AKENTEN APPIAH-MENKA UNIVERSITY OF SKILLS TRAINING AND ENTREPRENEURIAL DEVELOPMENT

A COMPARATIVE STUDY OF VIRTUAL AND REAL LABORATORY APPROACHES ON SENIOR HIGH SCHOOL STUDENTS' CONCEPTUAL UNDERSTANDING OF GEOMETRIC OPTICS

CALLISTUS SORVIEL KOG

2025

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BY

CALLISTUS SORVIEL KOG

(8221920001)

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NOVEMBER, 2025

DECLARATION

Candidate's Declaration

I hereby declare that this thesis, with the exception of quotations and references contained in published works which have been duly acknowledged; is the result of my own original work and that no part of it has been presented for another degree at this university or elsewhere.

Callistus Sorviel Kog

Signature: ……………………………… Date: …………………..................

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development.

Dr. Eric Appiah-Twumasi (Principal Supervisor)

Signature: ……………………………… Date: …………………..................

Prof. Ebenezer Ekow Mensah (Co-supervisor)

Signature: ……………………………… Date: …………………..................

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DEDICATION

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ABSTRACT

This study compared the effectiveness of real and virtual laboratories in the teaching and learning of geometric optics on senior high school (SHS) students' conceptual understanding in the Nandom and Lawra Municipalities of Ghana. Specifically, the study sought to determine the availability of teaching and learning materials for optics, the difference in conceptual understanding between students exposed to real and virtual laboratories, and how students develop conceptual understanding through virtual laboratories. A multi-phase mixed method design was adopted. Data were collected through pre- and post-tests, inventories of teaching and learning resources, and students' reflections, and analysed using descriptive, inferential, and thematic approaches. The results indicated that schools lacked adequate physical resources for practical optics instruction. Posttest analysis revealed no statistically significant difference between the experimental group ($M = 19.55$, $SD = 3.896$) and the control group ($M = 19.76$, $SD = 3.660$; $t_{(107)} = -0.295$, $p = 0.768$). Both groups showed improvements over the pretest, as students provided accurate explanations with correct terminology, identified normal incidence and matching refractive indices without misconceptions, and constructed appropriate ray diagrams. Thematic analysis revealed five key processes through which virtual laboratories enhanced conceptual understanding: interactive simulations, visual representations, independent exploration, real-time feedback, and increased confidence in applying concepts. It was concluded that both real and virtual laboratories effectively foster conceptual understanding, recommending their complementary use alongside improved laboratory resources, ICT infrastructure, and teacher professional development in Ghanaian SHSs.

CHAPTER ONE

INTRODUCTION

1.0 Overview

This chapter discusses the background of the study, as well as the statement of the problem. In this chapter is also found the main objective and specific objectives of the study and research questions. Also, the significance of the study, delimitations and limitations of this research are highlighted in this chapter. At the tail end of this chapter captures the organisation of the study.

1.1 Background to the Study

Today's modern societies are replete with scientific and technological innovations (Alemayehu, 2024). Therefore, it is impossible to overstate how important science and technology are. Science and technology, according to Achufusi and Utaka (2021), is a vast subject that includes everything from researching molecules and viruses to analysing stars and planets. Because science has an impact on how nations develop their technologies, emphasis has been placed on studying and advancing science. However, science can never be fully understood without the study of Physics.

Physics, which is a branch of science, is one of the subjects taught at the senior High School level of the Ghanaian educational system (Ministry of Education, 2023). According to Achufusi and Utaka (2021), Mansfield and O'sullivan (2020), as well as Faridi et al. (2021), the study of Physics deals with energy and matter and their interactions. Achufusi and Utaka further states that Physics is typically a prerequisite for courses in astronomy, geology, medicine, pharmacy, engineering, and other related fields. This means that the study of Physics at all levels of education is very important if a country is to be at par with the fast growing scientific and technological world, as noted by Grayson (2020) and Onoshakpokaiye and Avwiri (2025).

Physics curricula have many concepts that students find difficult to learn (Achor et al., 2019), of which one of them is optics (Obafemi & Onwioduokit, 2013). The Ghanaian SHS Physics syllabus has been divided into seven main sections. One of these sections is dedicated to the study of Optics. Optics is the science concerned with the genesis and propagation of light, the changes that it undergoes and produces, and other phenomena closely associated with it (Ministry of Education, 2023). That is, the branch of Physics that studies the behaviour and properties of light, including its interactions with matter and the construction of instruments that use or detect it. Optical science is relevant to and studied in many related disciplines including astronomy, various engineering fields, photography, and medicine (particularly ophthalmology and optometry, in which it is called physiological optics).

Practical applications of optics are found in a variety of technologies and everyday objects, including mirrors, lenses, telescopes, microscopes, lasers, and fibre optics (Ministry of Education, 2023). According to the Ministry of Education (2023), the topics in the physics syllabus have been selected to enable the students acquire the relevant knowledge, skills and attitudes needed for tertiary level education, other institutions, apprenticeship and for life. This means that studying optics serves as a cornerstone for numerous scientific disciplines, including photonics, telecommunications, imaging, and astronomy. Thus, a solid conceptual foundation in optics not only prepares students for advanced study but also equips them with the interdisciplinary skills needed to excel in diverse scientific and engineering domains. By nurturing conceptual understanding in optics, Tavdgiridze et al. (2024) argue that educators not only cultivate proficient optical scientists and engineers but also empower students to become lifelong learners capable of adapting to the evolving demands of the modern world.

With the importance of optics highlighted, evidence from literature suggests lack of conceptual understanding by students when it comes to optics studies. For instance, in a study conducted by Özdemir et al. (2020) it was found that greater percentages of opticians possessed low levels of conceptual understanding in optics concepts alongside having various misconceptions in concepts such as reflection, refraction and image formation on lenses. In a different study conducted by Tural (2015), it was found that higher percentages of students demonstrated misconceptions on optics concepts.

According to Tural (2015) students held misconceptions such as, convex lenses diverge light rays, concave lenses converge light rays, a right-side-up image replaces the previously observed inverted image, when a convex lens is removed, myopia is corrected via convex lens, and hyperopia is corrected via concave lens. Similarly, Kurniawati et al.'s (2018) study revealed that majority of high school students demonstrated low level of understanding in the concept of refraction of light, specifically on image formation by converging lenses. Also, high percentages of students did not understand the concept of propagation of light and visibility in the different situations. These studies, alongside other studies including that of Kaltakci-Gurel et al. (2016), Widiyatmoko and Shimizu (2018), Assem and Amoah (2018), and

Wahyuni and Taqwa (2022), have provided evidence to suggest that majority of physics students lack conceptual understanding in optics, as a major concept studied in physics.

The lack of understanding in optics, when not curbed, reflect in students' performance in external examinations such as the West African Senior Secondary Certificate Examination (WASSCE), which determines students' fate in higher education studies. This is because, concerns have been consistently raised by the West African Examinations Council's (WAEC) chief examiners on SHS students' difficulty in optics concepts during their external examinations (WAEC, 2017, 2018, 2019, 2020, 2021, 2023, 2024). According to the chief examiners, most candidates were not able to list the factors that determine the deviation of light ray travelling from air into a triangular glass prism (WAEC, 2017, pp. 327-328). Also, in 2018, it was reported that, candidates could not explain critical angle (WAEC, 2018, pp. 368-369).

Furthermore, in 2019, it was reported by the chief examiner that most candidates could not explain parallax and could not define the principal focus of converging lens. They could also not draw the correct ray diagram (WAEC, 2019, pp. 381-382), and in 2021, it was reported by the chief examiner that, candidates were not able to define the principal focus of a concave lens. Additionally, in 2023, the chief examiner highlighted students' weaknesses in optical areas like candidates' inability to use ray diagrams to explain how parallel light close to the principal axis are reflected by mirrors, candidates' difficulty in calculating the power of a convex lens that forms real images at two different positions separated by 20 cm (WAEC, 2023, pp. 667 & 674). Lastly in 2024, many candidates had difficulty in drawing ray diagrams for spherical mirrors according to the chief examiner (WAEC, 2024, p. 522). It can therefore be argued that, if this problem is overlooked, the future of our Physics students who will man the industrial and medical aspects of the economy will be in jeopardy.

In their attempt to find possible causes of students’ lack of understanding in physics concepts, such as optics, researchers have found that instructional approaches teachers employ in delivering their contents play major role in students’ understandings (Mekonnen, 2014; Obafemi & Iruloh, 2022). This means that some teachers rarely employ efficient instructional method in delivering their physics contents. Accordingly, students learn optics abstractly, resorting rote memorisation or procedural approaches (Ijeh et al., 2021; Ogonna, 2020). As a result, understanding in optics concepts becomes minimal, limiting their ability to tackle novel or complex problems effectively, and eventually reducing their performances in the classroom, as Holme et al. (2015) argue that a strong conceptual foundation is not only essential for academic success but also for the development of critical thinking and problem-solving skills. Conversely, when students possess a deep conceptual understanding, they can approach problems with confidence, applying their knowledge to devise innovative solutions and explore new avenues of inquiry. Also, according to Assem et al. (2023), students' conceptual understanding and academic performances are more strongly influenced by the caliber of the teachers who are putting a curriculum into practice. This means that, no matter how well-resourced the school is or how vast the curriculum is, instructional approaches have a big impact on how quickly students advance academically and how easily misconceptions may be cleared up for better understanding. As a result, physics instructors can significantly improve their students' knowledge and performance by using the suitable teaching approaches (Bigozzi et al., 2018).

Maganga (2016), states that the top graduates, who will serve as outstanding leaders and human resources for the nation and thus be in charge of that nation's economic and social development, are produced in large part by students' academic success. Therefore, it behooves on classroom teachers to bring the best out of their students through their classroom interactions. To agree with Ugwuanyi and Okeke (2020), there is thus an urgent need for a paradigm shift in the methods that the contents of physics are passed on to the students, especially in the twenty-first century classrooms. Since most physics contents including optics, are abstract, it is necessary to put students through interactive activities where concepts become real to them (Ceuppens et al., 2019; Erdem, 2019). In this way, students understanding (Wardani et al., 2017) and ultimately their overall academic performance (Assem et al., 2023) are likely to enhance.

The use of laboratories in science classes is crucial for fostering conceptual understanding in students through hands-on learning (Daineko et al., 2017). Thus, the significance of laboratory applications in instruction is evident, particularly in light of the fact that physics is an applied branch of science. Students actively participate in their learning in the Physics laboratory by observing and doing (Suprapto et al., 2019), leading to both an enhanced understanding and a permanent learning (Ruhaisa & Jiradawan, 2018). Researchers have acknowledged that laboratory studies boost students’ interest and abilities for the science subjects (Lehesvuori et al., 2023; Ojediran et al., 2014).

Also, real laboratories play a crucial role in enhancing students' understanding of physics concepts by providing hands-on experiences that bridge the gap between theory and practical application (Arshad et al., 2024). In a laboratory setting, students have the opportunity to manipulate physical apparatuses, conduct experiments, collect data, and analyse results firsthand (Antwi et al., 2021). This experiential learning approach allows students to engage directly with the principles they are studying, fostering a deeper comprehension of abstract concepts (Shana & Abulibdeh, 2020).

Moreover, real laboratories offer students the chance to develop essential scientific skills, such as critical thinking, problem-solving, and experimental design (Holmes & Wieman, 2018). By actively participating in experiments, students learn to formulate hypotheses, design procedures, make observations, and draw conclusions based on evidence (Johnson, 2017). These skills, according to Girwidz et al. (2022), are not only fundamental to understanding physics but are also transferable to other scientific disciplines and real-world contexts. Through the active participation in experiments, real laboratories provide a context for students to confront the limitations and uncertainties inherent in scientific inquiry (Girwidz et al., 2022).

Holmes and Smith (2023) add that students learn to recognise sources of error, refine experimental techniques, and interpret data within the framework of uncertainty analysis. This aspect of laboratory work, according to the Ministry of Education (2023), is essential for cultivating scientific literacy and fostering a healthy skepticism towards scientific claims. Through hands-on experimentation, students gain a deeper appreciation for the iterative nature of scientific discovery and the importance of empirical evidence in validating theories (Putri et al., 2017).

Even though laboratory applications play a significant role in students' understanding of physics concepts, they are not without certain limitations, particularly in underdeveloped nations (Boakye & Ampiah, 2017; Otchere et al., 2019). Some of the main problems faced in Ghana according to Dzah (2014) and Coffie et al. (2020) can be summarised as follows; the laboratory activities are expensive for planning and application, it is much time-consuming checking students' performance during the activities can be difficult in over-crowded classes, lack of laboratory or equipment, or insufficient laboratory conditions which limits the teacher to perform a simple laboratory activity.

In the real-world situation, sometimes due to these limitations, as mentioned in the preceding paragraph, teachers are forced to perform laboratory activities in crowded groups, or sometimes a demonstrational activity can be performed (Buabeng et al., 2014). When taking these limitations into consideration, looking for appropriate alternatives is inevitable. Among these alternatives, the use of educational technologies, more specifically use of computer in supporting the laboratory methods can be a logical one (Hamed & Aljanazrah, 2020). Researchers and educational practitioners believe that technology has provided new insights to support education (Freina & Ott, 2015; Kavanagh et al., 2017).

Accordingly, the Ministry of Education (2023), as highlighted in the physics syllabus, encourages physics teachers to integrate technology into their lessons. Also, Appiah-Twumasi (2020) as well as Gupta and Sansawal (2018) claimed that today's educational technology practices should indeed be contained in the constructivist paradigm. This plays out in terms of developing systems that are situated in the real world as much as possible and are as experiential as possible. Among these technological systems is virtual laboratories. In the current era of technology-based education, Lestari et al. (2023) are of the view that a virtual laboratory can be helpful as an alternative, even though it cannot completely replace a physical laboratory.

Virtual laboratories, also known as online laboratories (Budai & Kuczmann, 2018) or simulated experiments (de Vries & May, 2019), have emerged as innovative educational tools that replicate the experience of traditional hands-on laboratory experiments in a digital environment. These virtual environments utilise computer simulations, interactive multimedia, and virtual reality technologies to create immersive learning experiences that mimic real-world laboratory settings (Hamed & Aljanazrah, 2020). According to Budai and Kuczmann (2018) the emergence of virtual laboratories can be attributed to advancements in technology, increased access to computing devices and the internet, and a growing recognition of the need for flexible and scalable solutions to address challenges in laboratory-based education.

One of the key advantages of virtual laboratories is their accessibility, as Aşiksoy and Islek (2017) assert that they enable students to engage in laboratory activities anytime, anywhere, without the constraints of physical space or equipment availability. This accessibility is particularly beneficial for students in remote or underserved areas who may not have access to well-equipped laboratory facilities (Manchikanti et al., 2017). Additionally, virtual laboratories can accommodate large numbers of students simultaneously (Salmerón-Manzano & Manzano-Agugliaro, 2018), allowing for greater scalability and efficiency in delivering laboratory experiences to diverse learner populations.

Furthermore, virtual laboratories offer opportunities for differentiated instruction, allowing students to explore concepts at their own pace and receive personalised feedback and guidance tailored to their individual learning needs (Lopez et al., 2021). Virtual laboratories offer a safe and cost-effective alternative to traditional hands-on experiments, mitigating risks associated with handling hazardous materials or expensive and delicate equipment (Lestari et al., 2023). In this way, students can overcome the possible dangers that can be seen in the real laboratory conditions. For example, a dangerous experiment for human health is prepared in computer as simulations, so that students can see the experiments design and perform the experiment using the computer and observe the result. This reduces the possibility of accidents, injuries, or damage to property that may occur in a real laboratory setting.

By simulating experiments in a virtual environment, students can conduct investigations without the need for physical materials or specialised laboratory equipment, reducing the financial burden on educational institutions and promoting sustainable practices. Moreover, virtual laboratories provide opportunities for experimentation and exploration that may not be feasible or practical in a traditional laboratory setting (Seifan et al., 2020). Students can manipulate variables, observe phenomena, and collect data in real-time, fostering an active and inquiry-based approach to learning that enhances conceptual understanding and critical thinking skills.

According to Falloon (2019), interactive learning environment by using animations and simulations for abstract concepts, where students become active in their learning, provide opportunities for students to construct and understand difficult concepts more easily. Thus, students can get the opportunity to express their cognitive style and make choices from the computer screen through well-designed simulations (de Vries & May, 2019). In this way, students are given the opportunity to learn hands-on through the formulating of their own hypotheses about the subject matter and developing their own methods for solving problems (Falloon, 2019).

