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Development and Assessment of a Flipped Classroom Teaching Sequence for Enhancing Conceptual Understanding in Geometrical Optics

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Abstract

The flipped classroom model is increasingly recognised as a viable alternative to traditional teaching methods; however, its effectiveness largely depends on factors such as instructional design, implementation strategies, and the specific educational context. The current literature does not adequately address specific strategies for teachers to implement the flipped classroom model in practice. Therefore, the purpose of this study was twofold: first, to design a teaching sequence as a practical product that can be used to deliver lessons, and second, to assess the effectiveness of the teaching sequence as a tool for enhancing knowledge development in geometrical optics. The participants were third-year physical science students (N = 93) enrolled in a Bachelor of Education degree programme, who took a geometrical optics course lasting one semester. The methodology employed was design-based research, and this article provides a detailed description of the first iteration, including how the teaching sequence evolved over four years. The initial results obtained from tests performed during and after the implementation of the initial iteration of the teaching sequence showed that the teaching sequence was more effective in enhancing students' recall of facts and basic concepts than in promoting their ability to explain ideas or concepts and apply that knowledge to new situations. The teaching sequence was refined over four years, suggesting that while the flipped classroom model is a viable tool in physics teacher education, it is not a one-size-fits-all solution. Instead, a continuously evolving, context-sensitive design is necessary.

Keywords: flipped classroom model; teaching sequence; design-based research

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Academic Editors: Hani Morgan and Ignasi Iriondo

Received: 25 June 2025
Revised: 14 February 2026
Accepted: 21 February 2026
Published: 29 April 2026

1. Introduction

1.1. Background of the Study

Geometrical optics is a fundamental branch of optics that examines the behaviour of light as it interacts with lenses, mirrors, and other optical systems [1]. Despite its importance in real-life contexts, students often struggle with abstract concepts like Snell's Law, image formation, and lens aberrations in the curricula [2]. Traditional lecture-based instruction may fall short in addressing these challenges, highlighting the need for effective and efficient approaches to foster students' development as innovative thinkers supported by conceptual understanding [3]. Conceptual understanding refers to the ability to internalise principles beyond rote memorisation, enabling learners to apply knowledge flexibly [4].

https://doi.org/10.3390/higheredu5020038

In geometrical optics, this entails visualising ray diagrams, predicting image behaviours, and connecting mathematical formalism to physical phenomena.

The rise of a digital generation, shaped by rapid technological developments in society, has driven the need for innovations in teaching practices to better support both students and educators [5,6]. Studies suggest that the flipped classroom model (FCM) provides students with flexibility and ability to manage their study, work independently [7], and enhance conceptual mastery by freeing class time for targeted interventions [8], yet few focus specifically on optics [9].

FCM is a teaching strategy that combines face-to-face teaching with technology-enhanced instruction [5,10]. It is a form of blended learning that incorporates diverse instructional methods, including direct and indirect instruction, collaborative teaching, and individualised computer-assisted learning. Instructional content (e.g., videos, readings) is delivered before class, while in-person sessions are used for collaborative problem-solving and conceptual clarification [11]. Knowledge acquisition occurs through visual engagement outside the classroom and classroom discussions, as opposed to merely reading and listening to the teacher's monologue, as in the traditional approach [5]. FCM is characterised by two distinct components: (1) out-of-classroom preparation for in-class discussions and (2) use of class time for collaborative engagements that require reflection or application of concepts [12]. The before-class preparation introduces learners to foundational content that would traditionally be covered during lectures [13], allowing for class time to be reserved for active learning and problem-solving. In contrast, traditional teaching often involves students arriving at the classroom unprepared and passively receiving information from the lecturer.

Given the significance of geometrical optics within the school curriculum and its relevance to post-school applications, pre-service teachers must develop a strong conceptual understanding of the topic. Pre-service teachers are individuals currently enrolled in teacher education programmes who are preparing to enter the teaching profession. They require both pedagogical competence and subject-specific expertise. In this study, pedagogical knowledge is linked to their experience of applying the FCM during their training, with a focus on evaluating its effectiveness in enhancing their conceptual understanding of geometrical optics.

1.2. Literature Review

The flipped classroom model (FCM) is frequently lauded for its potential to transform passive learning environments into active hubs that foster higher-order thinking, motivation, and self-efficacy [14–16]. Evidence from teacher education programmes, for instance, demonstrates its capacity to enhance student performance and engagement, particularly for those from non-specialist backgrounds, such as those with no science background [17,18]. However, a critical synthesis of the literature reveals that this promise is not automatic; it is mediated by two interconnected factors: the rigour of empirical validation and the specificity of instructional design. It is at the intersection of these themes that a critical gap in the context of geometrical optics education becomes apparent, directly motivating the dual objectives of this study.

An examination of the rigour of empirical validation in FCM studies showed that there is a disconnect between enthusiasm (derived potential benefits) and empirical rigour (how they were arrived at). A closer examination of the empirical studies tempers the initial positive benefits of the FCM, suggesting that perceived successes may often be conflated with other instructional elements. For example, the study by [7], working with Indonesian prospective chemistry teachers, employed a mixed-method exploratory sequential design to evaluate a sustainability-oriented teaching learning sequence (TLS) on fire-retardant bamboo. Their study, conducted to assess the impact on self-efficacy and perceptions, found significant improvements (e.g., 88.9% in self-efficacy), yet these gains may reflect the novelty of the topic rather than the flipped structure itself. Their reliance on pre–post questionnaires (self-report data) without probing deeper cognitive shifts raises a critical question: does the FCM foster genuine conceptual mastery or merely procedural confidence?

Similarly, a study by Carli, Fontolan and Pantano [19] in an Italian high school transformed a face-to-face optics TLS into a distance-learning format using video experiments and simulations, framed by backward design and inquiry-based learning, as one way of implementing FCM. While students performed well (average grade 7.0/10), the lack of a comparative group undermines claims of the flipped model's superiority over traditional methods. In addition, the study's reliance on teacher-assessed rubrics and self-reports, rather than independent measures of conceptual understanding, leaves open an unanswered question: did the observed outcomes stem from the flipped design or simply the structured clarity of the TLS? Collectively, these studies highlight a recurring methodological shortfall in the FCM literature: a lack of rigorous, comparative designs capable of isolating the specific value-added of the flipped model beyond simply providing structured, clear instruction.

To strengthen the methodological gap in the literature, this study was grounded in the methodology of Design-Based Research (DBR). DBR is a pragmatic research paradigm that moves beyond simply evaluating an intervention to actively engineering and refining educational designs within real-world contexts [20,21]. Its core affordance lies in addressing complex problems of educational practice by forging a direct connection between theory, design, and implementation. Unlike controlled experiments that prioritise isolating variables, DBR embraces the complexity of the classroom, making it uniquely suited for investigating how a flipped classroom sequence functions in practice. The methodology is characterised by iterative cycles of design, enactment, analysis, and redesign [22]. This iterative process was central to this four-year study, allowing the researchers to systematically refine the teaching sequence based on empirical data from each implementation. Consequently, the final product (Section 3.5) is not a static lesson plan but a theoretically grounded and empirically validated design. Furthermore, the outcome of DBR is the generation of design principles or a theoretical framework that transcends the local context [23]. Therefore, this study employed DBR not merely as a procedure but as a foundational framework to ensure that the resulting teaching sequence was both a practical solution for teaching geometrical optics and a transferable model that contributes to the broader literature on flipped learning design.

A continuation of the examination of previous studies on FCM reveals the critical need for discipline-specific and conceptually grounded design. The challenge of effective implementation of FCM is compounded by a one-size-fits-all approach. The literature identifies the absence of universal design principles as a significant barrier to its effectiveness, noting that FCM's effectiveness is highly contingent on context and subject matter [24]. This is particularly acute in physics, which relies on sequential and scaffolded learning. Poorly designed pre-class materials can fail to establish the foundational knowledge necessary for in-class application, while passive group work and traditional assessments can undermine FCM's core goals [24,25]. This critique points to a necessity for content-oriented theories tailored to specific subjects [24]. It is in this context that the study focused on geometrical optics.

Nowhere is this need more evident than in geometrical optics. Although the FCM has been applied in areas such as mechanics, its potential in geometrical optics remains largely untapped. Conventional teaching in this domain often prioritises procedural drills (e.g., solving lens equations) over conceptual integration, resulting in a fragile understanding of fundamental ideas such as light propagation and image formation [26]. This creates a stark contradiction: we have a pedagogical model (FCM) acclaimed for fostering deeper understanding, applied within a discipline (physics) that demands it, yet absent from a sub-discipline (geometrical optics) where the need for conceptual remediation is arguably most acute. Thus, the development of a content-oriented sub-discipline (geometrical optics) theory was worthy of consideration for the study.

A critical synthesis of the above discussions indicates a need to bridge the gap between the general promise (the potential benefits of the FCM) and a specific, tested solution (the design). Synthesising these themes reveals that the broad promise of the FCM is insufficient. The literature is populated with studies that either lack the rigour to demonstrate the FCM's unique efficacy or apply the model without adequate discipline-specific adaptation. This constitutes the definitive research gap: the absence of a rigorously developed and empirically assessed FCM intervention explicitly designed to address conceptual understanding in the underserved domain of geometrical optics.

