings therefore demonstrate the value of interventions that are grounded in theory, responsive to classroom realities, and improved through repeated implementation and evaluation. The study has important implications for physics teacher education in physics. Teacher educators should integrate inquiry-based instructional approaches and hands-on optics activities into optics teaching to promote deeper conceptual understanding among preservice teachers. Curriculum developers and science educators may also consider incorporating PEK-supported activities into teacher preparation programmes. Future studies should extend the intervention to other areas of physics, involve participants from different institutions, examine long-term retention of conceptual understanding, and investigate classroom transfer.

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