Therefore, the utilisation of virtual laboratories or simulation programs helps overcome some of the challenges associated with traditional laboratory applications and positively contributes to the achievement of educational goals. Hamed and Aljanazrah (2020) reported that virtual laboratory, like traditional laboratory, has the capability to facilitate constructivist-learning activities. Hence, as an experiential learning tool, virtual laboratory is an enactive knowledge-creation environment. In the existing literature there are several studies on the use of virtual laboratories and real laboratories in science, particularly in physics. For example, Lang (2012) found no significant difference in the use of virtual laboratory and real laboratory on first year undergraduate physics students' performance. Similarly, Moosvi et al. (2020) found no significant difference on the use of real laboratory and virtual laboratory among university students. However, Darrah et al. (2014) and Ranjan (2017) found the use of virtual laboratory to be more effective than real laboratory on the performance of university students. Agboola and Olabimpe (2017) also found the use of virtual laboratory to be more effective on junior high school students' academic performance than real laboratory.

Since there are limited studies and apparently none of such study in the Ghanaian context particularly in the teaching and learning of optics, it became appropriate to expand knowledge in current literature by ascertaining the comparative effect of real laboratory and virtual laboratory on senior high school (SHS) students' conceptual understanding in optics. Furthermore, the contradicting results obtained by existing literature demands that more comparative studies on the effectiveness of real laboratory and virtual laboratory should be conducted, warranting the need for this study.

In this study, students' perceptions towards the use of real laboratory and virtual laboratory in the teaching and learning of optics was considered. According to Byukusenge et al. (2023), the viewpoints and perceptions of students are crucial in order to offer critical insights for the implementation of novel teaching techniques and for evaluating the effects of pedagogical changes. However, majority of studies comparing the effectiveness of real laboratory and virtual laboratory have been silent of soliciting students' perceptions on these two approaches in helping them understand concepts. As a result, this study goes further to determine the perceptions of students in the use of real laboratory and virtual laboratory in the teaching and learning optics. The above background elicited the need to understudy the extent to which physics teachers integrate technology in the teaching and learning of optics, and by doing so comparing the effect of virtual laboratory on SHS Physics students' conceptual understanding in Optics.

1.2 Statement of Problem

Physics curriculum has many concepts that students find difficult to learn (Achor et al., 2019), of which one of them is optics (Ministry of Education, 2023). Studies such as Dido et al. (2021) and Ceuppens et al. (2018) reported that physics students specifically demonstrate difficulties in image formation by a plane mirror, image formation by a convex lens, and drawing of ray diagrams. Also, concerns have been consistently raised by the West African Examinations Council's (WAEC) chief examiners on SHS students' difficulty in optics concepts during their external examinations (WAEC, 2017, 2018, 2019, 2020, 2021, 2023, 2024). According to the chief examiners, "most candidates were not able to list the factors that determine the deviation of light ray travelling from air into a triangular glass prism" (WAEC, 2017, pp. 327-328). Also, in 2018, it was reported that, "candidates could not explain critical angle" (WAEC, 2018, pp. 368-369). Furthermore, in 2019, it was reported by the chief examiner that "most candidates could not explain parallax and could not define the principal focus of converging lens." They could also not draw the correct ray diagram (WAEC, 2019, pp. 381-382), and in 2021, it was reported by the chief examiner that, "candidates were not able to define the principal focus of a concave lens." Also, in 2023 and 2024, WAEC chief examiners reported students' weaknesses in optics, including difficulties with ray diagrams for mirrors and calculating convex lens power (WAEC, 2023, pp. 667–674; 2024, p. 522). This means that optics truly presents a major challenge to SHS physics students.

A preliminary interaction with some SHS physics students in the study area revealed that optics is a topic in physics they find difficulty in understanding. For instance, one student said that "*sir, always I see the things we learn in light as something which do not exist even though I see light always. This is because, the terms we hear and some of the concepts are too complex, which makes me difficult to understand*." Another student also expressed that "*…we use light and see light every day, but sir, what I am hearing in the study of light, I think it goes beyond what we see and use. I do not even* *understand most of them*". Similarly, one student lamented their lack of understanding in optics that "*oh sir, I chose to come and do science because I know science is about the things we always see. But what I am seeing, especially this optics, is far different. I only see stars. I pray that WAEC do not bring questions on optics, otherwise it will be very difficult*."

However, the Ghanaian physics syllabus encourages teachers to employ activities that will help learners develop the needed skills in order to improve their understanding of concepts (Ministry of Education, 2023). One such approaches, according to the Ministry of Education (2023), is engaging is laboratory activities with materials and optical equipment which will make learning real to students. But the inadequacy of such equipment hinders learners to learn hands-on which deprives them of understanding (Assem et al., 2023). For instance, in a preliminary observation by the researcher in the Nandom Municipality, some physics teachers bemoaned their frustrations they encounter in organising practical activities during optics lessons.

In one teacher's own expression, it was said that "*…I know optics is one of the physics topics students cannot understand without practical activities. But as we speak, there are no glass prisms, and very few plane and concave mirrors, as well as lenses. So, we only do our best by illustrating some phenomena on the board for students*." Likewise, another teacher expressed that "*hmmm, in fact we lack a lot of experimental equipment. Even pins are limited in our lab. We can go to the lab and we cannot get sufficient plane mirrors. I have to ask students to come along with mirrors when we want to learn hands- on. Students usually complain but what can you do*?"

Thus, with the advancement of technology, using virtual laboratory (Gambari et al., 2013) has been advocated to replace and complement physical laboratories, which are without significant limitations like cost, time, class size, etc., (Lestari et al., 2023; Lopez et al., 2021) causing their inadequacy in the teaching and learning of optics. However, evidence suggests that virtual laboratory enhances students' performance in physics concepts (Darrah et al., 2014; Mohammed et al., 2020; Sabasales, 2018). But there is scarcity of such studies in the area of optics, and especially in the Ghanaian Physics teaching context. To fill this gap, there is therefore a need to assess the effectiveness of virtual laboratory in enhancing the conceptual understanding of SHS Physics students in optics.

1.3 Purpose of the Study

The purpose of this study was to ascertain the comparative effect of virtual and real laboratory approaches on senior high school students' conceptual understanding of geometric optics in Nandom and Lawra Municipalities.

1.4 Objectives of the Study

The following objectives were formulated to guide the study:

1. To determine the availability of teaching and learning materials for the study of optics within the Nandom and Lawra Municipalities.
2. To establish the difference in students' conceptual understanding in optics between students exposed to virtual laboratory and those exposed to real laboratory.
3. To determine how students develop conceptual understanding of geometric optics through virtual laboratory.

1.5 Research Questions

The following research questions guided the study:

1. What are the available teaching and learning materials for the study of geometric optics within the Nandom and Lawra Municipalities?
2. What is the difference in students' conceptual understanding in geometric optics between students exposed to virtual laboratory and those exposed to real laboratory?
3. How do students develop conceptual understanding of geometric optics through virtual laboratory?

1.6 Significance of the Study

With the initiative by the Government of Ghana to supply electronic tablets to SHS students, this study will inform physics teachers about the need to incorporate Information and Communication Technology (ICT) in the teaching and learning of physics, thereby turning the classroom into a student-centered one, which can contribute to the improvement in the conceptual understanding of physics students in geometric optics.

1.7 Justification of the Study

The rationale for this study was based on the observation that there are a number of investigations conducted on the use of the virtual laboratory on students' learning outcomes in physics, but not much has been researched in the area of optics, and in Ghana. Also, to gather comprehensive understanding of an instructional approach, students' perceptions are very crucial. However, there are seemingly scarcity of studies in literature that have focused on soliciting students' perceptions on the use of virtual laboratories in the teaching and learning of geometric optics.

1.8 Scope of the Study

Firstly, this study did not focus on all concepts on optics. The concepts considered were selected on evidence provided in literature and from chief examiners' reports of WAEC, indicating areas where learners encounter much difficulty. These concepts are reflection, refraction and ray diagrams or formation of images. Also, the study was delimited to second year SHS physics students. This is because optics is studied in year two according to the SHS physics syllabus. Lastly, the study focused on only senior high schools in the Nandom and Lawra Municipalities in Ghana.

1.9 Limitations of the Study

One limitation in this study was that participants were not selected randomly to participate in this study, hence there are possibilities that some unmeasured extraneous factors like students' attitudes and motivation could have affected the results of the study. As a result, the conclusion of findings in this study were made with extreme caution. Also, the study was conducted in Nandom and Lawra Municipalities, hence limiting the generalisation of the findings to other geographical areas. Furthermore, since geometric optics concepts were only considered in this study, the results of this study cannot be extrapolated to other topics or concepts in physics.

1.10 Organisation of the Study

There are five chapters in this study, and each one covers a different aspect of the study. The study's background, statement of the problem, purpose, and specific objectives are all presented in the first chapter. Chapter one also includes research questions, the study’s significance, delimitations, and limitations. Chapter two of the study's literature review included reviews of empirical studies, theoretical reviews, and conceptual reviews. The research design, population, sampling procedure, data collection tool, data collection processes, data processing and analyses, and ethical considerations are covered in detail in Chapter 3. The presentation and discussion of the results are covered in chapter four. The findings, conclusions, and suggestions are finally presented in chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.0 Overview

This chapter reviews relevant literature related to the integration of technology in the teaching and learning of geometric optics. It discusses the theoretical and conceptual frameworks underpinning the study, particularly constructivism and conceptual change theory, which explain how students develop and restructure knowledge in physics. The review further explores existing research on the teaching and learning of geometric optics, the role of real laboratories, and the integration of virtual laboratories in science education. Comparative studies between real and virtual laboratories are also examined to provide insights into their relative effectiveness. The chapter concludes with a summary of the reviewed literature, highlighting key gaps that inform the focus of the present study.

2.1 Theoretical Framework of the Study

The theoretical framework of this study is grounded in established educational theories that emphasise active learning and the transformation of learners' existing knowledge structures. Specifically, it draws upon constructivism and conceptual change theory to explain how students develop a deep understanding of geometric optics in physics education. These theories provide a lens through which to examine the processes involved in learning abstract concepts such as reflection, refraction, and image formation, particularly through experimental activities. By highlighting the role of experiential engagement and cognitive restructuring, this framework sets the stage for evaluating the efficacy of laboratory-based approaches, both real and virtual, in fostering conceptual understanding among senior high school (SHS) physics students in resource-constrained settings like the Nandom and Lawra Municipalities in Ghana.

2.1.1 Constructivism

Constructivism, as articulated by foundational scholars like Jean Piaget and Lev Vygotsky (Yildiz, 2025), posits that learning is an active process wherein individuals construct knowledge by integrating new experiences with existing cognitive structures, or schemas (Efgivia et al., 2021). Piaget's (1976) theory of cognitive development suggests that learners assimilate new information into their current schemas or accommodate those schemas when new experiences challenge existing understanding, a process particularly relevant to the abstract and often counterintuitive concepts in geometric optics. For instance, students may initially perceive light as always traveling in straight lines based on everyday observations, such as shadows, but must accommodate their schemas when encountering phenomena like refraction through a lens.

Vygotsky's (1994) contribution highlights the social dimension of learning, emphasising the role of the zone of proximal development (ZPD), where learners advance through interactions with peers, teachers, or tools that scaffold their understanding. In the context of geometric optics, laboratory-based learning aligns seamlessly with constructivist principles, as it allows students to engage actively with materials, whether physical lenses and mirrors in a real laboratory or interactive ray-tracing simulations in a virtual one, to test hypotheses and refine their mental models.

In a real laboratory, students might manipulate an optical bench to observe how a convex lens forms a real image, experiencing tactile feedback that reinforces assimilation as they connect physical actions to theoretical concepts like the lens formula.

According to Shivolo and Mokiwa (2024), this hands-on engagement fosters a sense of ownership over their learning, encouraging them to predict outcomes, observe results, and reflect on discrepancies, such as why an image appears inverted. Virtual laboratories, conversely, offer a flexible environment where students can repeatedly manipulate variables (Asare et al., 2023), such as focal length or object distance, without the constraints of physical equipment, promoting accommodation by visualising abstract principles like ray convergence in real-time. In resource-limited settings like Nandom and Lawra, where access to optical kits may be restricted, virtual laboratories can democratise experiential learning by providing simulations that mimic real-world phenomena, thus extending the ZPD through digital scaffolding. For example, a student can use a virtual optics simulation to explore Snell's law by adjusting angles of incidence, receiving immediate feedback that supports iterative learning.

The constructivist approach also emphasises the social context of learning (Saleem et al., 2021), where real laboratories facilitate collaborative experimentation, allowing students to discuss observations and negotiate meanings, such as debating why a concave mirror produces different images at varying distances. Virtual laboratories, while often more individualised, can incorporate collaborative features, such as shared simulations or online discussion prompts, to replicate this social dynamic (May et al., 2023). By grounding the study in constructivism, the comparison of real and virtual laboratories can assess how each method supports active knowledge construction, particularly in addressing the practical and contextual challenges of SHS physics education in Ghana. This theory highlights the potential of both approaches to foster inquiry-based learning, where students build robust conceptual frameworks through direct or simulated experiences with optical phenomena, ultimately enhancing their understanding of geometric optics.

2.1.2 Conceptual Change Theory

Conceptual change theory, as developed by Posner, Strike, Hewson, and Gertzog in their 1982 framework, provides a structured model for understanding how learners transition from naive or incorrect conceptions to scientifically accurate ones, a process critical for mastering geometric optics. The theory posits that conceptual change occurs when four conditions are met: dissatisfaction with existing conceptions, intelligibility of a new concept, plausibility of the new concept, and its fruitfulness in explaining phenomena (Posner et al., 1982).

In the study of optics, students often may enter classrooms with misconceptions rooted in everyday experiences. For example, believing that images in mirrors exist physically behind the surface or that light bends arbitrarily when passing through a lens (Ceuppens et al., 2018). According to Shafi et al. (2024), these intuitive ideas can persist unless actively challenged through experiences that create cognitive dissonance. Laboratory-based learning, whether real or virtual, serves as a powerful mechanism for facilitating this change by providing empirical evidence that confronts these misconceptions. In a real laboratory, students might set up an experiment with a plane mirror, expecting the image to be tangible, only to discover through measurement that it is virtual, creating dissatisfaction with their initial belief. This hands-on interaction makes the concept of virtual images intelligible as students measure distances and observe no physical light convergence behind the mirror, while its plausibility is reinforced by applying the law of reflection to predict outcomes accurately.

The fruitfulness of this new understanding becomes evident when students use it to explain real-world phenomena (Athanasopoulos, 2023), such as the appearance of objects in a rearview mirror. Virtual laboratories enhance this process by offering dynamic visualisations that isolate specific variables, such as adjusting the refractive index in a prism to observe light bending, which can make abstract concepts like Snell's law more intelligible and plausible. For instance, a simulation might allow students to see colour- coded light rays bending at precise angles, directly addressing misconceptions about refraction.

In the Ghanaian SHS context, where students may hold culturally influenced ideas, such as myths about rainbows affecting their understanding of dispersion, conceptual change theory underscores the need for targeted interventions. Real laboratories provide tactile and sensory experiences that can create memorable moments of dissatisfaction (Pavlou & Zacharia, 2024), such as when a student's prediction about a lens's focal point fails during an experiment, prompting a re-evaluation of their mental model. Virtual laboratories, however, excel in offering repeated, error-free trials that allow students to explore multiple scenarios quickly, enhancing plausibility by visualising invisible processes (Santos & Prudente, 2022), such as the path of light through a lens system. For example, a virtual lab might enable students to toggle between convex and concave lenses to compare image formation, reinforcing the fruitfulness of new concepts through immediate feedback.

The conceptual change theory’s relevance to this study lies in its focus on the cognitive restructuring enabled by laboratories, providing a framework to evaluate how real and virtual environments meet the conditions for conceptual change. In resource-constrained settings like Nandom and Lawra, where physical laboratories may be limited by equipment shortages, virtual labs can ensure equitable access to experiences that challenge misconceptions, while real labs may offer unique sensory cues that deepen commitment to new ideas. By comparing these approaches, the study can assess their relative effectiveness in facilitating conceptual change, ensuring that students not only learn the principles of geometric optics but also internalise them as meaningful and applicable knowledge.

2.2 Conceptual Framework

The conceptual framework for this study serves as a bridge between the theoretical foundations outlined in the previous section and the empirical investigation into the integration of technology in teaching geometric optics to SHS students in Ghana. Building upon constructivism and conceptual change theory, this framework operationalises key concepts into a structured model that delineates the relationships among variables central to the research. At its core, the framework posits students’ conceptual understanding of geometric optics as the primary outcome variable, influenced by exposure to either virtual or real laboratories as the main independent variable, with available teaching and learning materials acting as a moderating factor that shapes the effectiveness of these laboratory experiences.