It is precisely this gap that dictates the dual, integrated objectives of this study, which are to:

1. Design a flipped classroom teaching sequence as a practical product specifically tailored to improve conceptual understanding in geometrical optics;
2. Test the effectiveness of this teaching sequence in enhancing students' conceptual understanding, moving beyond self-report data to provide empirical evidence of its cognitive impact.

By adopting this problem-driven approach, the study directly responds to critiques within the literature. It moves beyond a simple "does it work?" question to ask, "how can a purpose-built FCM tool be created to address a specific conceptual deficit effectively?" This leads to the scientific question of: What instructional design principles within a flipped model are most effective for promoting conceptual understanding in foundational physics topics? Our study addresses this by focusing on geometric optics. The aim is to design and evaluate a conceptually driven flipped classroom sequence. By doing so, the study pursues the following research questions:

(a) How can a flipped classroom teaching sequence be designed to improve conceptual understanding of geometric optics?
(b) How does a flipped classroom teaching sequence affect students' conceptual understanding of geometric optics?

In direct response to the study's dual objectives, the iterative development and assessment conducted across four cohorts were expected to yield two key outcomes. First, the process was anticipated to result in a robustly designed teaching sequence (addressing RQa and Objective 1), refined through successive iterations to optimally target conceptual difficulties in geometrical optics. Second, the empirical assessment was expected to demonstrate that this sequence enhances students' conceptual understanding (addressing RQb and Objective 2). Ultimately, the study aimed to deliver not only a teaching tool but empirically validated evidence that a discipline-specific flipped classroom approach can effectively bridge the gap between procedural proficiency and deep conceptual understanding in geometrical optics.

In doing so, the study contributes a validated, content-specific TLS solution that bridges the critical divide between the broad potential of the FCM and its disciplined, effective application. It provides a teaching tool for geometrical optics that is empirically validated and purposively designed to address difficult concepts. More broadly, the study offers evidence of how the general promise of the flipped classroom can be translated into a practical and effective approach within a specific disciplinary context.

The remainder of this article is structured as follows: Section 2 (Methodology) details the design-based research methodology employed. It first presents the instructional design framework developed—articulating the principles that guided the creation of the pre-class materials and in-class activities—which constitutes the primary outcome of addressing RQa. It then describes the study context (participants, course), the specific geometric optics sequence developed, the instruments used (e.g., validated tests, open-ended questionnaire), and the data collection and analysis procedures (e.g., item analysis statistics) that were used to answer RQb.

Section 3 (Results) is organised around the two research questions. First, it presents the initially designed teaching sequence as the product of the initial design process (RQa). Second, it reports the quantitative and qualitative findings on its effectiveness (RQb), including salient themes from student interviews (questionnaire) regarding various aspects of the instructional approach, the changes based on student interviews, and the final design of the teaching sequence.

Section 4 (Discussion) interprets the results by revisiting the theoretical framework. It discusses how the specific design features of our sequence appear to have facilitated (or not) conceptual change, thereby proposing actionable design principles that address our overarching scientific question. This section also examines the study's limitations, assesses practical implications for instructors, and suggests directions for future research. Finally, Section 5 (Conclusions) summarises the study's key contributions: the empirically tested instructional sequence for geometric optics and the evidence-based design principles for flipped learning that can inform efforts to overcome conceptual difficulties in physics and other STEM domains.

2. Methodology

Having established the research gap in the introduction, this section details the methodology undertaken to answer the two research questions employed to address it. The methodology is presented in five subsections: Section 2.1 (Research Design) outlines the overall design-based research framework that guided the study, justifying its suitability for simultaneously developing an educational intervention (the flipped sequence) and studying its effects. The core of the intervention is presented in Section 2.2 (Design of the First Iteration of the Teaching Sequence), which elaborates the design principles and the resulting flipped classroom sequence for geometric optics, constituting the direct answer to RQa. Section 2.3 (Context and Research Participants) then describes the educational setting and the student cohort involved, establishing the scope and transferability of the study. Section 2.4 (Research Instruments) specifies the tools used to measure conceptual understanding. Finally, Section 2.5 (Data Analysis) explains the statistical analysis method applied to the collected data to evaluate the intervention's impact, thereby addressing RQb.

2.1. Research Design

Design-based research (DBR) is an approach to educational research that seeks to provide means to develop innovative teaching and learning environments while also seeking to develop contextualised theories of learning and teaching [27]. DBR was used during the entire study of the thesis from which this paper is extracted. A teaching sequence was developed during the initial phase of the study intervention design. This paper presents the first iteration of a four-part research series. This sequence served as the foundation for further innovations and iterations. DBR is particularly well-suited to the theoretical framework provided in this study as it focuses on the iterative development and testing of educational interventions in real-world settings. It involves designing learning activities grounded in social constructivist principles, implementing them, and refining them based on how well they help students progress through Bloom's taxonomy. Thus, the research design allows for studying both the process and the learning outcomes within the social constructivist framework, emphasising the cognitive development modelled by Bloom's taxonomy.

2.2. Design of the First Iteration of the Teaching Sequence

This first instructional sequence's design and activities followed five design principles [28] described below. These principles incorporate the suggestions in the model provided by [18] and the other authors cited earlier in Section 2.1.

1. Learning builds on prior knowledge: Prior exposure to the video lectures ensured a foundational base of knowledge upon which new knowledge could be built. The video lectures introduced basic facts, concepts, principles, information needed for class discussion, and activities to develop higher-order cognitive skills. Students were required to watch the video before coming to class, which was different from what students were normally used to doing in traditional classrooms.
2. Learning is a complex process requiring scaffolding: Understand that new content may require lecturer guidance, as students may be unable to master it independently [13]. Based on propositions by [13], it was necessary to demonstrate the new approach (FCM) by implementing it in class. Students would watch a video in class while the lecturer explained how they should interact with the content of the video lecture. Thus, it guided how the new content in the video lectures was to be interrogated. In this way, the students were assisted in identifying key aspects of the content during the exploration stage. Thereafter, during the classroom discussion, the students were engaged in higher-order learning activities, from simple to more demanding activities as per Bloom's taxonomy. Students formed groups, and the instructor provided guidance on how to carry out the activities. For example, students were asked to form groups of five members each, with the freedom to choose their group members. A worksheet with learning tasks, the objectives for each task, and steps to solve the task was provided. The worksheet was not provided online as the system was unreliable during the study.
3. Learning is facilitated through interaction with tools: Technological tools such as the internet, the Blackboard platform, smartphones, computers, video lectures, etc., as well as books and other learning resources, are some of the tools students are expected to be interacting with in their learning. The design requires the lecturer to make these tools readily accessible to students to support their learning. In this study, students were exposed to video lectures taken from YouTube, which were downloaded by the lecturer and posted on Blackboard.
4. Learning is facilitated through interaction with others: Student–student and student–lecturer interactions were prioritised under the theory of social constructivism. Classroom and post-classroom activities were conducted to promote dialogue among students within their groups. The motive behind this principle was to provide students with an opportunity to interact with each other and the lecturer, and a platform to test their understanding. WhatsApp groups formed amongst students led to a learning community comprising students and the lecturer.
5. Learning is facilitated through establishing specific behavioural practices and expectations: To align with the FCM, which expects the students to take responsibility and accountability for their learning, it is essential to establish behavioural practices that encourage greater investment in their studies. Activities were designed to promote student engagement through group collaboration and individual focus. Course design incorporated clear expectations for task deadlines, class attendance, and course

requirements. Group interactions adhered to established rules during discussions, and students were motivated to follow acceptable behavioural practices and meet expectations by awarding additional points for completing tasks. Classroom activities were planned to emphasise teamwork, while video lectures were designed for individual viewing. Figure 1 shows how the key ideas underscored by the five principles above flow and build upon each other. The flow diagram was used to design and develop the initial teaching sequence (see Section 3.1).