This model integrates the active knowledge construction emphasised in constructivism, where students build schemas through experimentation, and the cognitive restructuring process of conceptual change theory, where misconceptions are challenged and resolved through empirical engagement. In the Ghanaian SHS context, particularly in resource- limited areas like the Nandom and Lawra Municipalities, the framework accounts for contextual constraints such as limited access to physical equipment, digital infrastructure challenges, and curriculum demands, translating theoretical principles into measurable constructs like pre- and post-test scores for conceptual understanding, laboratory exposure types, and inventories of available materials.

By doing so, it directly addresses the research questions: Research Question 1 is operationalised through the assessment of teaching materials' availability; Research Question 2 examines the differential impact of laboratory exposure on conceptual understanding; and Research Question 3 explores the mechanisms, such as misconception resolution, facilitated by virtual laboratories. This framework thus provides a roadmap for the study's methodology, ensuring that data collection and analysis align with theoretical insights while being sensitive to the local educational landscape. To illustrate these relationships, the conceptual model can be visualised in Figure 2.1 that depicts causal and moderating pathways.

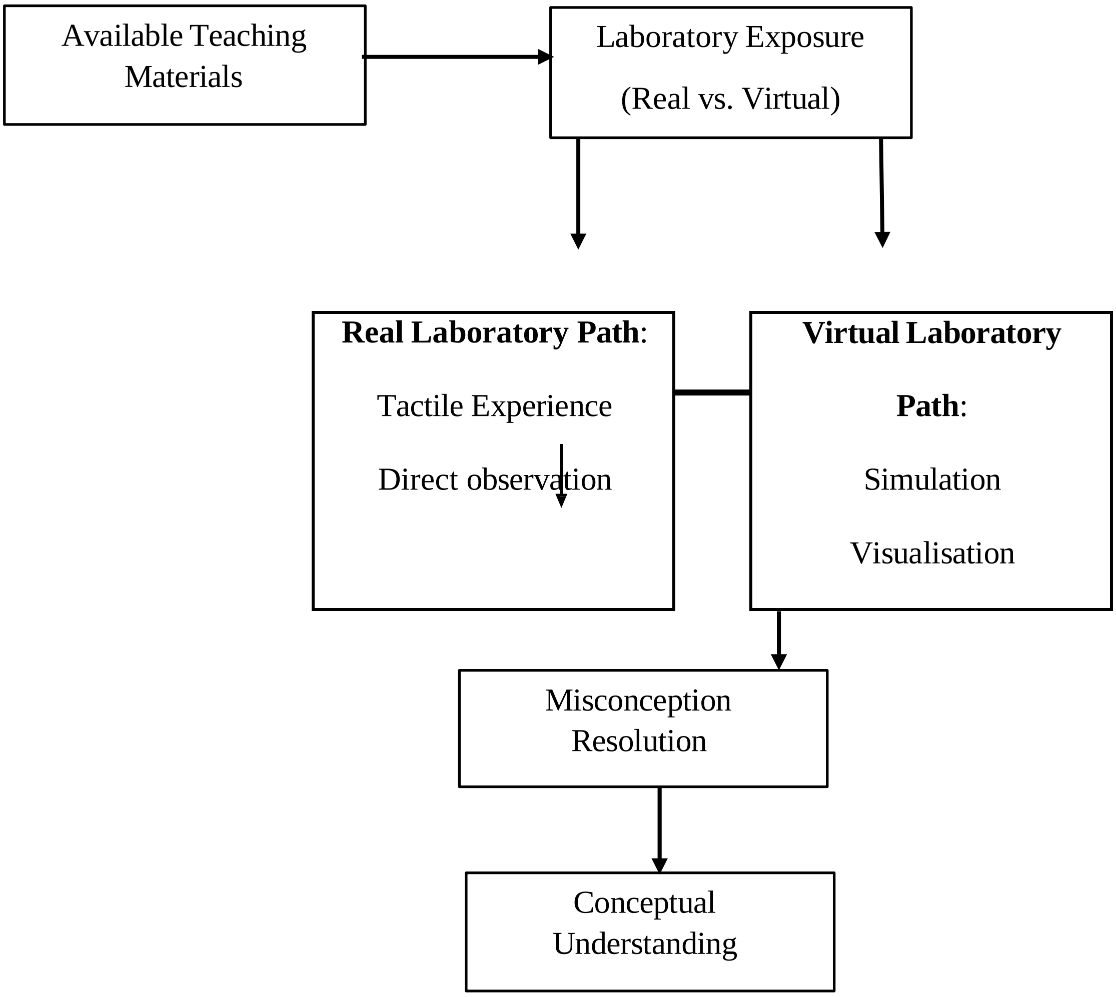


Figure 2.1: Conceptual framework of the study (Author's construct, 2025)

As shown in Figure 2.1, central to the conceptual model is the interplay of variables that illustrate how laboratory experiences foster conceptual development in geometric optics. The dependent variable, students' conceptual understanding, is conceptualised as a multifaceted construct encompassing knowledge of key optics principles (e.g., laws of reflection and refraction, image formation in lenses and mirrors), the ability to apply these principles to problem-solving, and the resolution of common misconceptions (e.g., distinguishing between real and virtual images or understanding ray paths in prisms). This understanding is measured through validated instruments like concept inventories or achievement tests, pre- and post-intervention, to capture changes attributable to laboratory exposure.

The independent variable, exposure to virtual or real laboratories, differentiates between traditional hands-on settings, where students interact with physical apparatus like optical benches and lenses, and digital simulations, such as PhET interactive optics tools, that allow virtual manipulation of variables. The framework hypothesises that both forms of exposure promote understanding but through distinct pathways: real laboratories emphasise tactile and sensory experiences that align with constructivist assimilation via direct observation, while virtual laboratories leverage visualisation and iteration to facilitate conceptual change by making abstract processes explicit and accessible. Moderating this relationship are the available teaching and learning materials, which include traditional resources, influencing the quality and equity of laboratory experiences in Ghanaian SHS settings where rural municipalities often face shortages. For instance, scarce physical materials may diminish the effectiveness of real laboratories, whereas virtual alternatives could mitigate this by requiring only basic digital access, thus moderating outcomes in favour of technology integration.

2.3 Teaching and Learning of Geometric Optics in Physics Education

The teaching and learning of geometric optics in physics education constitute a critical area of focus due to the subject’s foundational role in understanding light-related phenomena and its relevance to both scientific inquiry and everyday applications. Geometric optics, which encompasses concepts such as reflection, refraction, image formation, and the behaviour of lenses and mirrors (Pedrotti et al., 2017), poses unique challenges for students, particularly in resource-constrained environments like the Nandom and Lawra Municipalities in Ghana. This section therefore synthesises global and local literature to explore the pedagogical approaches, challenges, and common student misconceptions associated with learning geometric optics, as well as effective strategies to address them. It aligns with the study’s research questions by providing a backdrop for examining how laboratory-based interventions, both real and virtual, can enhance conceptual understanding in the Ghanaian SHS context. By reviewing studies on instructional methods, student difficulties, and curriculum design, this section highlights the need for innovative approaches, such as technology integration, to overcome barriers in optics education and sets the stage for comparing traditional and virtual laboratory methods.

Geometric optics is typically introduced in secondary school curricula as a bridge between theoretical physics and observable phenomena, requiring students to grasp abstract concepts like ray propagation while applying mathematical tools such as Snell’s law or the lens formula (Ministry of Education, 2023). Globally, research indicates that effective teaching of optics relies on active learning strategies that engage students in hands-on or inquiry-based activities. For example, a study by Asad et al. (2021) emphasise the importance of experiential learning, where students manipulate physical setups to observe light behaviour, reinforcing theoretical principles through direct observation.

In the Ghanaian context, the SHS physics curriculum, as outlined by the Ministry of Education (2023), includes topics like the laws of reflection and refraction, critical angle, and image formation, expecting students to develop both conceptual and procedural knowledge. However, literature, including studies by Buabeng and Amo-Darko (2025), Takyi et al. (2025) and Altinyelken and Hoeksma (2021), highlights significant challenges in implementing active learning due to limited resources, large class sizes, and insufficient teacher training in inquiry-based methods. In rural settings like Nandom and Lawra, these challenges may be amplified by shortages of optical equipment, such as prisms or converging lenses, which restricts opportunities for practical engagement. As a result, instruction may often rely heavily on lecture-based methods and rote memorisation, which research by Shishigu et al. (2018) suggests is less effective for fostering deep conceptual understanding, as students struggle to connect theoretical principles to real-world phenomena like the formation of rainbows or the function of eyeglasses.

A significant barrier in teaching geometric optics is the prevalence of student misconceptions, which are well-documented in literature. Research by Ceuppens et al. (2018), Kaltakci-Gurel et al. (2016), and Mitrović et al. (2020), identifies common erroneous beliefs, such as the notion that light travels only in straight lines without bending at interfaces, or that images in mirrors are physically located behind the surface. According to Kaltakci-Gurel et al. (2016), these misconceptions often stem from intuitive reasoning based on everyday observations, such as seeing reflections in water, which students misinterpret as tangible objects.

Ndahalomwenyo (2012) note additional cultural influences, such as local folklore about light phenomena (e.g., myths surrounding rainbows), which can complicate students’ understanding of dispersion or refraction. These misconceptions are particularly resistant to change without targeted interventions, as conceptual change theory suggests, requiring experiences that create cognitive dissonance. For instance, students may predict that light passing through a prism will not bend, only to observe otherwise during experiments, prompting a reevaluation of their mental models.

However, the scarcity of laboratory resources in Ghanaian SHS settings limits such opportunities, as noted by Coffie et al. (2020), who points to inadequate infrastructure as a barrier to practical physics education. This underscores the potential of virtual laboratories, which can simulate optical phenomena without requiring physical equipment, offering a cost-effective alternative to address these misconceptions.

Pedagogical strategies to enhance optics education often emphasise the integration of practical activities to bridge theory and application. Internationally, inquiry-based approaches, such as those advocated by Wardani et al. (2017) and Planinic et al. (2024), have shown success in improving students' conceptual grasp by encouraging them to design experiments, make predictions, and analyse outcomes. For example, setting up a simple experiment to measure the focal length of a lens can help students understand the relationship between object distance and image characteristics, reinforcing the lens formula.

In Ghana, however, such approaches are underutilised due to logistical constraints, as reported by Coffie et al. (2020), Musah (2022) and Dah (2021) who found that teachers in most senior high schools often resort to chalk-and-talk methods due to a lack of materials and training. Technology-based interventions, such as virtual simulations like PhET Interactive Simulations, have emerged as promising tools to overcome these barriers. Research by Erdoğan and Bozkurt (2023) as well as Penjor et al. (2022) demonstrates that simulations can enhance understanding by allowing students to manipulate variables, such as the angle of incidence in a refraction experiment, and visualise abstract concepts like ray paths in real-time.

In the Ghanaian SHS context, where access to computers or tablets is increasing, albeit unevenly, such tools could provide equitable access to experiential learning, particularly in under-resourced areas like Nandom and Lawra. Yet, Amemasor et al. (2025) caution that effective integration requires teacher professional development to align simulations with curriculum goals and address digital literacy gaps among students. The literature also highlights the role of assessment in optics education, particularly in identifying and addressing gaps in conceptual understanding.

Diagnostic tools have been developed by researchers including Kaltakci-Gurel et al. (2017), Salmadhia et al. (2021) and Putri et al. (2024), and have been used to measure students' grasp of key principles and detect persistent misconceptions. In Ghana, while such tools are less commonly used, the Ministry of Education (2023) advocate for formative assessments, such as concept mapping or practical-based tasks, to gauge students' progress in optics and provide feedback for instructional adjustments. These assessments are critical in the context of this study, as they offer a means to compare the effectiveness of real versus virtual laboratories, aligning with Research Question 2.

2.4 Teaching and Learning Resources for Geometric Optics Instruction

The selection and use of teaching and learning materials for geometric optics play a pivotal role in shaping effective pedagogy, particularly in the context of SHS physics education in resource-constrained settings like the Nandom and Lawra Municipalities in Ghana. This section synthesises literature on the types, applications, and effectiveness of materials employed in teaching geometric optics, focusing on both traditional and technology-based resources to support student learning of concepts such as reflection, refraction, and image formation through lenses and mirrors. The emphasis here is not solely on the availability of these materials but on their design, implementation, and impact on fostering conceptual understanding, aligning with the study’s broader aim to compare real and virtual laboratory approaches.

Traditional teaching and learning materials for geometric optics include textbooks, chalkboards, diagrams, and physical laboratory equipment such as lenses, mirrors, prisms, and optical benches (Ministry of Education, 2023). These resources are designed to support both theoretical instruction and practical exploration, enabling students to connect abstract concepts like Snell’s law or the lens formula to observable phenomena. Textbooks commonly used in Ghana’s SHS physics curriculum as per the Ministry of Education's (2023) syllabus, provide detailed explanations and problem sets to reinforce principles like image formation.

Physical equipment, such as convex lenses or plane mirrors, allows hands-on experimentation, which Snětinová et al. (2018) argue is critical for students to test hypotheses and internalise concepts through direct observation. In Ghana, however, the effective use of these materials is often hampered by practical constraints. Research by Adarkwah (2022), Duah et al. (2023) and Asumadu (2019) indicates that most schools face high student-to-resource ratios, with limited access to functional equipment due to cost and maintenance issues. This restricts opportunities for active learning, forcing reliance on lecture-based methods that, according to Ceuppens et al. (2018), are less effective for addressing misconceptions, such as students’ confusion between real and virtual images or their belief that light travels only in straight lines.

The design and implementation of traditional materials significantly influence their effectiveness in optics education. Textbooks, while comprehensive, often present content in a dense, theoretical format that can overwhelm students without supplementary activities, as noted by Li and Wang (2024). Chalkboard diagrams, while accessible, are static and may fail to convey the dynamic nature of light behaviour, such as the bending of rays in a prism. Physical laboratory equipment, when available, supports constructivist learning by enabling students to manipulate variables, such as adjusting the distance of an object from a lens to observe image characteristics.

However, studies by Adarkwah (2022), Duah et al. (2023) and Asumadu (2019) highlight that in most Ghanaian SHSs, such equipment are often scarce or outdated, and large class sizes, sometimes exceeding 50 students, limit hands-on engagement, reducing experiments to demonstrations observed passively. Moreover, cultural factors in Ghana, such as limited everyday exposure to optical devices like corrective lenses, can hinder students' ability to relate traditional materials to real-world contexts, as Dorsah and Okyere (2020) suggest in their study of local misconceptions about phenomena like rainbows. These challenges underscore the need for materials that are not only accessible but also designed to promote active engagement and conceptual change, aligning with the theoretical framework's emphasis on experiential learning.

Technology-based teaching and learning materials, particularly virtual laboratories and simulations, offer innovative solutions to enhance optics education by addressing the limitations of traditional resources. Virtual labs, such as PhET Interactive

Simulations or custom optics software, allow students to manipulate variables like angles of incidence or focal lengths in a digital environment, providing immediate visual feedback on light behaviour. Research by Erdoğan and Bozkurt (2023) demonstrates that such simulations foster conceptual understanding by enabling students to explore multiple scenarios, such as adjusting a lens's curvature to observe changes in image formation, without the need for physical equipment.

In the African context, Chepkorir et al. (2022) and Chumba et al. (2020) found that computer-based simulations improved science learning outcomes in Kenyan schools with limited laboratory facilities, suggesting their potential in Ghana as revealed by the study of Koomson et al. (2020). These tools align with conceptual change theory by creating opportunities for students to confront misconceptions. For example, visualising light bending in a prism to challenge naive assumptions about straight-line propagation.

In Nandom and Lawra, where access to physical laboratories may be limited, virtual materials could democratise experiential learning, as Ghana's information and communication technology (ICT) in Education policy has increased computer availability in some schools, according to Soma et al. (2021). However, challenges such as unreliable electricity, limited digital literacy, and inadequate teacher training, as noted by Ofosu-Asare (2024), must be addressed to ensure effective implementation. The design of these materials, which often includes interactive prompts and feedback loops, supports scaffolded learning, making abstract concepts like ray convergence more accessible and engaging.

Supplementary materials, such as teacher guides, worksheets, and mobile-based apps, can enhance the effectiveness of both traditional and technological resources by providing structured guidance. For instance, Rahayu et al. (2023) found that combining simulations with guided inquiry worksheets improved students' ability to apply optics concepts, such as predicting image positions using the lens formula. Also, mobile apps designed for offline simulations, such as the offline versions of PhET Simulations and Optics Lab (Putranta & Wilujeng, 2019), show promise for rural schools with intermittent internet access, offering interactive tools that align with the Ghanaian physics syllabus and support geometric optics instruction by allowing students to explore concepts like refraction and image formation without constant internet connectivity.

These materials can support teachers in facilitating active learning, encouraging students to construct knowledge through exploration, as advocated by constructivism. However, their success depends on teacher professional development to integrate them effectively, as Toma (2023) note that poorly implemented technology can confuse rather than clarify concepts. In Nandom and Lawra, where resource constraints may be acute, strategically designed materials, whether physical kits for small-group experiments or digital simulations for whole-class use, could bridge gaps in optics education.