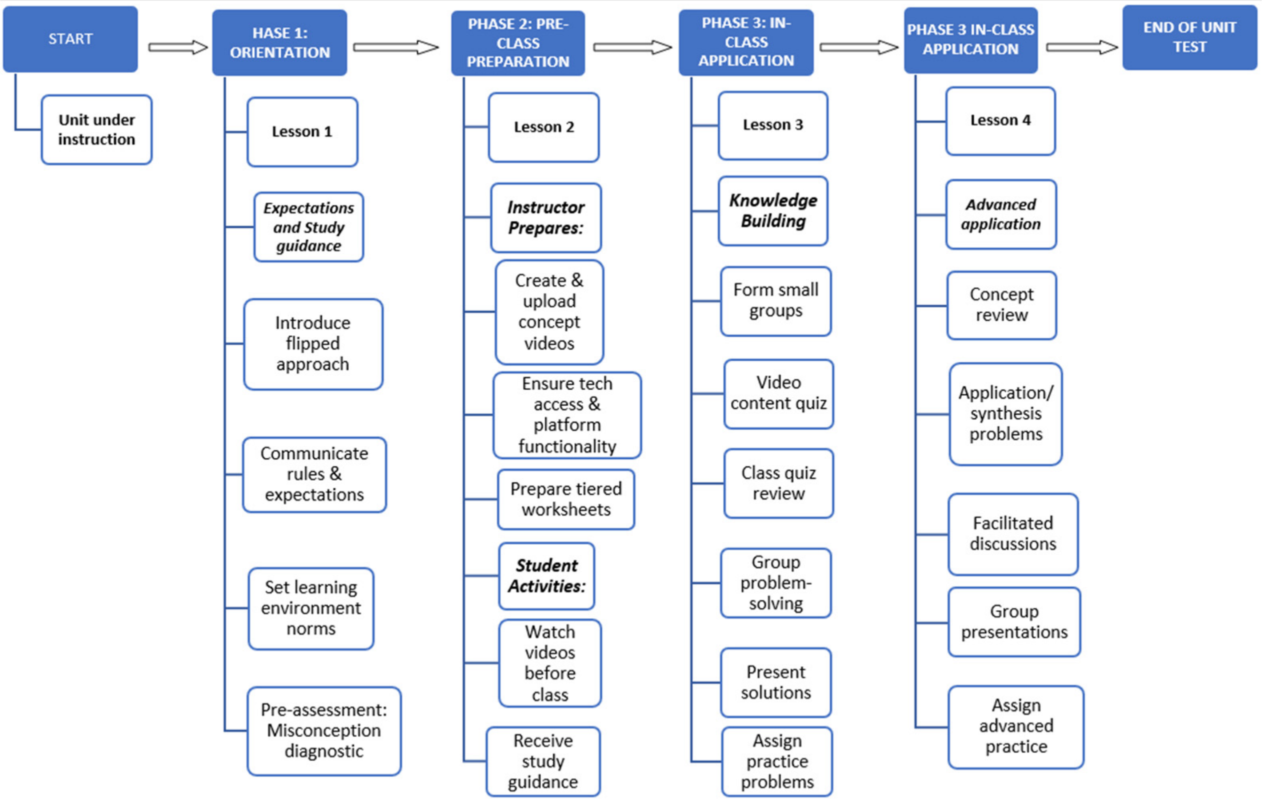

Figure 1. Initial design model for the flipped classroom instructional sequence.

Figure 1 maps the pedagogical rationale and temporal flow of the three-phase intervention, moving from learner orientation (Phase 1) to individualised preparation (Phase 2) and culminating in structured, collaborative in-class application (Phase 3). It visualises how the five core design principles explained in the previous paragraph are operationalised into specific activities to address the research objective of creating a conceptually focused learning sequence for geometric optics. Text in bold italics represents the issue under focus in that lesson.

2.3. Context and Research Participants

There were 93 student participants enrolled in the geometrical optics course offered at the third-year level to students studying for a Bachelor of Education in Physical Science at one of the South African Universities offering this course. All 93 students completed the study with no dropouts or attrition, helping to ensure full data availability for analysis. Their ages ranged from 20 to 21 (33%), 22–24 (53%), and 25 years and above (13%). There were more males (61%) than females (39%). The course was delivered in English, as English serves as the primary medium of instruction despite being a non-native language for all the participants, including the instructor. The institution emphasises teacher-centred instruction, is classified as under-resourced by national education benchmarks, has limited digital infrastructure (e.g., shared computer labs among various faculties, intermittent internet), and had no prior exposure to flipped classroom models. The course was meant only for those who major in physical science with a minor in mathematics, technology, or life science in their final years of the four-year degree programme. The course comprised three geometrical optics units: the Ray model, Refraction, and Reflection of light. The duration of class time was three hours per week. The same lecturer had taught the course for the past four years in the first semester. Before participation in the study, all students were provided with detailed information regarding its purpose, procedures, potential risks, and benefits. Participation was voluntary, and students were assured that their involvement or decision to withdraw at any stage would not affect their academic performance or standing in the course. Ethical approval for the study was obtained from the Ethics Research Committee of the University.

2.4. Research Instruments

The research instruments used were formative and summative tests and an open-ended questionnaire. The tests were developed as instruments to measure the level of student achievement. The open-ended questionnaire allowed students to reflect on their interactions and the use of technology through video lectures before class and elicit their views on using the FCM. Figure 2 illustrates how the data collection instruments (formative and summative assessments/tests) were employed after the implementation of the teaching sequence on a particular unit. The data collected were analysed to assess the level of mastery of the subject matter taught. The analyses and synthesis phases were used to evaluate student understanding and experience throughout the physics learning process.

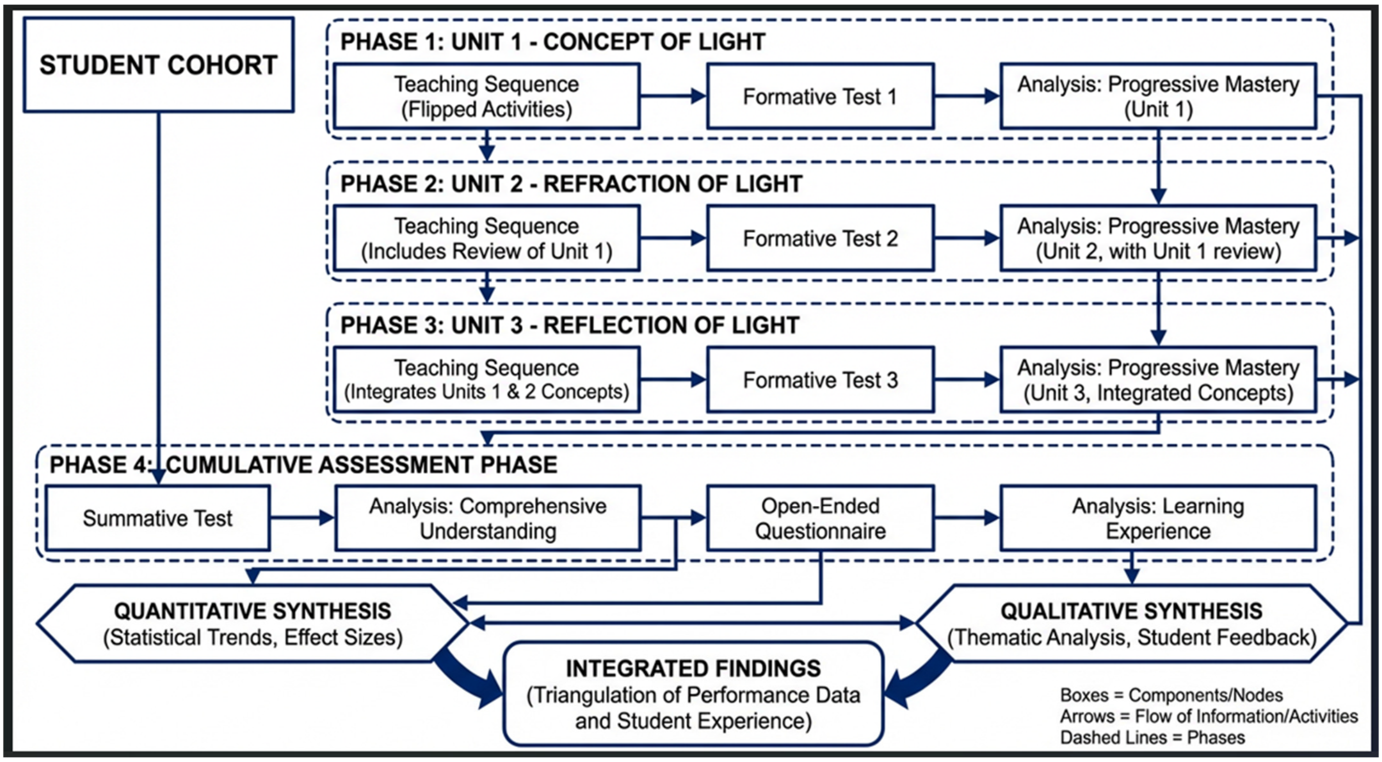

Figure 2. Sequential flow of data collecting instruments (tests) after implementation of the teaching sequence and the analysis of data collected.

2.4.1. Formative Tests

There were three formative tests, each corresponding to a particular course unit. The first formative test was about the concept of light and had 12 items: three focused on retrieval of information, three on comprehension, and six on application. The second test with six items was about refraction of light, of which two were on knowledge, two were on comprehension, and two were on application. The third test comprised thirteen items on the reflection of light, with three items focusing on knowledge, two on comprehension, and eight on application.

2.4.2. Summative Test

The summative instrument was a test given at the end of the course instruction as an end-of-semester examination. It comprised eight items. Its main purpose was to provide supporting evidence to determine students' understanding. Students were tested on concepts and applications by asking questions about the entire content of the course.

2.4.3. Validity of the Tests and Memo (Marking Guide)

To ensure the validity of the tests and memo, they were subjected to content and face validity by engaging three experienced senior physics lecturers in the department to check the extent to which the test items represented the course objectives and measured what they claimed to measure. In addition, memos were provided to ensure that the answers agreed with the questions' requirements.