2.5 Role of Real Laboratories in Enhancing Conceptual Understanding

Real laboratories, characterised by hands-on experimentation with physical equipment, play a pivotal role in physics education by providing students with tangible experiences that bridge theoretical concepts and observable phenomena, particularly in the study of geometric optics. This section explores the role of real laboratories in enhancing SHS students' conceptual understanding of optics concepts such as reflection, refraction, and image formation through lenses and mirrors. By synthesising empirical studies, this section examines the benefits of real laboratories. It also addresses challenges which are particularly acute in rural Ghanaian SHSs. Aligned with the study's theoretical framework of constructivism and conceptual change, this section supports Research Question 2 by providing a foundation for comparing real laboratories with virtual alternatives, highlighting how physical experimentation contributes to conceptual understanding in optics education.

Real laboratories offer a unique environment where students actively manipulate physical apparatus (Serrano-Perez et al., 2023), such as optical benches, lenses, mirrors, and prisms, to explore geometric optics principles. Constructivism posits that learning occurs through active engagement with the environment (Zajda, 2021), and real laboratories embody this by allowing students to construct knowledge through direct sensory experiences (Widodo et al., 2017). For instance, setting up an experiment to measure the focal length of a convex lens enables students to observe image formation firsthand, connecting abstract concepts like the lens formula to tangible outcomes.

Research by Liu and Fang (2023) demonstrates that such hands-on activities enhance conceptual understanding by allowing students to test hypotheses and reflect on discrepancies, such as predicting and then observing an inverted real image. In the context of geometric optics, a study by Uwamahoro et al. (2021) show that physical experiments help students overcome misconceptions, such as the belief that light travels only in straight lines, by providing empirical evidence of phenomena like refraction. For example, students manipulating a prism to observe light bending can directly challenge naive assumptions, aligning with conceptual change theory’s emphasis on creating dissatisfaction with incorrect ideas. In Ghanaian SHSs, where the physics syllabus emphasises practical skills (Ministry of Education, 2023), real laboratories are critical for enabling students to apply theoretical knowledge, such as calculating angles of incidence and refraction, in a controlled setting that mirrors scientific inquiry.

The tactile and sensory nature of real laboratories is a key strength in fostering conceptual understanding. The physical act of adjusting equipment, such as aligning a light source with a lens or measuring distances on an optical bench, provides kinesthetic feedback that reinforces learning. Such sensory engagement makes abstract concepts more concrete (Nurjanah et al., 2024), as students can feel the resistance of a lens holder or see the sharpness of an image change with positional adjustments. This aligns with constructivist principles, as students assimilate new observations into existing schemas or accommodate them by revising misconceptions (Bhattacharjee, 2015). For instance, a student who initially believes that a mirror’s image is physically behind the surface may, through hands-on measurement, recognise it as virtual, thus undergoing conceptual change.

Such experiences are particularly valuable for addressing culturally influenced misconceptions, which may confuse students’ understanding. Real laboratories also foster collaborative learning (Pavlou & Zacharia, 2024), as students often work in groups to set up experiments, encouraging discussions that, per Vygotsky's (1978) social constructivism, deepen understanding through peer interaction. For example, debating why a concave mirror produces different images at varying object distances can solidify students' grasp of reflection principles.

Despite these benefits, real laboratories face significant challenges. High costs associated with procuring and maintaining equipment (Awan, 2015), such as precision lenses or light sources, are a major barrier. Anecdotal evidence suggests that many Ghanaian SHSs lack functional laboratory facilities, with schools often sharing a single optical kit among dozens of students. This scarcity limits hands-on opportunities, reducing experiments to teacher-led demonstrations that, according to Assem et al. (2023), are less effective for fostering individual understanding. Safety concerns also arise, as handling glass lenses or laser-based setups requires careful supervision, which may be challenging in large classes common in Ghana, where student-to-teacher ratios can exceed 50:1, as reported by Duah et al. (2023). Accessibility issues are compounded by logistical constraints, such as unreliable electricity for powering light sources, which further restricts laboratory use in rural municipalities. These challenges highlight the practical limitations of real laboratories in aligning with the Ministry of Education's (2023) syllabus's practical requirements, and underscore the need to explore alternatives like virtual laboratories, as proposed in Research Question 2.

Empirical evidence supports the efficacy of real laboratories in enhancing conceptual understanding, though results vary by context. Studies like those by Husnaini and Chen (2019) and Wardani et al. (2017) show that students in well-equipped laboratories demonstrate significant improvements in conceptual tests, such as the

Optics Concept Inventory, with pre- and post-test gains indicating better grasp of principles like Snell's law. Research by Tindan and Anaba (2024), Snětinová et al. (2018) as well as Twumasi and Hanson (2018) found that students exposed to hands-on experiments outperformed peers in lecture-based settings, particularly in tasks requiring application.

However, these studies often assume access to adequate resources, which is not always the case in rural Ghana. A local study by Annan et al. (2019) suggest that even limited laboratory exposure can improve outcomes, but the impact is diminished by equipment shortages and lack of teacher training in inquiry-based methods. For instance, a teacher in Nandom or Lawra may struggle to facilitate experiments due to missing prisms or broken lenses, limiting the laboratory's potential to foster conceptual change. These findings highlight the need for context-specific strategies to maximise the benefits of real laboratories while addressing their limitations, setting the stage for comparison with virtual laboratories that may offer more accessible alternatives.

2.6 Integration of Virtual Laboratories in Science Education

The integration of virtual laboratories into science education represents a transformative approach to teaching complex concepts, such as those in geometric optics, by leveraging digital simulations to provide interactive, accessible, and cost-effective learning experiences. This section explores the role of virtual laboratories in enhancing SHS students' conceptual understanding of optics principles, including reflection, refraction, and image formation. By synthesising global and regional literature, this section examines the evolution, advantages, and challenges of virtual laboratories, emphasising their interactivity, flexibility, and ability to visualise abstract concepts. Grounded in the study’s theoretical frameworks of constructivism and conceptual change, virtual laboratories align with active learning and misconception resolution by enabling students to experiment in simulated environments. This section supports Research Question 2 by providing a basis for comparing virtual and real laboratories and informs Research Question 3 by exploring how virtual laboratories facilitate conceptual development.

Virtual laboratories, defined by Ali et al. (2022) as computer-based or mobile-based platforms that simulate real-world experiments, have evolved significantly with advancements in educational technology. Tools like PhET Interactive Simulations, Virtual Physics Labs, and Optics Lab allow students to manipulate variables such as angles of incidence, refractive indices, or lens focal lengths in a digital environment, replicating the outcomes of physical experiments. Research by Shambare (2023) highlights that these simulations emerged to address limitations of traditional laboratories, such as high costs and logistical constraints, while maintaining pedagogical rigor.

In geometric optics, virtual laboratories enable students to visualise ray paths, observe image formation in lenses, or explore light dispersion in prisms without requiring physical equipment (Erdoğan & Bozkurt, 2023; Ndihokubwayo et al., 2020). For instance, a student can adjust the curvature of a virtual lens to see real-time changes in image position, making abstract concepts like the lens formula more tangible. This aligns with constructivist principles, as students actively construct knowledge through exploration and reflection, similar to hands-on labs but with greater flexibility. In the

Ghanaian context, where the physics syllabus emphasises practical understanding (Ministry of Education, 2023), virtual labs offer a scalable solution for schools in Nandom and Lawra, where physical laboratories may be under-equipped.

The advantages of virtual laboratories lie in their interactivity, cost-effectiveness, and ability to provide immediate feedback (Asare et al., 2023; Kashaka, 2024), which enhance conceptual understanding (Faour & Ayoubi, 2018). Unlike real laboratories, Hernández-de-Menéndez et al. (2019) highlight that virtual laboratories allow students to conduct unlimited trials without risk of equipment damage, enabling iterative experimentation that supports conceptual change. For example, a student who mistakenly assumes light does not bend in a medium can repeatedly adjust angles in a virtual refraction simulation, observing Snell’s law in action, which creates dissatisfaction with misconceptions and fosters plausibility of scientific explanations, as per Posner et al.'s (1982) conceptual change model.

Studies by Ndihokubwayo et al. (2020) as well as Banda and Nzabahimana (2021), demonstrate that students using virtual simulations, such as PhET’s simulations, show significant gains in conceptual tests, outperforming peers in traditional settings. In sub- Saharan Africa, research by Kibiwott and Njoroge (2024) and Ndegwa et al. (2023) in Kenya found that virtual laboratories improved science learning outcomes in schools with limited physical resources. Virtual laboratories also offer accessibility, requiring only basic digital infrastructure like computers or mobile devices (Alnagrat et al., 2023), which aligns with Ghana’s ICT in Education policy that has increased device availability in some SHSs. In Nandom and Lawra, where equipment shortages may hinder real laboratories, virtual alternatives can democratise access to experiential learning, enabling students to engage with optics concepts like ray convergence or critical angle calculations.

Despite their advantages, integrating virtual laboratories into science education presents challenges, particularly in resource-limited contexts. Limited digital infrastructure, such as unreliable electricity or insufficient computers, can hinder implementation, as noted by Kashaka (2024) and Alnagrat et al. (2023). In rural areas, schools may have only a few shared computers, restricting simultaneous access for large classes (Shambare & Jita, 2025). Digital literacy gaps among students and teachers also pose barriers (Asare et al., 2023), as effective use of simulations requires familiarity with interfaces and inquiry- based approaches. Research by Shambare and Jita (2025) highlights that without adequate teacher training, virtual labs may be underutilised or misaligned with curriculum goals, reducing their impact. For instance, a teacher unfamiliar with a simulation's features might fail to guide students in exploring refraction, limiting the tool's ability to address misconceptions.

Additionally, virtual laboratories lack the tactile feedback of real laboratories, which Kapici et al. (2019) argue, is critical for kinesthetic learners who benefit from physical manipulation. According to Deriba et al. (2023), cultural factors, such as students' limited exposure to technology, may further complicate adoption, as unfamiliarity with digital tools can create initial resistance. These challenges underscore the need for strategic implementation, including offline-compatible apps like PhET's downloadable simulations or Optics Lab, which can mitigate connectivity issues in rural SHSs. The literature also emphasises strategies to maximise the effectiveness of virtual laboratories in optics education. Combining simulations with guided inquiry activities, such as worksheets that prompt students to predict and analyse outcomes, enhances learning outcomes, as shown by Mahtari et al. (2020). For example, a worksheet directing students to adjust a virtual prism's angle to observe dispersion can reinforce understanding of wavelength-dependent refraction. In Ghana, where the physics syllabus requires practical competencies (Ministry of Education, 2023), virtual laboratories can be tailored to simulate specific experiments, such as measuring focal lengths, ensuring curriculum alignment.

A study by Kapici et al. (2019) suggest that blended approaches, integrating virtual laboratories with teacher-led discussions or occasional real laboratory activities, can optimise conceptual understanding by combining digital flexibility with social interaction. In Nandom and Lawra, where resource constraints may limit physical laboratories, such blended strategies could leverage available ICT infrastructure, like shared computer labs, to support active learning. Furthermore, mobile-based simulations, accessible on low-cost devices, offer a practical solution for rural schools, as Ghana's ICT policy promotes mobile learning (Ministry of Education, 2023). These strategies align with Research Question 3, which seeks to understand how virtual labs facilitate conceptual development by providing scalable, interactive tools that address misconceptions and support inquiry-based learning.

2.7 Comparative Studies on Virtual Versus Real Laboratories

Comparative studies on virtual versus real laboratories provide empirical insights into their relative impacts on student outcomes, particularly conceptual understanding, directly addressing Research Question 2 by analysing differences in effectiveness across various educational contexts. This section synthesises findings from key research, focusing on experimental designs and quasi-experimental studies that measure achievement through pre- and post-tests or similar metrics. While results are mixed, many indicate that virtual laboratories can be equivalent or superior in certain scenarios, especially for abstract concepts in physics.

In a position paper reviewing literature on simulated versus hands-on laboratories, Burkett and Smith (2016) argued that virtual laboratories achieve comparable results for content mastery and scientific reasoning but fall short in practical skills, teamwork, and understanding empirical complexity. They recommended using simulations to supplement, not replace, hands-on labs, aligning with positions from the National Research Council (NRC), National Science Teachers Association (NSTA), American Chemical Society (ACS), and College Board, while noting gaps in measuring all standard laboratory goals.

In a quasi-experimental study with 50 grade 10 students in Lebanon, Faour and Ayoubi (2018) compared virtual laboratories (using PhET's Circuit Construction Kit) to interactive demonstrations with real equipment for teaching direct current electric circuits. Both virtual laboratory and real laboratory groups showed significant improvements in conceptual understanding (measured by Determining and Interpreting Resistive Electric Current Concepts test), but the virtual laboratory group had a significantly higher post-test mean score. No significant differences were found in attitudes towards physics (measured by Physics Attitude Scale).

In a quasi-experimental study with 7th-grade students on electricity, Kapici et al. (2019) compared hands-on labs, virtual labs (using Go-Lab), and their combinations/sequences. Sequential approaches (virtual then hands-on or hands-on then virtual) outperformed isolated use for conceptual knowledge and inquiry skills (inferring, classifying, determining variables, designing experiments), with no significant difference between the two sequences.

In another quasi-experimental study with 90 undergraduate students at Birzeit University in Palestine, Hamed and Aljanazrah (2020) examined the effectiveness of virtual experiments (using PhET simulations and videos) as preparation for real laboratory sessions in general physics compared to traditional face-to-face preparation. The experimental group showed significantly higher achievement scores and better laboratory performance (practical skills) than the control group. Students viewed virtual laboratories positively for flexibility, time-saving, and better preparation, suggesting a blended model as effective, especially during COVID-19 restrictions.

Furthermore, in a meta-analysis of 15 studies ($N = 2642$) from 2015-2020 comparing virtual and traditional laboratories in science education (biology, chemistry, physics, earth science) at secondary and undergraduate levels, Santos and Prudente (2022) found a medium overall effect size (Hedges' $g = 0.587$) favouring virtual laboratories for student achievement. Subgroup analysis revealed stronger effects for secondary students ($g = 0.689$) than undergraduates ($g = 0.012$), and in chemistry ($g = 0.787$) and physics ($g = 0.652$) compared to biology ($g = -0.044$). High heterogeneity ($I^2 = 91\%$) suggests contextual variations, with no evidence of publication bias.

In conclusion, comparative studies demonstrate that virtual laboratories often yield comparable or enhanced outcomes in conceptual understanding compared to real laboratories, particularly in resource-limited environments where cost, safety, and accessibility are concerns. Mixed results underscore the influence of subject area and learner level, with virtual laboratories showing promise for physics topics by enabling visualisation and repetition.

2.8 Mechanisms of Conceptual Development through Virtual Laboratories

As previously discussed, virtual laboratories, as digital platforms simulating real-world experiments, facilitate conceptual development in science education, particularly for complex topics like geometric optics, by leveraging unique affordances that align with constructivist and conceptual change theories. This section aligns with Research Question 3 by exploring how virtual laboratories foster conceptual understanding of concepts. Drawing on global and regional literature, it examines key mechanisms, including interactive visualisation, immediate feedback, iterative experimentation, and scaffolding, that enable students to construct and refine mental models. These mechanisms are particularly relevant in contexts where physical laboratories are limited, offering insights into how virtual labs can address misconceptions and promote deep learning in the Ghanaian SHS context.

Interactive Visualisation: Virtual laboratories provide dynamic visualisations that make abstract optics concepts concrete (Herga et al., 2016), a critical mechanism for conceptual development. For instance, tools like PhET Interactive Simulations or Optics Lab allow students to see ray paths, lens convergence, or light dispersion in real-time, which is often invisible in real-world settings. Research by Kapici et al.

(2019) highlights that such visualisations enhance understanding by simplifying complex phenomena, aligning with constructivism’s emphasis on active knowledge construction. In Ghana, where students may have limited exposure real laboratory equipment, as noted by Duah et al. (2023), visualisations can bridge experiential gaps, making concepts like Snell’s law more accessible and fostering assimilation into existing schemas.

Immediate Feedback: Virtual laboratories deliver real-time feedback on student actions, enabling rapid correction of errors and reinforcement of correct understanding (Barmaki & Hughes, 2015). For instance, when a student adjusts a virtual lens’s focal length and sees the immediate impact on image formation, they receive instant confirmation or disconfirmation of their predictions. This aligns with conceptual change theory’s condition of dissatisfaction (Posner et al., 1982), as incorrect assumptions such as expecting a virtual image to be tangible are directly confronted. A study by Chernikova et al. (2020) demonstrates that immediate feedback in simulations improves conceptual test scores by allowing students to refine mental models iteratively. In settings, where large class sizes limit teacher feedback, virtual laboratories can provide individualised guidance, supporting students in resolving misconceptions about image characteristics or ray behaviour.