2.4.4. Reliability of the Tests

Reliability was established by calculating the phi (lambda) dependability index ($\varnothing$). This is an agreement coefficient dependent on the cut-off point of the tests. In this study, the cut-off point was 50%. The index measures the internal consistency or homogeneity of items in a test and was found to be $\varnothing$ (0.50) = 0.92, indicating high reliability.

2.4.5. The Open-Ended Questionnaire

The open-ended questionnaire had 13 items and was used to elicit the students' experience of the FCM. The items focused on the instructional approach, class activities, class discussions, graded activities (including quizzes and homework problems), video lessons, textbook material, communication in the subject area, student support, understanding of geometrical optics, how content was taught, skills gained, attitude towards the subject after instruction, and how this approach may be extended to study other modules. The design focus in the first iteration aimed at developing a sequence of lessons with their corresponding activities based on the FCM framework.

2.4.6. Data Collection Procedure

The tests were administered under the supervision of the instructor and other departmental colleagues, while the end-of-semester examination was administered following the normal university timetable. All formative and summative tests lasted one and a half hours. The questionnaire was administered at the end of the course and took an hour to complete.

2.5. Data Analysis

The test items were scored using a marking guide with predefined criteria for correct responses, where each item measured a specific objective. Scores were analysed through item analysis statistics, which evaluates test performance against established objectives. This process includes calculating item difficulty (p), determined by dividing the number of correct responses (R) by the total number of responses (N) ($p = R/N$), expressed as a decimal or percentage [29]. The p-value reflects the proportion of students answering an item correctly.

Item analysis applies Classical Test Theory (CTT) to evaluate test items using its foundational assumptions. CTT assesses students' knowledge gained from the FCM activities by analysing test performance in a specified domain [30]. This method is computationally simple, cost-effective, and suitable for small sample sizes. CTT provides insights into individual performance [31] and evaluates test quality by examining item statistics. Since test scores are the sum of individual item scores, analysing each item helps identify problematic content areas and refine instruction [32]. Item difficulty levels were classified as shown in Table 1.

Table 1. Interpretation of item difficulty index.

Bloom's Domain	**Difficulty: $p \leq 0.30$ (Low Proficiency)**	**Moderate: $0.31 \leq p \leq 0.70$ (Moderate Proficiency)**	**Easy: $p > 0.70$ (High Proficiency)**
Remembering	Cannot recall basic terms/facts.	Recalls most facts but with gaps.	Accurately recalls all key information.
Understanding	Misinterprets core concepts.	Explain ideas partially.	Articulates concepts clearly with depth.
Applying	Fails to transfer knowledge.	Applies concepts in simple contexts.	Solves novel problems independently.

Data from the open-ended questionnaire were coded according to the technique described by [32].

3. Results

This section presents the empirical findings of the study, organised according to the two primary research questions: (a) How can a flipped classroom teaching sequence be designed to improve conceptual understanding of geometric optics? (b) How does a flipped classroom teaching sequence affect students' conceptual understanding of geometric optics? The structure moves from presenting the designed product to reporting on its effectiveness. Section 3.1 (Initial Design of the Teaching Sequence (RQa)) first provides the detailed blueprint of the instructional sequence, including examples of pre-class and in-class learning activities. This output directly fulfils the design objective of RQa. Section 3.2 (Effectiveness of the Designed Teaching Sequence (RQb)) then reports the results from the assessment activities using descriptive statistics to assess the magnitude and significance of changes in student understanding. Finally, Section 3.3 (Opinions on Instructional Aspects) complements the quantitative data by presenting thematic insights from student interviews, offering a nuanced view of how the intervention influenced specific conceptual pathways. Together, Sections 3.2 and 3.3 provide a multi-faceted answer to RQb. Section 3.5 concludes the section by presenting the final product of the designed teaching sequence achieved through the various iterations.

3.1. Initial Design of the Teaching Sequence (RQa)

A generic pilot teaching sequence was developed in the first iteration, using the design criteria of [28] (see Table 2).

The reversal of the roles of the in and out of classroom activities was expected to encourage students to independently engage with instructional content before attending class.

Table 2. A generic pilot teaching sequence developed in the first iteration.

Unit Under Instruction	
Teaching Phases	**Lessons Planned for the Unit and Principles Guiding Them**
Phase 1 Information dissemination	Lesson 1: Expectations and regulations [learning is facilitated through the establishment of specific behavioural practices and expectations] • Inform students about the new approach to teaching and learning involving online videos and other materials; • Provide students with course/unit expectations or regulations, e.g., attendance rules, meeting deadlines, and missing tasks regarding formative quizzes, tests, summative assessments, and reflection on class activities; • Emphasise the need for establishing productive learning environments, e.g., a classroom environment that encourages active participation, respectful communication, group activities, and willingness to ask questions; • Assess students' misconceptions of the unit through a written task and consider literature findings.
Phase 2 Out-of-class personalised learning	Lesson 2: Virtual class Knowledge and understanding. Step 1: Preparation of teaching and learning materials. [learning is facilitated through interaction with tools] • Prepare video material for the whole unit to familiarise students with basic concepts, equations, laws, and theories related to the unit under study; • Ensure the availability or accessibility of computers or smartphones for students to work with online material; • Secure functionality of online platforms such as Blackboard; • Ensure the availability of prescribed textbooks and other reference books through the library; • Prepare worksheets with problems at different cognitive levels. Step 2: Ascertaining the student's prior knowledge. [learning builds on prior knowledge] • Upload video material on the online platform (Blackboard) and tell students to watch it before they come to the next class session. Allow enough time between uploading the videos and the class session. • Offer guidance and support on how students study key ideas from video material.
Phase 3 In-class group learning	Lesson 3: Engaging students with practice problems. [learning is a complex process requiring scaffolding] Step 1: Organising students for class activities. [Learning is facilitated through interaction with others] • Divide students into small groups (five or fewer) with members selected by themselves; • Assign each group a specific worksheet problem to which they will present the solution before others in class; • Encourage students to work collaboratively on solving problems and discussing within their groups. Step 2: Practising exercise: knowledge and understanding. • Students write a short quiz based on the uploaded online video material to assess understanding; • Grade student work on quiz performance; • Revise quizzes with students together as a class; • Review key ideas of the content uploaded on the online platform; • Provide worksheets with problems testing students' knowledge and understanding of the content's key ideas; • Ask students to work out solutions for these problems in their groups; • Offer guidance and support to students as they engage with problems; • Provide students with the opportunity to make presentations of their findings; • Provide additional problems for post-class practice at the end of the lesson. Lesson 4: Practising exercise: application and evaluation [still part of the principles applied to lesson 3] • Review key ideas with students as discussed in lesson 3; • Provide worksheets for problems requiring application, synthesis, and evaluation of students' knowledge and understanding of the unit's key ideas; • Facilitate discussions about the problems on the worksheets; • Provide students with the opportunity to present their findings; • Provide additional problems for post-class practice at the end of the lesson.
End of unit test	

3.2. Effectiveness of the Designed Teaching Sequence (RQb)

Students' performance within each category of Bloom's cognitive domains, on each of the three formative tests and one summative test, administered after implementing the first iteration of the teaching sequence, is presented in Figure 3. The four assessments were on: the ray model of light, refraction of light, reflection of light, and the end-of-semester examination.

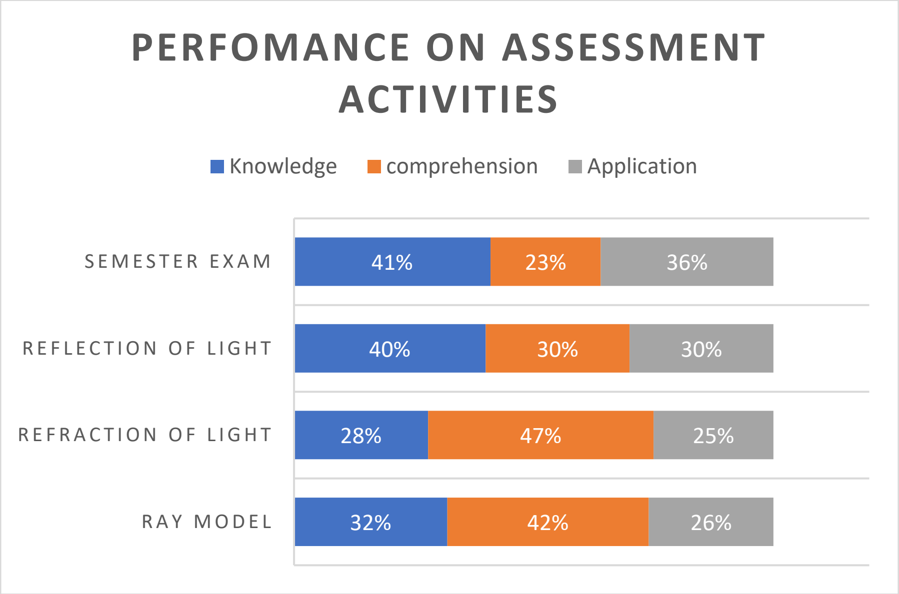

Figure 3. Students' performance in formative and summative assessment activities.

These figures were obtained by analysing performance scores through item analysis statistics, which evaluates test performance against established objectives, as explained in Section 2.5 under methodology.

Examining the effectiveness of the flipped classroom teaching sequence on enhancing conceptual understanding, these results (Figure 3; Table 3) show that for the ray model test and the refraction of the light test, students displayed a common trend. They performed best in the comprehension category, demonstrating an understanding of the concepts (42% and 47%, respectively). However, their knowledge proficiency was relatively lower (32% and 28%, respectively), indicating a gap in their grasp of fundamental principles. The lowest proficiency was in the application category for both tests, with scores of 26% and 25%, respectively, suggesting that students struggled to apply their knowledge of the ray model and refraction effectively to solve practical problems.

Table 3. Students' proficiency levels linked to the difficulty index (p).

Domain	Ray Model	Refraction	Reflection	Final Exam	Effect Size (Cohen's d)	Interpretation
Knowledge	32% $0.31 \le p \le 0.70$	28% $p \le 0.30$	40% $0.31 \le p \le 0.70$	41% $0.31 \le p \le 0.70$	+0.4 (Medium)	Mild retention of unit content.
Comprehension	42% $0.31 \le p \le 0.70$	47% $0.31 \le p \le 0.70$	30% $p \le 0.30$	23% $p \le 0.30$	−1.1 (Large Decline)	Significant forgetting by final exam.
Application	26% $p \le 0.30$	25% $p \le 0.30$	30% $p \le 0.30$	36% $p \le 0.30$	+0.3 (Small)	Minimal integration of unit skills.

In contrast, the reflection of the light test showed a different pattern. Here, students demonstrated a greater knowledge proficiency at 40%, implying a solid foundation in the subject matter. However, their comprehension and application proficiencies were at 30%, indicating a relatively balanced but slightly lower understanding and ability to apply the concepts practically.

On the other hand, the end-of-semester examination also had variations in proficiency levels. Knowledge proficiency was 41%, suggesting a satisfactory understanding of the material, although it could still be improved. Comprehension was at 23%, notably lower than in the other tests, indicating potential issues in students' deep understanding of the subject. At 36%, application proficiency was comparatively stronger than comprehension, but there is still room for improvement. These results reveal a mixed picture of student proficiency levels.

Thus, the findings are significant in revealing specific areas of strength and weakness in students' understanding of geometrical optics. For each of the three units studied, weaknesses are observed in specific areas of the cognitive domains after the assessment of the unit. According to Bloom's cognitive classification, conceptual understanding may comprise both comprehension of knowledge and the ability to apply it. The results demonstrate that students generally had stronger comprehension and knowledge in some areas but struggled with practical application, indicating that further emphasis on application in all units of study may be needed in the teaching sequence. This information guided the educator in tailoring his teaching methods to address these lacking areas. To determine the effectiveness of the teaching sequence, these sequences yielded results that show students' performance was generally poor and below the cut-off point set by the instructor (see Figure 3). The results, therefore, implied that the design of the teaching sequence had weaknesses that needed to be modified. The researcher thought everything had been addressed in the first design, but after the first iteration, realised that it did not work as expected. Prior knowledge was necessary to show the video, which did not seem to work, and a pretest to assess the misconceptions was needed. Thus, in the second iteration, the sequencing of the strategies and what was involved was altered. It was necessary to restructure the instructional activities into three main stages: (i) a planning stage, which looked into course goals, misconceptions (assessed through a pre-test), unit objectives, type and quantity of learning activities in terms of videos clips, in-class tasks and experiments for each unit; (ii) an implementation stage, which looked into details of tasks and interactions that took place during the technology integration phase and the face to face phase; and (iii) an assessment and evaluation phase involving designing detailed and implementation of assessment tasks.

3.3. Opinions on Instructional Aspects

In addition to written tests, students' opinions were also sourced through open-ended questions to determine the influence of FMC on their learning. To analyse the open-ended questionnaire data, a clear coding procedure, based on a structured thematic approach, was employed. For the first cohort of student participants, a coding scheme was developed using an inductive technique. During the iterative reading of the responses, emergent themes were assigned new inductive codes, as illustrated in the second column of Table 4. For data obtained from subsequent cohorts, however, the coding scheme was refined through a combination of deductive and inductive techniques. Themes developed from the earlier group served as a set of a priori codes for the following group, while new themes that did not fit the initial framework were assigned additional inductive codes.

Table 4. Students' opinions about various aspects of the instructional approach.

	Items	Findings
1	Comment on how the instructional approach affected your learning	Developed independent learning skills (7%), Improved understanding of the subject matter (54%), Student awareness of other methods of lesson delivery (4%), Made learning process less difficult (19%), Motivation to study the subject matter (4%), Unhappy with instructional approach (12%)
2	Has this class changed how you study? Please explain	Videos to prepare notes (39%), Lecture notes and prescribed study material for studying (3%), Other materials with videos lectures (30%), Study motivation (19%), Understanding the subject matter (5%), Memorising due to less time and more work (1%), Yes with no explanation (3%)
3	Comment on how class activities helped your learning	Deepened subject matter knowledge (63%), Developed self-evaluation (9%), Worked harder due to their challenging nature (13%), Helped prepare for tests and examinations (7%), Developed professional teaching skills (2%), Dissatisfied with activities (4%), No comment (2%)
4 (i)	Comment on how often you participated in class discussions	Only in assigned group discussions (16%), In group but rarely in whole-class discussions (21%), In group but sometimes in whole-class discussions (30%), In group and always in whole-class discussions (29%), No response (4%)
4 (ii)	Comment on how the classroom atmosphere encouraged your participation	Active learning encouraged participation (54%), Credit incentives encouraged participation (3%), Criticism from classmates discouraged participation (25%), Instructor encouraged participation (3%), Encouraged by the instructional approach (8%), Discouraged by the instructional approach (2%), No response (5%)
5	Comment on how the graded activities and tests helped your learning	Feedback on student progress (31%), Prepared students for final examination (12%), Students innovation on how to study the subject matter (13%), Encouraged preparation for other lessons (15%), Discouraged by the activities (19%), Encouraged use of knowledge and understanding of concepts studied (5%), No response (5%)
6	Comment on how the video resources in this class helped your learning	Provided individualised learning (4%), Useful to use in other physics courses (16%), Accommodated different learning styles of students (18%), Saved time as content and explanations were packaged together (4%), Well-explained examples (31%), Opportunity for replay (22%), Preparation for the next class (5%)
7	Comment on how any other material (textbooks, online material) in this class helped your learning	Deepened understanding of basic information covered in videos (67%), helped with instructor guidance (3%), Unlike videos, other materials lacked focus and hence were not used (30%)
8	Comment on how the information you received about the class helped your learning	Helped planning for other lessons (7%), Widened scope of knowledge (16%), Explanation with examples (36%), Required more than one person to make meaning out of it (4%), Dissatisfaction with the information provided (7%), Provided guidance on how to work with study material (29%)
9	Comment on how the support you received from others helped your learning in this class	In-class support was better than out-of-class (5.0%), Improved understanding of the concepts (40.0%), Support was helpful (no reasons provided) (5.0%), Information sharing (38.3%), Developed confidence (8.3%), Dissatisfaction with support given (3.3%)
10	Comment on how your understanding of geometric optics has changed as a result of the class content	Can explain concepts to others (17%), Changed ideas about how things work in the real world (29%), Gained more information (54%)
11	Comment on how the way the content was taught helps you remember key ideas	Use of video clips (37%), Organisation of content delivery (26%), Use of real-life examples (9%), Presentations and discussions (12%), Emphasis given to main ideas (14%), Discontent with instructional approach (2%)
12	Comment on what skills you have gained as a result of this class	Effectively communicate scientific ideas (51%), Work collaboratively (27%), Ability to work independently (11%), Ability to solve physics problems (5%), Dissatisfaction (1%), Ability to use physics concepts in unfamiliar situations (5%)
13	Comment on how this class changed your attitude toward this subject	Belief in own ability to engage in difficult tasks with favourable outcomes (7%), Interest in and enjoyment of the subject (32%), Subject promotes intellectual engagement with others (39%), Appreciates that ability and competency grow with effort in the subject (13%), Value in assigned learning tasks (7%), No change in attitude (2%)
14	What will you carry into other classes or aspects of your life?	Visual impressions (22%), Strategies of teaching and learning promote understanding and transfer of knowledge (58%), Promote positive attitudes and beliefs in the subject (15%), Collective effort overcomes academic challenges (5%)

The analysis was conducted in three primary stages. First, two researchers independently performed line-by-line coding of a representative subset (20%) of the responses to familiarise themselves with the data and to develop and refine the codebook. Second, the entire dataset was coded using the finalised codebook. Finally, the researchers collaboratively reviewed the coded data to consolidate codes into overarching themes, identifying connections, patterns, and divergent cases. Any discrepancies in coding were discussed until consensus was reached, after which the codebook definitions were further refined for clarity before proceeding with the remainder of the data.

The findings are summarised in Table 4. On average, there were about six categories in which data were classified for each question. The proportion of students holding a view about that category is expressed as a percentage.