Iterative Experimentation: The ability to repeat experiments without resource constraints is a hallmark of virtual laboratories (Hamed & Aljanazrah, 2020), promoting conceptual development through trial and error. For instance, students can explore multiple scenarios, such as varying object distances in a lens simulation, to understand relationships like the lens formula. This iterative process supports conceptual change by making new concepts plausible and fruitful, as students test and refine their understanding (Strike & Posner, 1982). In optics, this mechanism allows students to confront persistent misconceptions, such as confusing real and virtual images, by repeatedly observing outcomes in a controlled digital environment.

Scaffolding and Guided Inquiry: Virtual laboratories often integrate scaffolding tools, such as prompts, hints, or structured worksheets, to guide students through the inquiry process (Zacharia et al. 2015), aligning with Vygotsky's (1994) zone of proximal development. For example, a simulation might prompt students to predict the effect of changing a mirror's curvature before adjusting it, fostering hypothesis-driven learning. A study by Wartono et al. (2019) shows that such scaffolding enhances inquiry skills and conceptual understanding by supporting students in defining problems, designing experiments, and interpreting data. In the Ghanaian context, where teachers may lack training in inquiry-based methods (Annan et al., 2019), virtual labs with built-in scaffolds can compensate, ensuring students engage meaningfully with optics concepts like critical angle or dispersion.

Challenges and Contextual Considerations: While these mechanisms are powerful, their effectiveness in Ghanaian SHSs depends on overcoming barriers like limited digital infrastructure and low digital literacy, as noted by Alnagrat et al. (2023) and Deriba et al. (2023). For instance, unreliable electricity in rural areas may disrupt virtual laboratory use, while unfamiliarity with digital interfaces can hinder engagement. However, offline- compatible tools, such as downloadable PhET simulations, can mitigate connectivity issues, as discussed in section 2.4. Additionally, virtual laboratories lack the tactile feedback of real laboratories, which

Kapici et al. (2019) argue is crucial for kinesthetic learners. Blended approaches, combining virtual visualisations with occasional hands-on activities, may optimise conceptual development, as suggested by Kapici et al. (2019). These considerations highlight the need for context-specific implementation strategies to maximise virtual laboratories' impact in Ghana.

2.9 Summary of Literature Review

The literature reviewed highlights that geometric optics occupies a crucial place in the physics curriculum, yet it remains one of the most difficult areas for students to master. Globally and locally, students often hold persistent misconceptions about concepts such as image formation, reflection, and refraction. These difficulties stem from intuitive beliefs, cultural influences, and inadequate opportunities for experiential learning. Constructivist and conceptual change perspectives emphasise that such misconceptions can only be addressed through active engagement and repeated experimentation. However, in the Ghanaian context, particularly in rural areas such as Nandom and Lawra, resource limitations may hinder effective practical instruction. Teachers frequently rely on chalk-and-talk methods, while shortages of laboratory materials and large class sizes reduce students' opportunities to explore optics concepts in meaningful ways.

The review also revealed that both real and virtual laboratories have emerged as effective strategies for enhancing students' conceptual understanding in physics. Real laboratories provide tactile and sensory experiences that reinforce theoretical learning, while virtual laboratories offer flexibility, repeatability, and the ability to visualise abstract phenomena in real time. Comparative studies across different contexts have shown mixed outcomes, with some indicating equivalence between the two approaches and others suggesting advantages of virtual laboratories for certain abstract concepts. Yet, in contexts like Ghana, where laboratory resources are scarce and digital integration is still evolving, there is limited empirical evidence on the relative effectiveness of these two approaches in supporting conceptual understanding of geometric optics.

Additionally, while international research has described the strengths of virtual laboratories in terms of interactivity, accessibility, and immediate feedback, there remains limited insight into how students in rural, resource-constrained Ghanaian SHSs actually develop conceptual understanding when exposed to such tools. This is important because the processes by which misconceptions are confronted and resolved may differ across cultural and infrastructural contexts. Literature suggests that combining inquiry-based strategies with technological tools enhances learning outcomes, but few studies have examined how these dynamics play out in rural Ghanaian schools where infrastructure, teacher preparedness, and student digital literacy levels vary widely.

From the foregoing, three major gaps emerge that warrant the present study. First, there is insufficient evidence on the availability and adequacy of teaching and learning materials for geometric optics in the Nandom and Lawra Municipalities, which has direct implications for physics instruction. Second, while comparative studies of real and virtual laboratories exist elsewhere, there is a lack of context-specific research examining their relative effectiveness in enhancing conceptual understanding among Ghanaian SHS students. Third, little is known about the specific processes through which virtual laboratories support conceptual change in optics within rural Ghanaian contexts. These gaps provide a strong justification for this study, which seeks to investigate the integration of technology in teaching geometric optics by comparing real and virtual laboratories in order to enhance conceptual understanding in SHS physics.

CHAPTER THREE

METHODOLOGY

3.0 Overview

This chapter describes the study area of the research. It also describes the research design used to collect data for the study. The chapter further outlines population, sample and sampling techniques used to select the sample size for the study. This chapter also gives detailed description of research instruments used to collect data for the study. Validity and reliability of the research instruments are also discussed in this chapter. The chapter continues with data collection procedure and how the data generated was analysed, and ends with ethical issues which were considered in the study.

3.1 Study Areas

The study was conducted in the Nandom Municipal and Lawra Municipal. The Nandom Municipal lies in the north western corner of the Upper West Region of Ghana between Longitude 2°25 W and 2°45W and Latitude 10°20 N and 11°00 S. It is bounded to the East and South by the Lambussie Municipal and Lawra Municipal respectively and to the North and West by the Republic of Burkina Faso, and has Nandom as its capital town. The total area of the Municipal is put at 567.6 square km. This constitutes about 3.1% of the Region’s total land area (Ghana Statistical Service, 2021). The Municipal is constituted by 88 communities with 86% of the inhabitants living in rural areas. The population density is about 89 per square kilometer. It is the most densely populated Municipality in the Region. Its closeness to Burkina Faso offers it a strategic location for international interactions and exchanges. The Nandom

Municipal has two SHSs, which are all public schools, where only one offers physics as elective subject. There are also two public and two private technical and vocational training institutes (TVET), and one public midwifery training college (Ghana Statistical Service, 2021).

The Lawra Municipal is one of the 261 Metropolitan, Municipal and District Assemblies (MMDAs) in Ghana, and forms part of the 11 Municipalities and Districts in the Upper West Region. It located in the north western corner of the Upper West Region in Ghana between Long. 2°25 W and 2°45W and Lat. 10°20 and 11°00 and has its administrative capital as Lawra. The total area of the Municipal is put at 514 square km. This constitutes about 5.7% of the Region's total land area, which is estimated at 18,476 square km. It is bounded to east and south by the Jirapa Municipal and Lambussie Karni District and to the north and west by the Republic of Burkina Faso. There is one tertiary institution, two public SHSs, one of which offer physics as elective subject and one public SHTS which also offer physics and one TVET institute (Ghana Statistical Service, 2021).

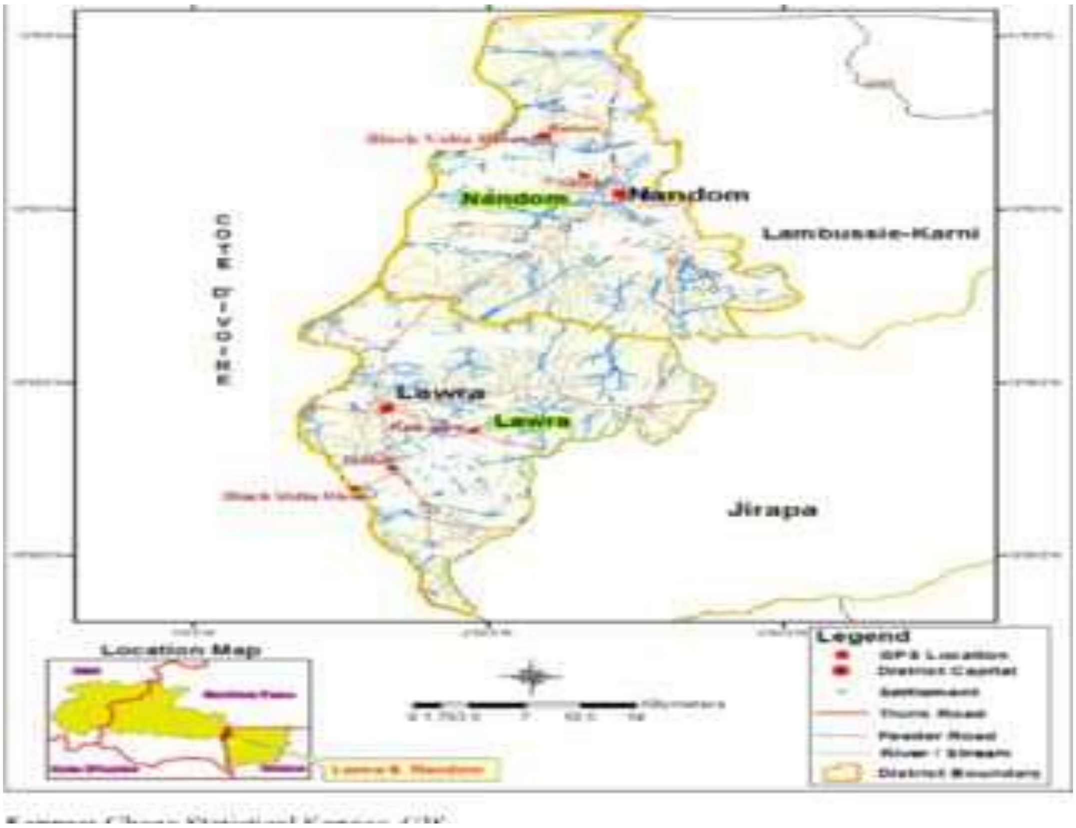


Figure 3.1: Map of the Study Areas (Ghana Statistical Service, 2021)

3.2 Research Paradigm

The pragmatism paradigm was the philosophical basis for this study. Pragmatism is a philosophical paradigm that emphasises practical consequences and real-world outcomes as the basis for determining the truth or value of beliefs, theories, or actions (Maarouf, 2019). Central to pragmatism is the idea that truth is not static but rather dynamic and evolving, shaped by human experience and the context in which it occurs (Kelly et al., 2018). That is, pragmatism rejects the notion of absolute or fixed truths and instead focuses on the usefulness and effectiveness of ideas in achieving desired goals (Brierley, 2017). Rather, in addition to acknowledging the existence and significance of the natural or physical world, pragmatism also acknowledges the emergent social and psychological world, which consists of human institutions, language, culture, and subjective cognition (Johnson & Onwuegbuzie, 2004).

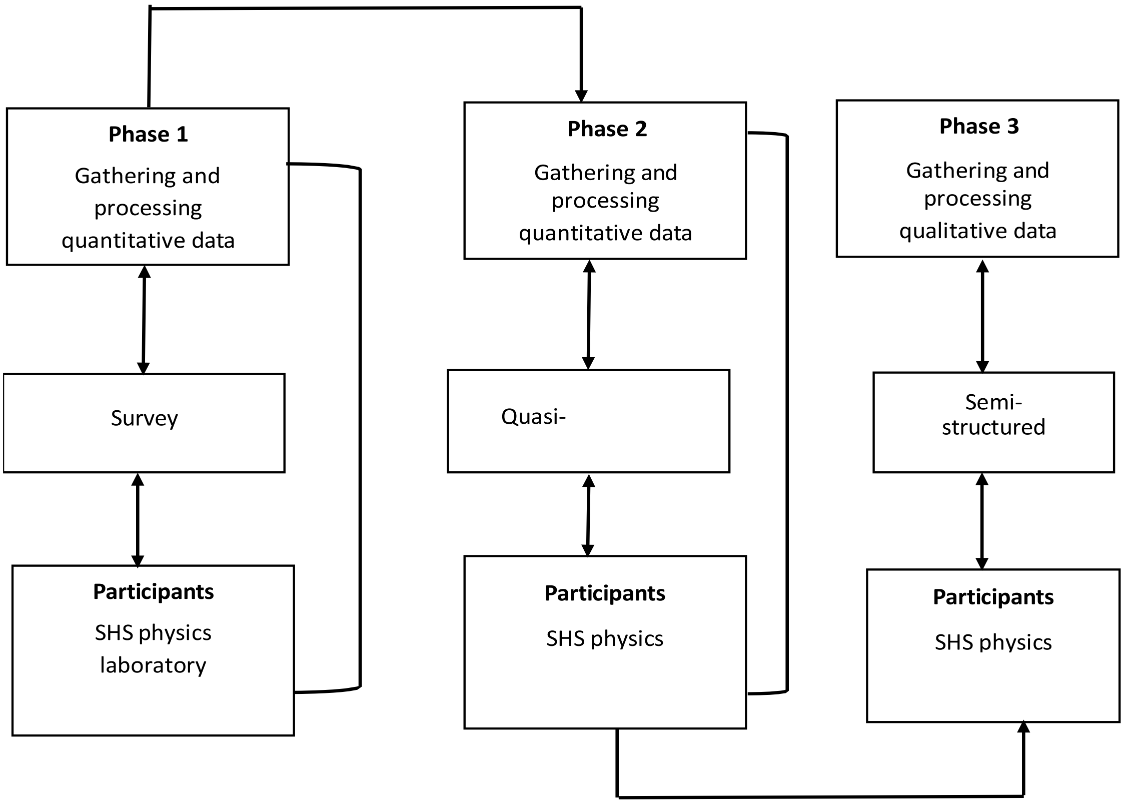
Accordingly, pragmatists believe that research should be planned and carried out in the most effective manner to address the research questions (Allemang et al., 2021). This means that pragmatism is appropriately aligned with a mixed method research approach using quantitative and qualitative techniques to gather and analyse data to answer research questions. Therefore, aligning with the philosophical assumptions of pragmatism, this study sought to employ the mixed method research approach where qualitative means was used to gather and analyse data to answer research questions 1 and 3, while quantitative means was used to gather and analyse data to answer research question 2.

3.3 Research Design

This study is mixed method research. In light of this, the multiphase mixed method design was employed to gather and analyse quantitative and qualitative data sequentially to answer the research questions (Almeida, 2018; Creswell, 2014). The multiphase mixed method designed as used in this study, involved multiple distinct phases of data collection and analysis, combining both qualitative and quantitative methods within each phase (Schoonenboom & Johnson, 2017). Thus, different types of data were collected and analysed iteratively throughout the research process. Particularly, the design was marked by an initial quantitative phase which provided data and findings which helped develop the quantitative phase of the study. The collection and analysis of the initial quantitative data was done through survey.

This helped to determine the available teaching and learning materials for study of optics within the Nandom Municipality, thereby answering research question 1. The data collected during the first phase of this study informed the second quantitative phase where quasi-experimental pretest/posttest non-equivalent control group design was employed to ascertain the effectiveness of virtual laboratory and real laboratory on students' conceptual understanding in optics. The use of quasi- experiment means that participating students were not randomly selected to participate in the study. The quantitative analysis yielded statistical results and numerical findings that formed the basis for further exploration.

After the quantitative data analysis, the research then proceeded to the qualitative phase, where data were collected through semi-structured interview. The qualitative data collection aimed to provide deeper insights, explanations, or interpretations of the quantitative findings gathered from the experiment, through the discovery of students' perceptions on the use of virtual laboratory in the teaching and learning of optics. Figure 3.1 shows a framework of the study design.



Framework of study design (author's construct, 2025)

3.4 Population

According to Cohen et al. (2018) populations can be classified as target population or accessible population. Thus, the target population refers to the total set of people or things that researchers are interested in generalising the findings to (Bhattacherjee, 2012). The accessible population on the other hand is the total number of instances or components that meet the predetermined criteria and are available to the researcher as a pool of study subjects or participants (Appiah-Twumasi, 2016). In this study, the target population comprised all SHS physics students in the Nandom Municipality and Lawra Municipality in the Upper West Region of Ghana, while the accessible population were all SHS 2 students who studied physics as elective within both Municipalities.

3.5 Sampling Procedure and Sample

A sample from the population was selected as a representative of the population due to constraints such as time, cost and workforce. Therefore, to select a sample from the population, the multi-stage sampling procedure was used. The multi-stage sampling technique was employed since different sampling techniques were used to select participants at different phases in the design. This is summarised in Table 3.1.