In the open-ended questionnaire, 54% of the students believed the general instructional approach improved their understanding of the subject matter (Table 4, item 1). Another opinion in item 10 seems to support this opinion, where 54% of the students claimed to know more about geometrical optics than before. Item 12 supports the same idea, with 51% of the students saying that they can communicate their geometrical optics knowledge skillfully, although this was not seen in the formative and summative assessments. Furthermore, in item 14, 58% of the students thought proper teaching and learning strategies were used, promoting understanding and knowledge transfer. This is a confirmation that students benefited positively from this instructional approach. The in-class activities that may have led students to view the instructional approach in this manner may be reasoned as follows:

Firstly, 63% of the students considered the nature of the classroom tasks assigned to them (level of cognitive demand of classroom tasks) to have deepened their understanding of the subject matter (Table 4, item 3). Secondly, 54% believed the classroom atmosphere involved active learning strategies that encouraged participation (Table 4 item 4(ii)). Thirdly, 67% of the students felt that supplementary learning materials, such as online and textbooks, with 39% acknowledging the role of *videos* as well, helped deepen their understanding of the foundational knowledge covered in video lectures (Table 4, items 7, 2, and 3). Finally, 40% of the students pointed out that support from others (external support) contributed to understanding concepts (Table 4, item 9). These seem to be the key factors that improved students' understanding of the subject matter.

To improve the teaching sequence's efficiency, it may be necessary to focus on improving these four factors, as they seem to have had a reasonable impact on half the class. Other factors may also be considered, such as those that brought dissatisfaction to some students.

Each year, data were collected from a new cohort of students using the same open-ended questionnaire, but changes were made to the formative and summative assessments. The questions were rearranged in the formative and summative assessments, and the values were adjusted. Changes were implemented after evaluating student performance and considering their feedback on learning needs. Not only did student performance give insight into the redesign of the teaching sequence, but also the main issues consistently highlighted by students over the four years as weaknesses of each design intervention. The adjustments made to the teaching sequence also helped improve student performance and led to the design of the final teaching sequence.

3.4. Changes Made During Iterations: An Example from Year 1

The FCM-based teaching sequence was refined over multiple years, with each new cohort informing further modifications. To illustrate this process, the following section presents a detailed example from Year 1, demonstrating how assessment results and student feedback shaped modifications to the teaching sequence. There were three areas of modification in which assessment results (Table 3) and student feedback (Table 4) were grouped to improve the teaching sequence.

3.4.1. The First Area of Modification: Structural Refinements to the Teaching Sequence

Initial assessment data (Figure 3) showed variability in students' cognitive performance across Bloom's first three domains: knowledge, comprehension, and application. This prompted key modifications to the teaching sequence. The sequence was restructured into three instructional stages: planning, implementation, and assessment and evaluation. Phase 1 aligned with planning to support information sharing and student preparation; Phases 2–4 fell under the implementation stage to ensure progressive learning; and assessment and evaluation became standalone to allow for continuous feedback rather than only summative assessments. These changes created a flexible, iterative framework for ongoing refinement.

3.4.2. The Second Area of Modification: Enhancing Learning Materials and Resources

Student feedback (Table 4) highlighted four areas of strength: classroom tasks, atmosphere, supplementary learning materials, and external support, but also exposed gaps in self-directed learning and resource accessibility. This was a weakness in the instructional implementation of the structural design. In response, the following modification was introduced:

Phase 2 refinement of online learning materials: Instructional videos were enhanced with integrated self-assessment quizzes to promote independent learning.

3.4.3. The Third Area of Modification: Addressing Cognitive Challenges in the Application

Phase 3 forms part of the instructional implementation of the structural design. Classroom tasks and atmosphere (Table 4) were considered strong factors that affected the implementation of the teaching sequence. Test results (Figure 3) showed that students struggled with application-level tasks. Refinement of this phase led to scaffolding in problem-solving activities, leading to the following modifications: Instructor-led demonstrations were introduced to model problem-solving strategies and reduce cognitive overload. In addition, students raised the problem of incomplete coverage of examinable content. Therefore, refinement focused on adjustments to class discussions, emphasising core concepts and test-relevant material, and improving content retention.

Phase 4 also forms part of the implementation stage and deals with supplementary materials to support after-class discussions and consolidate what has been learned during class. Refinement of this phase entailed modifying students' study skills by encouraging them to use the library (textbooks) and distributing targeted handouts for difficult topics.

3.4.4. Fourth Area of Modification: Continuous and Consistent Feedback Integration

Phase 5 formed part of the assessment and evaluation stage, focusing on providing continuous and consistent feedback. Modification meant refinement through strengthening external support mechanisms (e.g., instructor-led Q&A sessions) to reinforce key concepts before exams.

This example illustrates the iterative approach applied in subsequent years. It highlights how iterative refinements were made based on assessment data and student feedback. For each new cohort, the process of evaluating cognitive strengths and weaknesses, collecting feedback, and refining instructional strategies was repeated, ensuring that the FCM-based teaching sequence remained flexible and effective. Over four years, three further iterations were conducted, each building on the results of the previous cycle. The final refined teaching sequence is presented in Table 5.

Table 5. The final teaching sequence developed in the last iteration.

	Unit Under Instruction
Teaching Phases	**Lessons Planned for the Unit and Principles Guiding Them**
Planning Phase: (Information dissemination)	Introduction to the unit of study This is the first encounter with students in class where this information is explained: Purpose • Provide the purpose of studying the unit, e.g., This unit aims to develop in the student a foundational base and greater understanding of how light propagates, reflects, refracts, and interacts with optical systems. Content • e.g., discussion of the concept of light in terms of the three models of light: ○ The ray model and its assumptions; ○ The wave model; ○ The particle model. Learning outcomes • e.g., Upon completion of the course unit, students should be able to demonstrate knowledge and understanding of the concept of the ray model of light so they can: ○ Define the concept of a ray of light; ○ State and interpret the assumptions of the ray model of light; ○ Correctly predict the behaviour of light when interacting with a transparent medium; ○ Explain how observers at different locations may be able to see the same object at the same time; ○ Explain why it is impossible to separate a single ray of light from a beam of rays. Assessment activities • e.g., Quiz on the ray model of light: ○ Write an open-ended short quiz about the ray model during class time, the first lesson after orientation class. Video lecture content is posted on BB before the quiz is written (duration 20 min). The quiz is meant to motivate students to watch and study content on video lectures. • e.g., End-of-unit test on the ray model of light: ○ Write a one-hour open-ended test at the end of the study unit. • e.g., Lab report on an experiment demonstrating the ray model of light: ○ Design, conduct, and complete lab investigations and reports for each study unit.
Pre-class Phase (out-of-class personalised learning)	Proposed organisation of learning activities Students are given time to interact with the learning material independently before class. Stage 1: Activation • e.g., Watch video lectures and read other learning material: ○ Provide video lectures and other learning material, explaining the concepts of the ray model of light and its assumptions, the wave model, and the particle model, with the aid of diagrams. Stage 2: Demonstration • e.g., Read an article or watch a tutorial on the ray model of light: ○ Provide video lectures demonstrating the use of the models of light in solving simple problems involving models of light. Stage 3: Application • e.g., Complete a worksheet with questions on the article or tutorial: ○ Include recall and comprehension exercises for students to work on their own in each of the video lectures.

https://doi.org/10.3390/higheredu5020038

Table 5. *Cont.*

	Unit Under Instruction
Teaching Phases	**Lessons Planned for the Unit and Principles Guiding Them**
In-class Phase (collaborative learning)	Proposed organisation of learning activities Students work with the lecturer and peers in class in a collective effort. Stage 1: Activation ● e.g., Written quiz: ○ Provide a short quiz on the ray, wave, and particle models of light, which should contribute to their coursework mark, to be written by students; ○ Revise the quiz immediately after writing it and use it to provide a brief review and discussion of the content in video lectures. Stage 2: Demonstration ● e.g., Mini tutorial: ○ Demonstrate how to solve some problems before the whole class, and thereafter allow students to work on their own/in pairs/groups on problems that are not too difficult on models of light; ○ Conduct a simple demonstrative experiment to observe the behaviour of light on different media. Stage 3: Application ● e.g., Worksheet problems: ○ Provide students a worksheet of problems on models of light and their assumptions, which are more challenging than in the previous case, to be solved in groups of five or fewer members. Stage 4: Integration ● e.g., Class discussion, Laboratory experiment: ○ Design and conduct experiments on the ray model of light; ○ Complete the lab investigations report for the unit studied; ○ Group discussions to connect the experiment results with the theoretical knowledge learned; ○ Thereafter, the groups present their solutions, fully explaining the procedure before the class in front of other classmates, so their findings can be peer-reviewed, guided by the lecturer as a facilitator.
Post-class Phase (consolidation)	Proposed organisation of learning activities ● Students continue to work outside of class in a collective effort on designated problems. Consolidation stage ○ Complete a worksheet summarising the lesson's key points before students leave; ○ Weekly 15 min cumulative review quizzes (spaced retrieval); ○ Students continue to work and complete higher-order problems on the worksheet ("Synthesis" worksheets with interleaved problems); ○ Students and lecturers form a learning community via social media to share ideas on how to address challenges encountered when solving physics problems on the worksheet (online forum for student-generated Q&A); ○ Make use of social media (or other means of communication), with well-guided rules, for consultations with each other.
Assessment and Evaluation Phase (graded and non-graded activities)	Proposed organisation of learning activities Students write a formative test covering all aspects of the content taught in line with the objectives. Lecturer and students discuss possible solutions in class after marking.

3.5. Design of the Final Teaching Sequence

The teaching sequence was redesigned after four iterations based on the analysis of student proficiencies, particularly in areas of weakness identified within the first three cognitive domains of Bloom's taxonomy. All learning activities are organised into the Planning Phase (information dissemination), Pre-class Phase (out-of-class personalised learning), In-class Phase (collaborative learning), Post-class Phase (consolidation), and Assessment and Evaluation Phase (graded and non-graded activities).

Thus, the pre-class phase and in-class phase are further organised into stages 1–3 and 1–4, respectively, to address the needs of each cognitive domain. The post-class phase is also a design feature that takes into consideration the criticism raised by some students that peer criticism discouraged participation (25%) (see Table 4, item 4 (ii)). The inclusion of the learning community aspect on this feature is in response to this finding. It takes into consideration the varied digital skills across the student community, as well as safety protocols such as posted community guidelines, moderated discussions, and modelled constructive feedback language. Furthermore, accessibility features such as the use of a familiar platform (WhatsApp), an in-class onboarding tutorial, and multiple modes of participation (text, image, voice) to lower technical barriers would also be accommodated under this feature. Thus, the feature creates a safe, socially accessible environment, thereby mitigating a social threat and a technical barrier.

3.6. Summary

As a conclusion to the results provided in this section, in direct response to the study's dual objectives, the iterative development and assessment conducted across four cohorts yielded two key outcomes. First, the process resulted in a robustly designed teaching sequence (addressing RQa and Objective 1), refined through successive iterations to optimally target conceptual difficulties in geometrical optics. Second, the empirical assessment demonstrates that this sequence enhances students' conceptual understanding (addressing RQb and Objective 2). A central and critical finding of this study was the significant decline in conceptual comprehension, as measured by the final exam compared to the immediate post-test (Cohen's $d = -1.1$). Ultimately, the study aimed to deliver not only a teaching tool but empirically validated evidence that a discipline-specific flipped classroom approach can effectively bridge the gap between procedural proficiency and deep conceptual understanding in geometrical optics.

4. Discussion

This section interprets the results presented above, connecting them back to the theoretical framework and the broader scientific question regarding effective design principles for conceptual understanding. It is divided into four parts. Section 4.1 (Mitigation of Confounding Factors) explains how hidden variables associated with the exposure and outcome were minimised to improve the validity of the results. Section 4.2 (Interpretation of Key Findings) examines the most significant results from Sections 3.2 and 3.3, explaining why the observed outcomes likely occurred by linking them to specific design features outlined in Section 3.1 and the theories from Section 2.1. Section 4.3 (Implications for Theory and Design Principles) synthesises these interpretations to propose actionable, generalisable principles for designing flipped classrooms that target conceptual difficulties, thereby contributing directly to the overarching scientific question. Finally, Section 4.4 (Limitations and Future Research) acknowledges the boundaries of the present study and suggests how subsequent research can build upon and extend these findings.

https://doi.org/10.3390/higheredu5020038

4.1. Mitigation of Confounding Factors

This study aimed at developing and assessing a teaching sequence for geometrical optics using the FCM teaching approach. While findings provide valuable insights into the effectiveness of the FCM teaching sequence, methodological factors such as prior knowledge disparities, motivation differences, and digital competencies might have influenced outcomes [33]. For example, based on prior knowledge, students with a strong foundational understanding can easily integrate new information, thereby leading to a positive outcome, while those with weak foundations or misconceptions must first unlearn and then relearn. Thus, the 'gains' measured may not have been created by the teaching method but could just reflect pre-existing differences. The method itself might not have helped the struggling students catch up. Similarly, motivation drives the effort, persistence, and self-regulation that a student invests in their learning. Highly motivated students will watch all the pre-class videos, attempt all the practice problems, and participate actively in class. Unmotivated students may do the bare minimum or disengage entirely. Thus, high engagement and good performance in a flipped classroom could be a result of the student cohort being unusually motivated, not the method itself. Furthermore, digital competencies often rely on students independently navigating online platforms (e.g., LMS like Blackboard), streaming video lectures, using discussion forums, and submitting digital assignments. A student's comfort and skill with these technologies directly impact their ability to even access the learning materials. Poor performance may be misinterpreted as a failure to understand the content, when in fact it is a failure to utilise the technology required to engage with the content.

These factors were mitigated by conducting pretests and multimodal resources (for prior knowledge), setting up participatory activities, and providing tech support (adaptive digital tools). For example, students reported enhanced comprehension through supplementary materials (54–67%), engagement via collaborative tasks (29–32%), and effective digital support (2–22%). Such strategies strengthened internal validity and reduced confounding effects.

4.2. Interpretation of Key Findings

4.2.1. Key Findings and Theoretical Integration

The final FMC teaching sequence comprised five phases—planning, pre-class, in-class, post-class, and assessment—guided by student feedback. It provides insight into how the individual components of the flipped classroom, Design-Based Research (DBR), and Bloom's taxonomy can be combined and established. The approach helps to introduce a new theoretical model, analytical framework, or original methodological tool. The primary theoretical contribution and novelty of this work lie in its specific integration into a structured, phased, and iterative framework, explicitly detailed in Table 5. This table is not merely a lesson plan but presents a transferable pedagogical model for developing flipped classroom sequences that systematically enhance conceptual understanding. The framework delineates a coherent progression across five distinct phases (Planning, Pre-class, In-class, Post-class, and Assessment and Evaluation), each explicitly linked to core pedagogical principles and specific learning activities designed to scaffold cognitive engagement from knowledge activation to integration. The model's generalisability stems from its structured yet adaptable design, which provides a clear blueprint for sequencing learning activities both inside and outside the classroom, guiding the application of DBR cycles, and intentionally targeting different levels of Bloom's taxonomy across phases. Therefore, Table 5 serves as a replicable framework that other educators and researchers can adapt to structure and implement conceptually focused flipped learning in other scientific domains beyond geometrical optics.

On the other hand, results shown in Figure 3 and Table 3 show varied performance across Bloom's levels: Knowledge (28–41%), Comprehension (23–47%), and Application (25–36%). Variability at the comprehension level reflects differences in students' prior knowledge, as constructing meaning depends on pre-existing schemas. Higher cognitive load in the Application tasks, coupled with limited scaffolding, likely constrained performance despite adequate gains in Knowledge and Comprehension. These patterns illustrate how cognitive load theory and scaffolding principles explain differential learning across Bloom's levels, showing that instructional support must be calibrated to the complexity of cognitive tasks. Classroom discussions, peer support, and supplementary materials were key contributors to the effectiveness of the FMC teaching sequence, aligning with the FCM literature [34].

4.2.2. Addressing the Retention Decline: The Role of the Post-Class Phase

A central and critical finding (Figure 3 and Table 3) of this study was the significant decline in conceptual comprehension measured at the final exam compared to the immediate post-test (Cohen's *d* = -1.1, in Table 3). This steep "forgetting curve" highlights a key weakness of the initial flipped sequence: it successfully promoted short-term conceptual gain but failed to ensure long-term consolidation and integration of knowledge across the three optics units (Light, Refraction, Reflection).

This empirical finding directly informed the core refinement of our model, leading to the intentional design of the Post-class Phase in the final proposed framework (see Table 5). This phase is not merely an addendum but is specifically engineered to counteract the forgetting observed in our data. It moves beyond simple "additional practice problems" to structured, spaced, and interleaved consolidation activities. Specifically, the Post-class Phase is designed to mitigate forgetting through three mechanisms:

1. Spaced Retrieval Practice: Scheduled, low-stakes quizzes administered days and weeks after a unit is completed, forcing students to retrieve and reconstruct knowledge from memory, a process proven to strengthen long-term retention [35].
2. Interleaved and Cumulative Review: Instead of reviewing topics in isolation, post-class worksheets present problems that require the integrated application of concepts from all three units (e.g., a problem involving both refraction and reflection). This combats the compartmentalization of knowledge and builds more robust, interconnected schemas.
3. Metacognitive Reflection: Guided reflection prompts ask students to compare their initial misconceptions (documented in Phase 1) with their final understanding, and to explain key concepts in their own words. This "explanation effect" fosters deeper processing and personal ownership of the material.

4.2.3. Addressing Social Threat and Technical Barriers

The student perception data (Table 4) revealed two critical implementation challenges: a social threat (25% felt discouraged by classmates' criticism) and a technical barrier (varying digital competencies), which informed the inclusion of the 'learning community via social media' aspect in the final model (Table 5). To maintain a safe and accessible environment, the community may be structured with explicit, facilitator-moderated protocols grounded in principles of online community building [36] and the need to foster social presence. This would include posted netiquette rules, the use of modelled sentence stems for constructive feedback, and active instructor monitoring. To ensure accessibility and address varied digital competencies—a dimension of the digital divide extending beyond mere access [37]—the design opted for a familiar, low-bandwidth platform like WhatsApp, which has demonstrated utility in educational contexts [38]. A mandatory orientation session would be included to build essential skills, and participation would be designed with multiple modes (text, image, voice), in line with principles of inclusive design.