Table 3.1: Multi-Stage Sampling Procedure for the Study

Stage	Sampling Technique	Activity	Sample Size (N)
Quantitative Phase (survey)	Purposive Sampling	Selection of all SHSs who offer physics as elective	3 SHSs
Quantitative phase (experiment)	Purposive sampling	Selection of one SHS offering physics from each Municipal	2 SHSs
	Simple Random Sampling	Selection of one intact SHS 2 physics class from each school	109 SHS physics students
Qualitative Phase	Simple random sampling	Selection twelve students for semi-structured interview	15 SHS physics students

The multi-stage sampling used in this study as summarised in Table 3.1 shows that in the initial quantitative phase of the study, purposive sampling was used to select all SHSs who offered physics as elective subject within the Nandom Municipal and Lawra Municipal. This was because not all available SHSs offered physics as elective within both municipals. As a result, it was found that there were three SHSs which offered physics as elective within both municipals. In the second quantitative phase of the study which was characterised by the employment of the quasi-experimental design, one SHS was purposively selected from each Municipal to participate in the experiment. Purposive sampling was employed at this stage to select a school which had some optical instruments in one Municipal and another which lacked optical instruments in another Municipal. It should however be noted that, where there were insufficient optical instruments to be used for the experiment, they were borrowed from other schools and were duly returned to the respective schools afterwards. Moreover, there were more than one intact SHS 2 physics class in each school, hence, simple random sampling was used to select one intact class from each participating SHS in the experimental phase. This provided a total of 95 SHS 2 physics students who participated in the study. Following the experimental phase was the qualitative phase of the study, where simple random sampling was used to select twelve participants from the experimental group for a semi-structured interview.

3.6 Research Instruments

Two research instruments were used to gather data to this study. These were an achievement test (Optics Concept Test), an inventory, and an interview guide. The detailed descriptions of the instruments are given in sections 3.6.1 to 3.6.3.

3.6.1 Optics Concept Test (OCT)

The optics concept test (see Appendix A), with its marking scheme (see Appendix B) was used to assess conceptual understanding in geometric optics. The instrument consisted of eight open-ended items aligned with the SHS physics syllabus and covered the contents of reflection, refraction, and formation of images on plane mirrors and lenses. The use of the open-ended items is justified on the basis that they helped to assess the conceptual understanding of students in the selected geometric optics concepts. The same set of items were used as pretest and posttest, therefore, students' scores in the pre-test were not given to them, neither were the questions discussed with them after the pretest.

3.6.2 Geometric Optics Instruments Inventory

The Geometric Optics Instruments Inventory as shown in Appendix C was a structured tool designed to provide valuable insights into the availability and state of optical instruments in the respective educational settings in the study areas. The instruments on the inventory were selected to align with the geometric optics concepts considered in this study.

3.6.3 Semi-Structured Interview Guide

The semi-structured interview guide (see Appendix D) was designed to determine SHS physics students' perceptions towards the use of virtual laboratory in the study of optics after the intervention. There were five open-ended items in the interview guide that allowed participants to freely share their thoughts about their experiences using virtual laboratories, however, under the direction of the researcher.

3.7 Pilot-testing of the Instruments

Since they were all self-designed, the instruments were pilot-tested in order to determine their validities and reliabilities. The pilot-testing of the instruments was conducted using one intact class (N = 57) from the Lawra Municipal who did not partake in the main study. The pilot testing helped to refine the items to improve clarity and consistency. The results of the pilot test were used to determine the reliability of the instruments.

3.8 Validity of the Instrument

The instrument was validated by employing content validity. In determining the content validity, four SHS physics teachers with 12 years of teaching experience, as well as two science education lecturers from the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), were invited to evaluate the items' abilities to measure their intended outcomes. The feedback from the experts were considered to improve the construction of the items.

3.9 Reliability of the Instruments

The reliability of the instruments was determined by employing inter-rater reliability analysis, specifically Cohen’s Kappa. In this way, two raters were invited to score students’ answers to the items independently using the same rubrics designed to score students’ responses. The scores from each rater for each student were thus analysed to determine their consistency. In determining the consistency of scores from the raters, a Kappa value of 0.84 was obtained, indicating a preferable internal consistency of scores from the raters. This therefore deemed the instrument reliable to be used in the main study.

3.10 Intervention Stages

The intervention stage, which took place between the periods of July, 2024 and August, 2024, lasted for four weeks where three lessons (each lasting for 2 hours) were scheduled within each week. Lessons in the experimental group were carried out using PhET interactive simulations. The PhET interactive simulation for optics is an educational tool designed that was created by the University of Colorado Boulder (Meadows & Caniglia, 2019), to help users understand the principles of optics. This simulation provides a hands-on virtual environment where users can explore how light interacts with different materials and interfaces.

Week 1: Introduction to Basic Concepts

Activity 1: Explore Reflection

Virtual Laboratory Link: **https://phet.colorado.edu/en/simulations/bending-light**

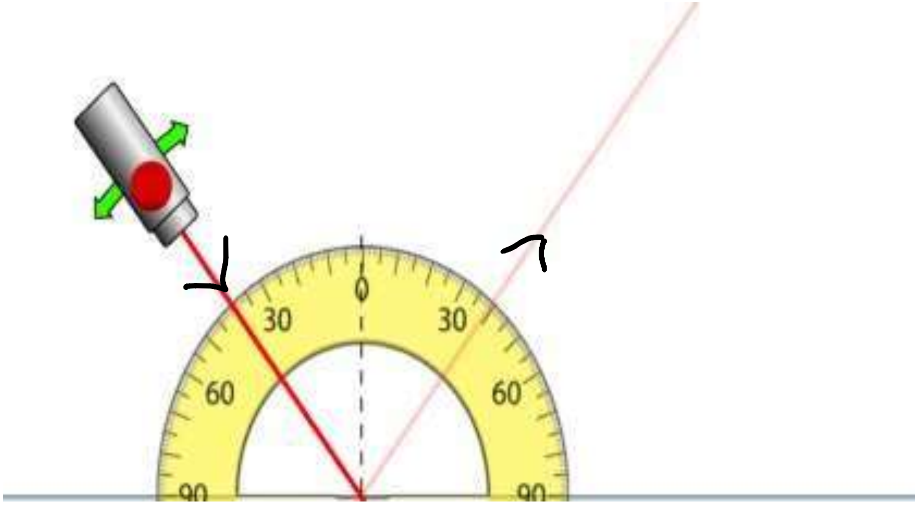
Objective: State the law of reflection.

Simulation: "Bending light"

Steps:

1. Start the simulation and select the "Intro" tab.
2. Place a single ray of light at an angle to a reflective surface.

3. Measure the angle of incidence and the angle of reflection using the protractor tool.
4. Record the measurements and verify that the angle of incidence equals the angle of reflection.



Activity 2: Explore Refraction

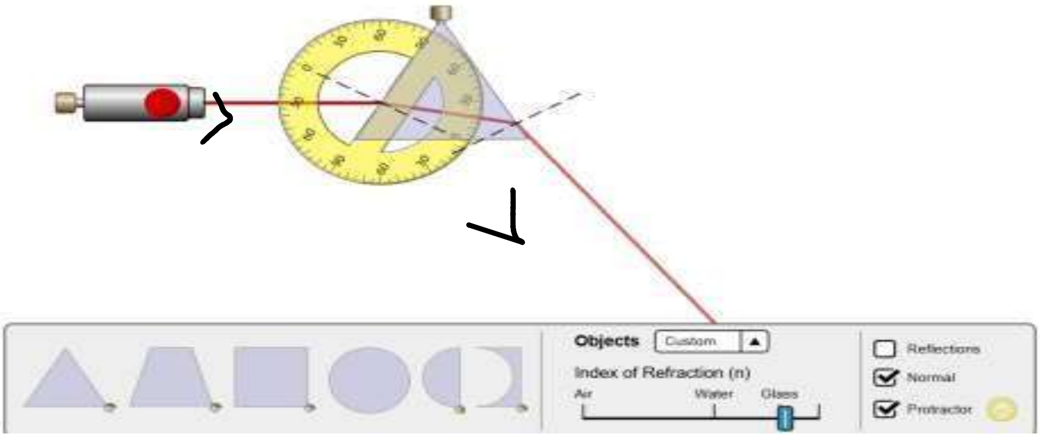
Virtual Laboratory Link: https://phet.colorado.edu/en/simulations/bending-light

Objective: Explain how light bends when it passes through different media.

Simulation: "Bending Light"

Steps:

1. Switch to the “Prisms” tab in the simulation.
2. Place a glass prism in the path of the light ray.
3. Observe how the light bends when it enters and exits the prism.
4. Change the medium on either side of the prism (air, water, glass) and observe changes in the angle of refraction.
5. Record the angles and discuss Snell's Law.



Objects: Custom

Index of Refraction (n)

☐ Reflections

☑ Normal

☑ Protractor

Stage 4: Snell's Law and Total Internal Reflection

Virtual Laboratory Link: https://phet.colorado.edu/en/simulations/bending-light

Activity 1: Understanding Snell's Law

Objective: Learn and apply Snell's Law to predict the behaviour of light as it passes between different media.

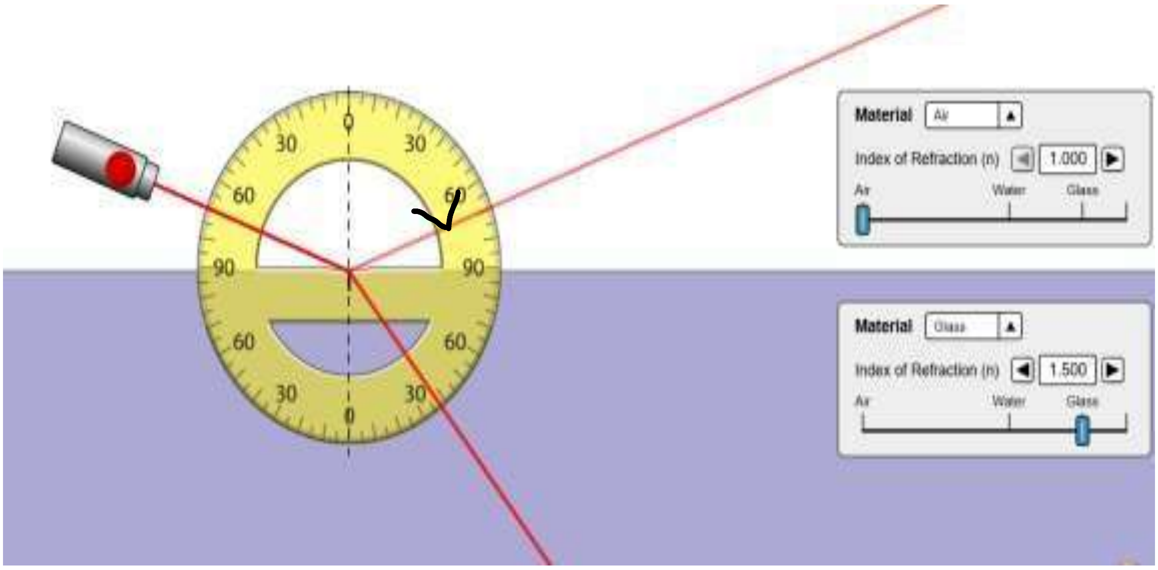
Simulation: "Bending Light"

Steps:

1. Open the simulation and select the "Intro" tab.
2. Set up the medium by choosing air as the first medium and glass as the second medium.
3. Shine a single ray of light at the boundary between air and glass.
4. Measure the angle of incidence (θ_1) and the angle of refraction (θ_2) using the protractor tool.
5. Record the refractive indices of air ($n_1 = 1.00$) and glass ($n_2 \approx 1.50$).
6. Calculate the sine of the angles and verify Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$.

7. Change the angle of incidence and repeat the measurements to see how the angles and calculations change.

7


Material: Air
Index of Refraction (n): 1.000

Material: Glass
Index of Refraction (n): 1.500

Activity 2: Principle of Total Internal Reflection

Virtual Laboratory Link: https://phet.colorado.edu/en/simulations/bending-light

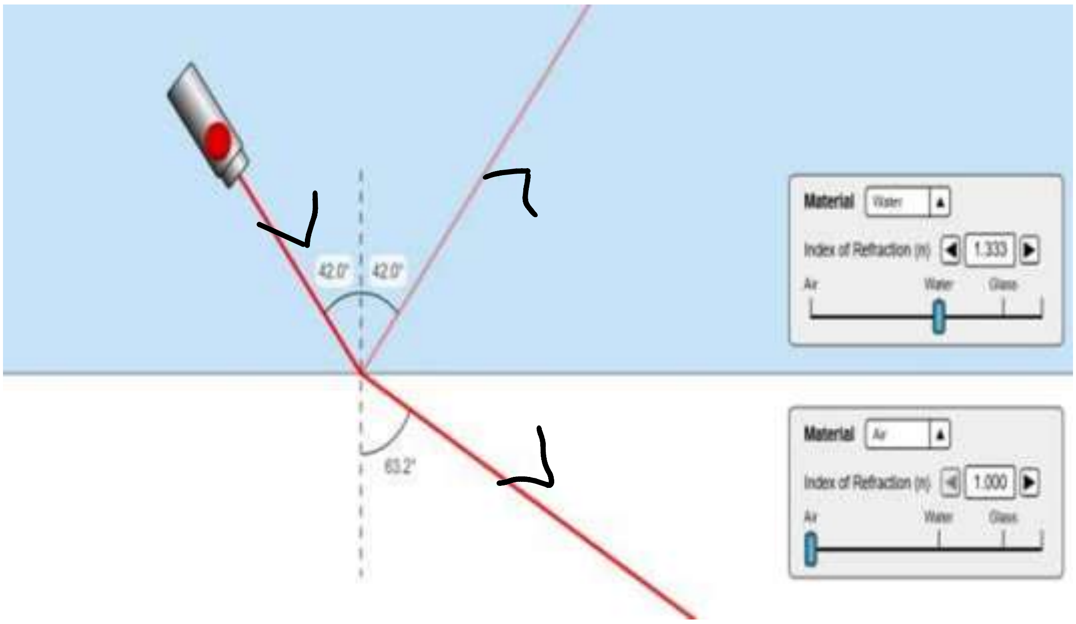
Objective: State the conditions for total internal reflection and how it is applied in technologies like fiber optics.

Simulation: “Bending Light”

Steps:

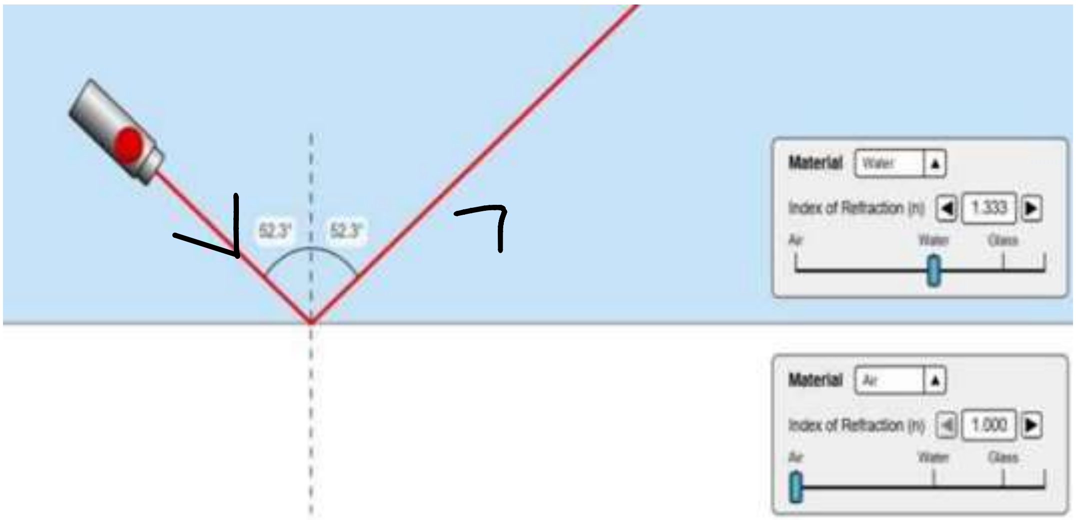
1. Select the "More Tools" tab in the simulation.
2. Choose water as the first medium and air as the second medium.
3. Shine a single ray of light from the water into the air, and gradually increase the angle of incidence.
4. Observe the angle of refraction until the refracted ray no longer exits the water but reflects entirely within the water (this is the critical angle).

5. Measure the critical angle at which total internal reflection occurs.
6. Increase the angle of incidence further and observe the behaviour of the light ray, confirming that it reflects completely within the water, as shown below:



Material: Water
Index of Refraction (n): 1.333

Material: Air
Index of Refraction (n): 1.000



Material: Water
Index of Refraction (n): 1.333

Material: Air
Index of Refraction (n): 1.000

Ray Diagrams

Stage 5: Ray Diagrams for Mirrors and Lenses

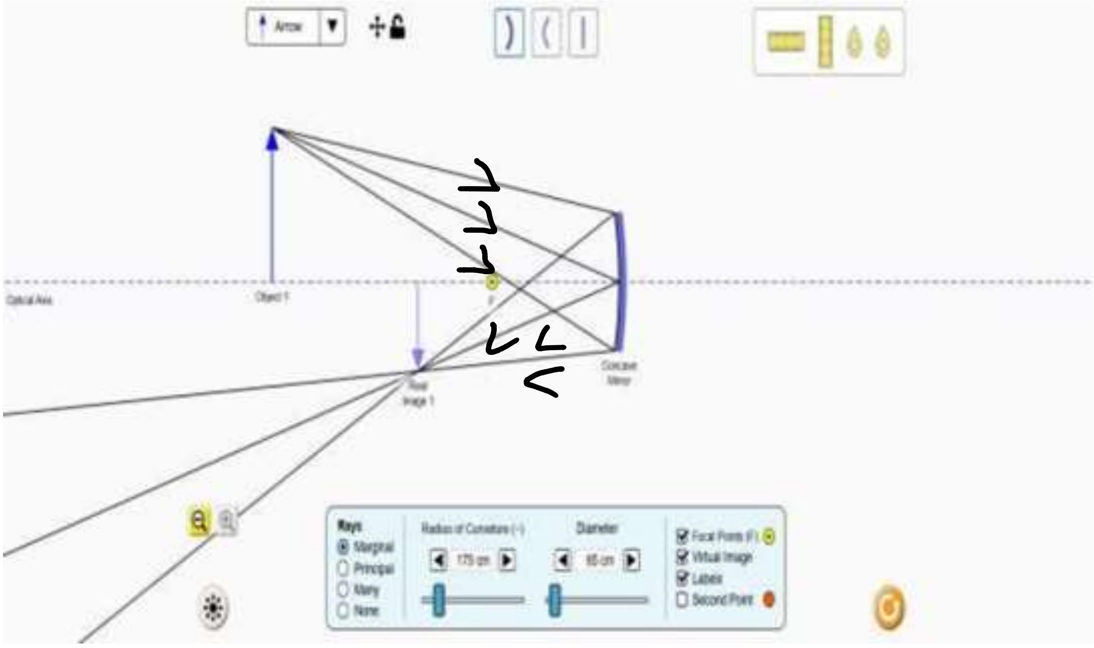
Activity 1: Ray Diagrams for Concave and Convex Mirrors Virtual Laboratory link: https://phet.colorado.edu/en/simulations/filter?subjects=physics&type=html

Objective: Learn how to draw ray diagrams for concave and convex mirrors and explain image formation.

Simulation: “Geometric Optics”

Steps:

1. Open the simulation and select the “Intro” tab.
2. Choose a concave mirror: Place an object (like an arrow) at different distances from the mirror. Observe and draw the following rays:
3. Parallel Ray: From the top of the object, parallel to the principal axis, reflecting through the focal point.
4. Focal Ray: From the top of the object through the focal point, reflecting parallel to the principal axis.
5. Center of Curvature Ray: From the top of the object through the center of curvature, reflecting back on itself.
6. Determine the intersection of these rays to locate the image.
7. Record the characteristics of the image (real or virtual, inverted or upright, magnified or reduced).
8. Switch to a convex mirror: Repeat the steps above.
9. Note the differences in ray behaviour and image formation as shown below:

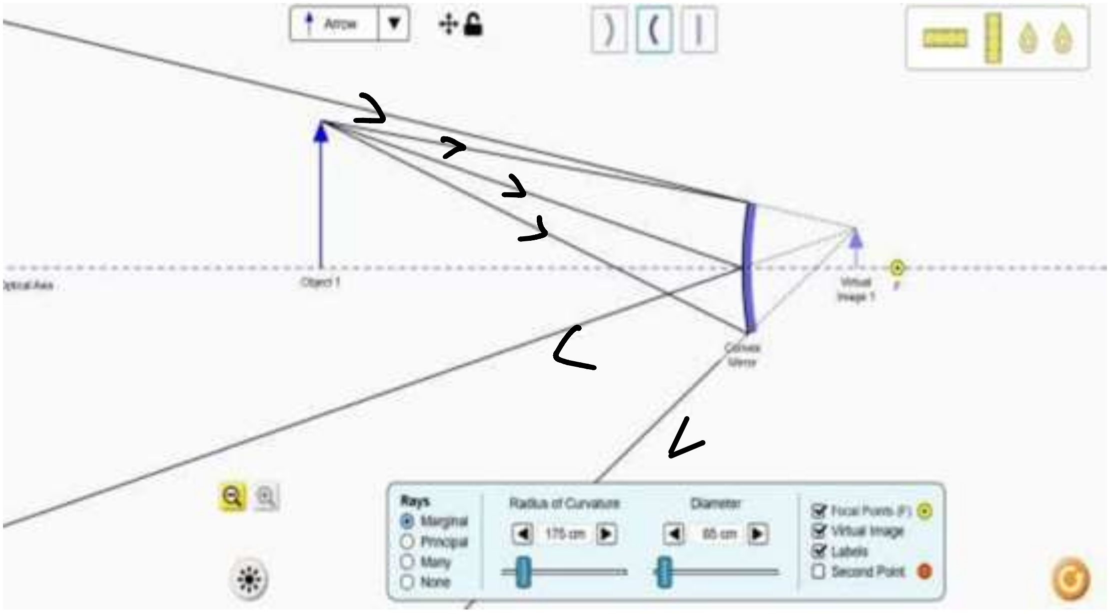


Rays
● Marginal
○ Principal
○ Many
○ None

Radius of Curvature (-) 175 cm

Diameter 65 cm

☑ Focal Points (F)
☑ Virtual Image
☑ Labels
☐ Second Point



Rays
● Marginal
○ Principal
○ Many
○ None

Radius of Curvature 175 cm

Diameter 65 cm

☑ Focal Points (F)
☑ Virtual Image
☑ Labels
☐ Second Point

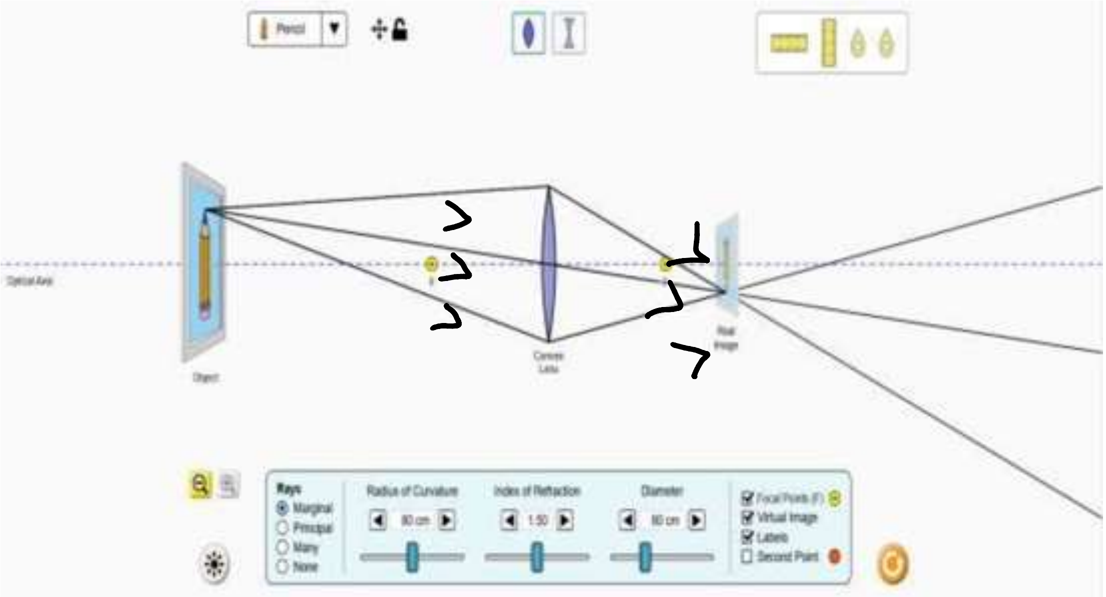
Activity 2: Ray Diagrams for Concave and Convex Lenses

Objective: Understand how to draw ray diagrams for concave and convex lenses and comprehend image formation.

Simulation: "Geometric Optics"

Steps:

1. Select the "Lenses" tab:
2. Choose a convex lens:
3. Place an object at various distances from the lens. Draw and observe the following rays:
4. Parallel Ray: From the top of the object, parallel to the principal axis, refracting through the focal point on the opposite side.
5. Focal Ray: From the top of the object through the focal point on the near side, refracting parallel to the principal axis on the opposite side.
6. Center Ray: Through the center of the lens, traveling in a straight line. Locate the image where the rays intersect.
7. Record the image characteristics (real or virtual, inverted or upright, magnified or reduced).
8. Switch to a concave lens: Repeat the steps above.
9. Note the differences in ray behaviour and image formation as shown below:



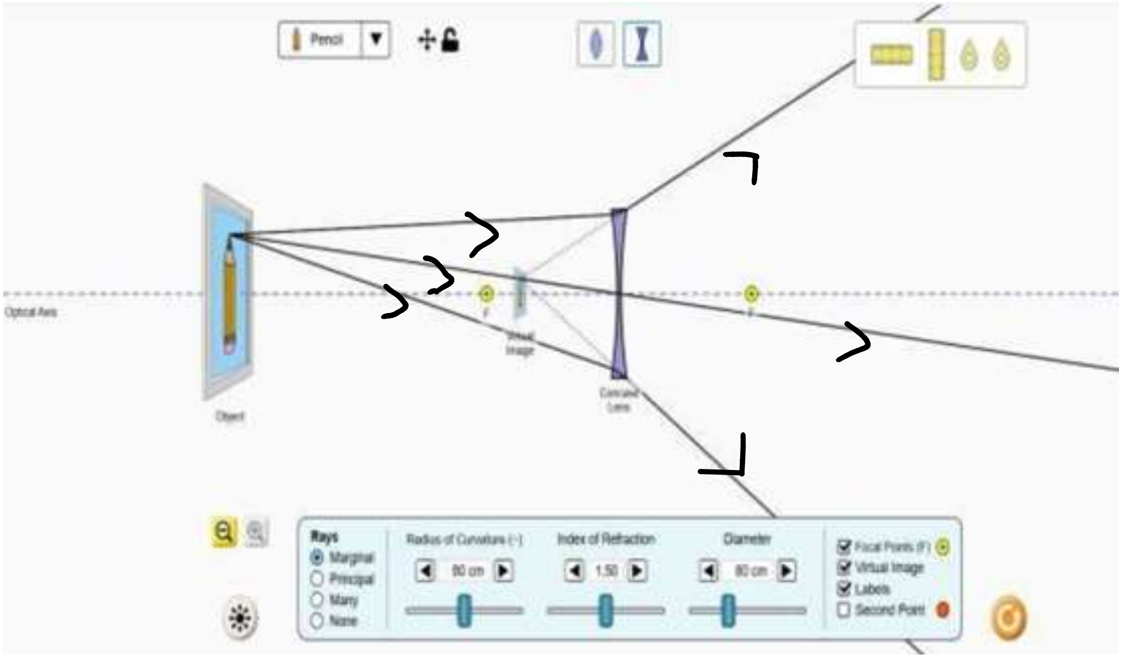
Rays
● Marginal
○ Principal
○ Many
○ None

Radius of Curvature: 80 cm

Index of Refraction: 1.50

Diameter: 80 cm

☑ Focal Points (F)
☑ Virtual Image
☑ Labels
☐ Second Point



Rays
● Marginal
○ Principal
○ Many
○ None

Radius of Curvature (-): 80 cm

Index of Refraction: 1.50

Diameter: 80 cm

☑ Focal Points (F)
☑ Virtual Image
☑ Labels
☐ Second Point

Lessons in the control group was organised in the physical laboratory, where participants followed similar activities, like the experimental group but with the use of real optical instruments, as shown in Figures 4.1 to 4.5.

3.11 Post-intervention Activities

After the four weeks of intervention, participants in both experimental and control groups were given a prior notice to get prepared for post-intervention test (posttest). The researcher with the help of the physics teachers in the selected schools administered the post-intervention test (OCT). The completed tests were collected and scored after which the results were analysed. Following the post-intervention test, the qualitative aspect of this study, which was marked by the conduction of semi-structured interview to solicit students' perception on the use of virtual laboratory in the study of optics, was done. Students' voices were recorded with their consent and later transcribed for analysis.

3.12 Procedure for Data Analysis

In this study, data were analysed quantitatively and qualitatively based on the research questions. The quantitative data employed in this study were responses from the geometric optics concept inventory as well as students' raw scores to items in the OCT, while qualitative data employed students' opinions from the semi-structured interview.

3.12.1 Quantitative Data Analysis

Descriptive statistics were used to summarise the availability, quantity, and condition of instruments. Specifically, frequency counts were used to determine the number of instruments available for the teaching and learning of a particular geometric optics concept in the various schools in the study areas, as well as the conditions of those instruments. These helped in answering research question 1. Moreover, mean and standard deviation were used on the data obtained from the OCT. This helped to quantitatively assess the conceptual understanding of SHS physics students in geometric optics. In this way, the results obtained before and after the intervention were compared to determine the difference in conceptual understanding between the experimental and control group. Thus, any difference in mean score between the experimental and control group was tested via an independent sample t-test at 0.05 level of significance. Since conceptual understanding cannot only be assessed quantitatively (Holme et al., 2015), to obtain a comprehensive picture of students' conceptual understanding in geometric optics, sample students' answers to the items were presented and analysed qualitatively using content analysis. These quantitative and qualitative approaches led to the answering of research question 2.

3.12.2 Qualitative Data Analysis

Qualitatively, content was used to complement the quantitative analysis of research question 1. This helped to provide a detailed information about how well students understood the geometric optics concepts under consideration in this study. Furthermore, thematic analysis was employed to answer research question 3. The thematic analysis was conducted on the responses of participants with regards to how they developed their conceptual understanding during the use of virtual laboratory in the teaching and learning of geometric optics. This helped to provide an understanding of participants' views within the context of the experimental intervention.

3.13 Ethical Considerations

Following ethical guidelines and standards was crucial for carrying out this investigation. Introductory letter from the Department of Integrated Science of AAMUSTED was used to seek permission from the Nandom Municipal and Lawra Municipal education directorates and from the heads of participating schools. Strict adherence was upheld throughout the research procedure to safeguard the participants' rights, welfare, and privacy. Every participant gave their informed consent, with a focus on their voluntary involvement. There were precautions taken to minimise any possible discomfort or harm, and participants were guaranteed the freedom to leave the study at any moment without facing repercussions. Protocols were followed during data management and storage to protect participants' privacy and confidentiality. As a result, the identity of the schools and participants and any private information were made anonymous.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Overview

This chapter presents the results for the study and their discussions. The chapter begins by outlining the demographic characteristics of the respondents to provide context to the study. The results were organised and discussed based on the research questions, with tables, images, and narrations used for easy interpretation and understanding of the findings.

4.1 Demographic Information

This section presents the demographic information of the participants of this study as shown in Table 4.1.

Table 4.1: Demographic Information

Demographic	Nandom Municipality	Lawra Municipality	Total
Number of schools offering physics	1	2	3
Number of physics students	231	236	467
Average class size	48	49	48.5

As can be seen in Table 4.1, Nandom Municipality had one school that offered physics while Lawra Municipality 2 schools, giving a total of 3 schools involved in the study. Furthermore, Nandom Municipality had 231 physics students, while Lawra Municipality had 236 physics students, contributing to a total of 467 students across the two Municipalities. With respect to class size, Nandom Municipality had an average class size of 48 students, while Lawra Municipality had an average class size of 49 students, giving an overall average class size of 48.5, approximately, 49 physics students. The relatively large total number of students suggests a high demand for teaching materials, which may put pressure on the availability and condition of optical instruments, particularly when considering class sizes.

4.2 Results

This section presents the results of the study, organised according to the research questions.

4.2.1 Results for Research Question 1

Research question 1: What are the available teaching and learning materials for the study of optics within the Nandom and Lawra Municipalities?

This research question was answered by collecting data from the three SHSs across the Nandom and Lawra Municipalities. The analysis focused on identifying the required optical tools for key concepts in geometric optics including verification of the laws of reflection, determining the number of images formed by inclined mirrors, verification of Snell's law, and determining the focal length of a convex lens. The availability (measured using the quantity and condition) of the tools was assessed in relation to the average class size in each school to evaluate the adequacy of resources for conducting experiments effectively. This analysis highlights the disparities in the resource distribution, the functionality of the equipment, and the potential deficits that could hinder effective teaching and learning of geometric optics concepts. The results are presented in Table 4.2, categorised by school.