Therefore, the negative effect size and classmate criticism are not just a limitation of the initial intervention; they are the diagnostic data that validated the necessity of adding a dedicated consolidation phase. The final model (Table 5) posits that a complete flipped classroom design for conceptual mastery must explicitly address the entire learning cycle—Activation (Pre-class), Construction (In-class), and, crucially, Consolidation (Post-class)—to transform short-term performance into durable understanding.

4.2.4. Comparison with Previous Studies

The final teaching sequence (Table 5) synthesises this study's design principles, which are not only a product of DBR iteration but are also deeply resonant with established instructional models, thereby strengthening their theoretical validity. The sequence's phased structure—moving from pre-class activation to in-class application and post-class consolidation—directly mirrors the iterative, inquiry-based cycle of the 5E Instructional Model [39], providing a robust, theory-grounded scaffold for the flipped classroom that systematically moves students from engagement to evaluation. Furthermore, the careful design of each activity to achieve a specific cognitive level aligns with the principle of constructive alignment [40], ensuring that learning outcomes, teaching and learning activities, and assessment tasks form a coherent, synergistic system that fosters deep understanding. This alignment is particularly evident in the use of pre-class videos for foundational knowledge (remember/understand) and complex in-class problems for application and analysis, a deliberate structuring supported by the flipped classroom literature [11]. By framing this DBR-generated framework within these validated theories, the explanatory power of our design choices is enhanced and positions the sequence as a tangible, literature-supported instantiation of how to effectively structure a flipped classroom for complex conceptual domains.

Consistent with [21,41,42], this study adopted an iterative, research-based design emphasising scaffolding, formative assessment, and technology-enhanced learning. Divergences arise in pedagogical focus: this study and [41] emphasise content-specific theories, whereas [21,42] prioritise process-oriented or phenomenon-based models. Assessment approaches also differ; mixed methods here provided richer insights than rubric-only approaches in other studies. Integrating content-specific theory with technology-enhanced inquiry could further optimise conceptual and procedural learning across contexts.

4.3. Implications for Theory and Design Principles

Practically, the FMC teaching sequence offers a structured framework to teach complex concepts through phased scaffolding and iterative refinement, adaptable to diverse settings. Theoretically, it demonstrates how variations in performance across Bloom's domains can be interpreted through cognitive scaffolding of prior knowledge, guiding educators in designing targeted interventions and researchers in understanding learning mechanisms.

4.4. Limitations and Future Research

4.4.1. Challenges in Implementation

Implementing the flipped classroom model (FCM) in this context presented several significant practical challenges that required continuous adaptation. First, infrastructural and technological barriers were pervasive. Despite preparatory efforts, inconsistent access to reliable internet and computers created a digital divide among participants. Students from rural backgrounds, in particular, faced difficulties downloading video materials or accessing the online platform (Blackboard) outside of campus computer labs. This occasionally delayed their preparation and undermined the core premise of uniform pre-class engagement. Second, platform limitations affected the design; the institution's Blackboard system had limited functionality for interactive quizzes and analytics, reducing our ability to implement sophisticated just-in-time teaching based on pre-class data. Third, pedagogical readiness was a hurdle. As the instructor had no prior formal training in FCM, the initial design and in-class facilitation involved a steep learning curve, balancing content delivery with unfamiliar facilitation of active learning. Finally, student acclimatization to this learner-centred approach was slow. Many students, accustomed to traditional lecture-based instruction, initially exhibited resistance to group work and the expectation of self-directed pre-class study, necessitating additional time for orientation and motivation.

4.4.2. Limitations of the Study

These implementation challenges directly translate into key limitations that must be considered when interpreting the findings. The study's ecological validity is high, as it reflects real-world constraints, but this also limits the model's ideal implementation. The observed outcomes (both in conceptual gains and student perceptions) likely represent a conservative estimate of the FCM's potential, as technological barriers and novice instructor facilitation may have dampened its effectiveness. Generalizability is therefore context-bound; the findings are most applicable to similar third-world or resource-constrained higher education institutions. Furthermore, the digital divide meant that the experience of the intervention was not uniform across the cohort, potentially confounding results related to engagement and performance. The study design also did not include a control group taught via traditional methods, limiting our ability to make strong causal claims about the FCM's relative advantage, though this was a deliberate choice given the exploratory and design-based nature of the research.

4.4.3. Suggestions for Future Research

This study opens several important avenues for future research, particularly for advancing inclusive and context-sensitive pedagogical innovation.

1. Low-Tech Flipped Models: Future studies should investigate the design and efficacy of "low-tech" or "asynchronous–synchronous hybrid" flipped models that mitigate digital divides. This could involve using SMS/WhatsApp for content distribution, offline video bundles on USB drives, or audio podcasts, making the pre-class phase more accessible in low-bandwidth or low-device settings.
2. Professional Development Impact: Research is needed on effective, scalable training programmes to prepare instructors in resource-constrained settings for flipped learning. Studies could compare student outcomes in FCM classes led by trained versus untrained facilitators to quantify the value of pedagogical support.
3. Cultural and Affective Factors: Qualitative work should explore the socio-cultural dimensions of introducing active learning in contexts with strong traditions of teacher-centred education. Investigating how to build students' self-efficacy and shift epistemological beliefs towards constructivist learning would be valuable.
4. Longitudinal and Comparative Studies: A longitudinal study tracking the same cohort could reveal if student adaptation to the FCM improves over time. Additionally, a mixed-methods comparative study across urban and rural student groups within the same institution could better isolate and understand the impact of background on flipped learning success.
5. Institutional Policy Research: Future work should examine the institutional policies and support systems (e.g., improved campus Wi-Fi, loaner device programmes, curriculum time allocation) necessary to sustainably implement blended learning models in similar universities.

In summary, taking into consideration the contextual challenges highlighted in the previous paragraph, data were collected at a single institution without longitudinal tracking, limiting generalisability [17]. Future research should explore diverse contexts and the impact of resource disparities on FCM outcomes. Practically, the study highlights actionable strategies for implementing FCM outcomes. Implementation depends on institutional support for technology and ongoing teacher development [43,44]. The FCM is most effective as part of a broader ecosystem of pedagogical innovation, rather than a standalone solution.

5. Conclusions

This study developed an FCM-based teaching sequence for geometrical optics through iterative design, student feedback, and multimodal resources. Performance varied across Bloom's levels: comprehension reflected prior knowledge differences, and application was constrained by cognitive load and scaffolding.

Theoretically, the sequence advances understanding of how scaffolding and cognitive load management shape learning across knowledge, comprehension, and application levels. It demonstrates that the FCM can address cognitive and motivational disparities while fostering conceptual understanding, bridging theory and practice.

Beyond classroom application, the sequence provides a transferable framework for designing evidence-informed, pedagogically robust interventions. By aligning learning outcomes to the cognitive principles, the study offers actionable insights into student learning mechanisms, reinforcing the broader relevance of research-based instruction design in STEM education.

The study faced its own share of implementation challenges, which contextualise its findings. Conducted within a third-world institution, the research faced infrastructural limitations, including unreliable internet access, platform inefficiencies, and a digital divide that affected equitable student participation. Additionally, the instructor's lack of prior training in the flipped classroom model and students' predominantly rural backgrounds required continuous adaptation and extended orientation periods. Despite these difficulties, the study offers significant added value by demonstrating that a flipped classroom sequence can be feasibly implemented and can improve conceptual understanding even under resource constraints, while also revealing critical design elements—such as a structured post-class consolidation phase and a thoughtfully moderated social learning community—that address context-specific barriers. These insights inform several avenues for future research, including investigations into low-tech flipped models for low-bandwidth settings, scalable professional development programmes for novice facilitators, and deeper exploration of socio-cultural factors affecting active learning adoption in similar global South contexts. Addressing these directions will further strengthen the transferability and impact of flipped learning in under-resourced educational environments.

Author Contributions: Conceptualization, V.N.D. and J.K.; methodology, V.N.D.; validation, J.K.; formal analysis, V.N.D.; investigation, V.N.D.; resources, V.N.D.; data curation, V.N.D. and J.K.; writing—original draft preparation, V.N.D.; writing—review and editing, V.N.D. and J.K.; supervision, J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Turfloop Research Ethics Committee TREC/26/2017:IR 2017-03-03.

Informed Consent Statement: Before participation in the study, all students were provided with detailed information regarding its purpose, procedures, potential risks, and benefits. Participation was voluntary, and students were assured that their involvement or decision to withdraw at any stage would not affect their academic performance or standing in the course.

Data Availability Statement: This article is part of a Doctoral study undertaken by the corresponding author under the supervision of the co-author.

Conflicts of Interest: The authors declare no conflict of interest.

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