Table 4.2: Availability of Optical Teaching and Learning Resources for Verification of the Laws of Reflection in Nandom and Lawra Municipalities

School	Average class size	Required tools	Quantity needed (per set-up)	Total needed	Available	Condition	Deficit
A	52	Plane mirror	1	52	15	15 functional	37
		Drawing board	1	52	0	-	52
		Paper clip/pins	4	208	0	-	208
		Optical pins	2	104	50	50 functional	54
B	51	Plane mirror	1	51	20	20 functional	31
		Drawing board	1	51	30	25 functional	26
		Paper clip/pins	4	204	0	-	204
		Optical pins	2	104	30	30 functional	74
C	49	Plane mirror	1	49	10	10 functional	39
		Drawing board	1	49	6	6 functional	43
		Paper clip/pins	4	196	0	-	196
		Optical pins	2	98	50	50 functional	48

The results in Table 4.2 indicates that verification of the laws of reflection requires four essential tools, which are plane mirrors, drawing boards, paper clips/pins, and optical pins, with each student requiring one set-up to perform the experiment individually (see Figure 4.1).

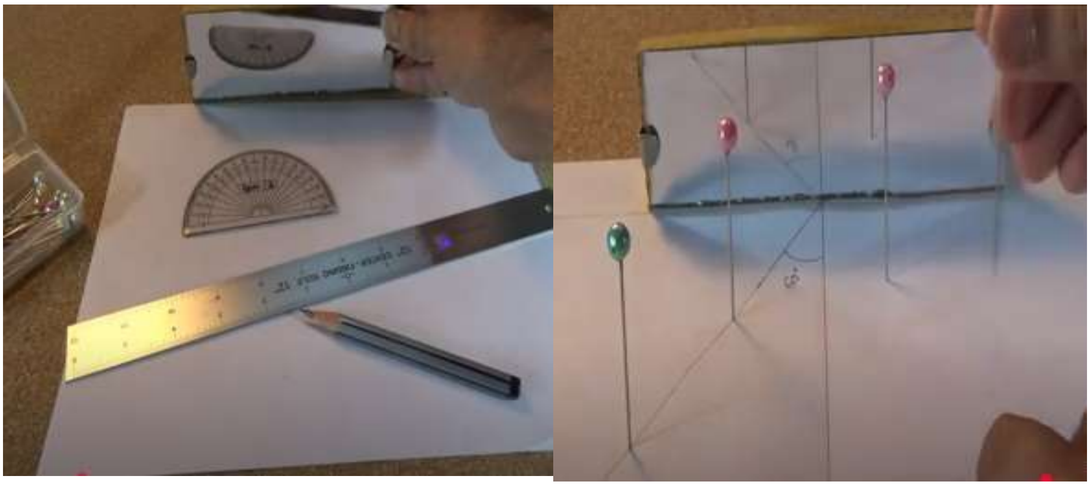


Figure 4.1: Experimental set-up for verification of the laws of reflection

It can be seen from Table 4.2 that none of the schools had sufficient resources to meet the requirements, especially when compared to their respective class sizes. For instance, in school A, with an average class size of 52, the deficits for the required tools were striking. While the school had 15 functional plane mirrors, it faced a deficit of 37 to meet the required 52 setups. The lack of drawing boards and paper clips/pins was especially concerning, as none of these resources were available, leaving a deficit of 52 and 208, respectively. Optical pins were the only resource available in somewhat adequate numbers, with 50 functional units, leaving a manageable deficit of 54. These shortages make it nearly impossible for students to conduct the experiment individually. Even group work would be severely limited unless significant adjustments were made.

Similarly, in school B, with an average class size of 51, the results showed that the school had 20 plane mirrors, all of which were functional, leaving a deficit of 31 plane mirrors required to meet the class size. However, the availability of drawing boards was inadequate, with only 30 available, 25 of which are functional, leaving a deficit of 26. The situation was worse for paper clips, as none were available, resulting in a deficit of 204. Optical pins also presented a challenge, with only 30 available, creating a deficit of 74. While school B was comparatively better resourced than the other schools for the verification of the laws of reflection, the resource gaps still prevented equitable access to hands-on experiments for all students.

School C, with an average class size of 49, faced the most severe challenges in terms of resource availability. The school had only 10 functional plane mirrors, resulting in a deficit of 39. The availability of drawing boards was even more alarming, with just six functional boards, leaving a deficit of 43. As with the other schools, paper clips/pins were completely absent, resulting in a deficit of 196. Optical pins were somewhat better provided for, with 50 functional units, leaving a deficit of 48. These deficiencies indicate that students in school C were significantly disadvantaged in performing this experiment, with a lack of essential tools making both individual and group experiments highly impractical.

The availability of the teaching and learning resources for the determination of the number of images formed by inclined mirrors was also analysed. This experiment requires two plane mirrors per setup (see Figure 4.2), meaning that the total number of mirrors needed is double the class size for each school.

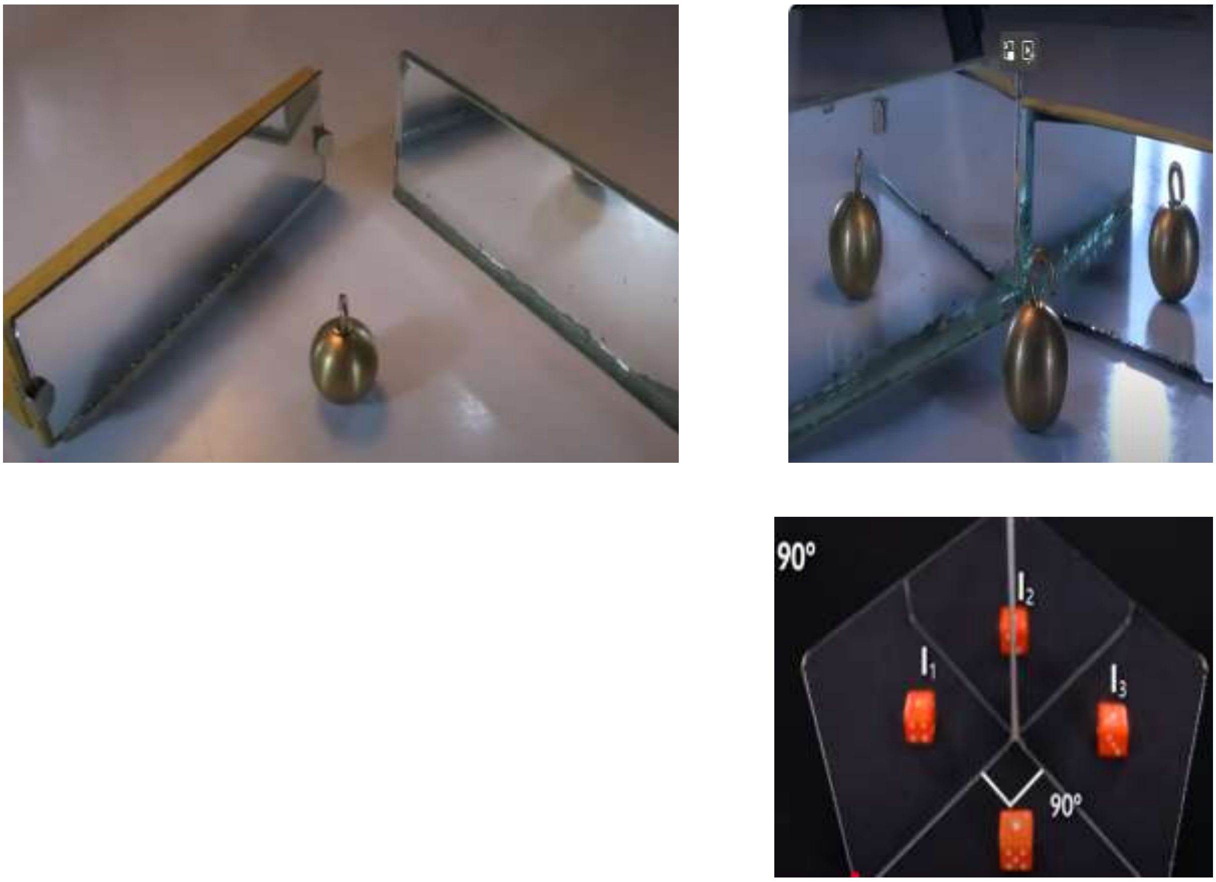


Figure 4.2: Experimental setup for Determining the Number of Images Formed by Inclined Mirrors

The availability of optical teaching and learning resources for determining the number of images formed by inclined mirrors, in Nandom and Lawra Municipalities are therefore presented in Table 4.3.

Table 4.3: Availability of Optical Teaching and Learning Resources for Determining the Number of Images Formed by Inclined Mirrors in Nandom and Lawra Municipalities

School	Average class size	Required tools	Quantity needed (per set-up)	Total needed	Available	Condition	Deficit
A	52	Plane mirror	2	104	15	15 functional	89
B	51	Plane mirror	2	102	20	20 functional	82
C	49	Plane mirror	2	98	10	10 functional	88

As shown in Table 4.3, across all three schools, there was shortage of plane mirrors, which are the sole required tool for this experiment. School B had the largest number of functional mirrors (20), while school C had the fewest (10). However, all three schools faced deficits exceeding 70 mirrors, demonstrating that none of them were adequately equipped to provide individual setups for students. While school B was marginally better resourced for the experimental determination of the number of images formed by inclined mirrors, this severe shortage indicates that only a fraction of the students could actively engage in the experiment at any given time.

Furthermore, the availability of teaching and learning resources for the verification of Snell’s law was determined. The verification of Snell’s law requires several teaching and learning tools, including a triangular prism, a drawing board, paper clips, and optical pins for each setup as shown in Figure 4.3.

Figure 4.3: Experimental setup for verification of Snell's law

These resources are critical for students to understand the refraction of light through a prism, the angle of minimum deviation, and verify the relationship between the angle of incidence and the angle of refraction. The results for the availability and condition of these resources across the three schools within the Nandom and Lawra Municipalities are presented in Table 4.4.

Table 4.4: Availability of Optical Teaching and Learning Resources for Verification of Snell's Law in Nandom and Lawra Municipalities

School	Average class size	Required tools	Quantity needed (per set-up)	Total needed	Available	Condition	Deficit
A	52	Triangular prism	1	52	15	15 functional	37
		Drawing board	1	52	0	-	52
		Paper clip	4	208	0	-	208
		Optical pins	4	208	50	50 functional	158
B	51	Triangular prism	1	51	30	30 functional	21
		Drawing board	1	51	30	25 functional	26
		Paper clip	4	204	0	-	204
		Optical pins	4	204	30	30 functional	174
C	49	Triangular prism	1	49	10	10 functional	39
		Drawing board	1	49	6	6 functional	43
		Paper clip	4	196	0	-	196
		Optical pins	4	196	50	50 functional	146

As shown in Table 4.4, in school A, with an average class size of 52, the school needed 52 prisms but had only 15 functional prisms, resulting in a deficit of 37. this shortage prevented most students from having individual access to this critical tool. Concerning drawing boards, none were available, resulting in a deficit of 52. This means students could not complete the setup as intended unless alternative surfaces were used, which could compromise accuracy. Also, school A lacked all 208 required paper clips, rendering it impossible to secure paper during the experiment. Again, out of 208, optical pins needed, only 50 functional pins were available, creating a deficit of 158. This limits students' ability to accurately mark the incident and refracted rays.

In school B, as shown in Table 4.4, with an average class size of 51, the resource situation for the experimental determination of Snell's law was slightly better but still inadequate. For instance, regarding triangular prisms, school B, required 51 and had only 30 functional prisms, leaving a deficit of 21 prisms. Although better than school A, this shortage still limits the number of students who can actively participate in the experiment. Regarding drawing boards, of the 51 required, only 30 were available, with 25 functional, resulting in a deficit of 26 boards. Again, school B needed 204 clips to complete the experimental verification of Snell’s law, but had none, leaving a deficit of 204 clips. Out of 204 optical pins needed, only 30 functional pins were available, creating a deficit of 174 pins.

In school C, it can be observed from Table 4.4 that with the average class size of 49, the resource deficits for the experimental verification of Snell’s law were most severe. For instance, school C required 49 triangular prisms but had only 10 functional prisms, resulting in a deficit of 39 prisms. Also, 49 drawing boards were required for each experimental session, however, only 6 functional boards were available, leaving a deficit of 43 boards. Again, of the 196 required clips, there was none, leaving a deficit of 196 clips. Regarding optical pins, only 50 functional pins were available out of the required 196 pins, leaving a deficit of 146 pins.

Another concept considered in this study was the determination of the focal length of a concave mirror across the three schools, focusing on five major required tools, which are a concave mirror, a screen, a mirror holder, a meter rule and a light source (see Figure 4.4).

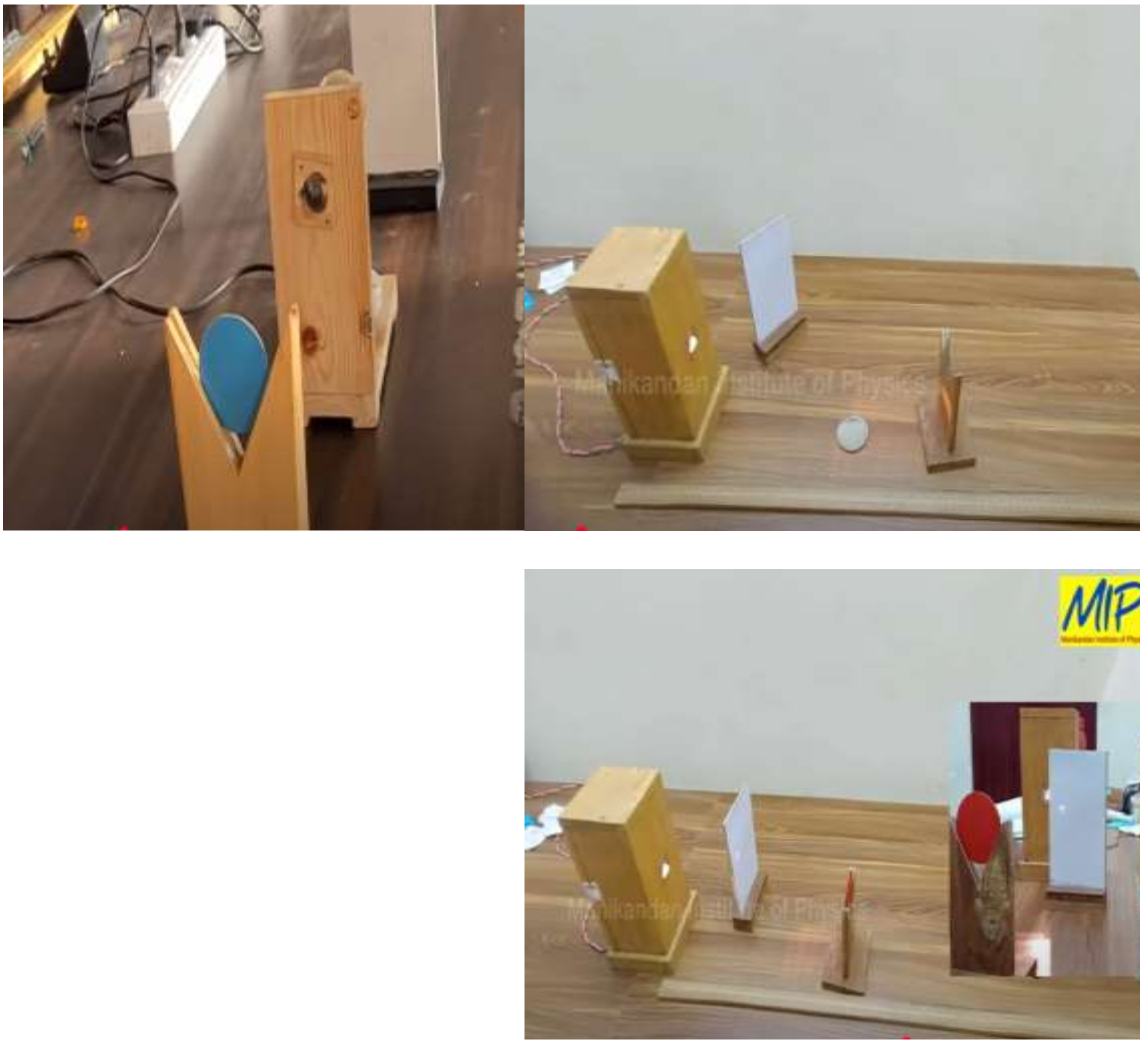


Figure 4.4: Experimental setup to determine the focal length of a concave mirror

The results for the availability of teaching and learning resources for the determination of the focal length of a concave mirror across the three schools are presented in Table 4.5.

Table 4.5: Availability of Optical Teaching and Learning Resources for Determining the Focal Length of a Concave Mirror in Nandom and Lawra Municipalities

School	Average class size	Required tools	Quantity needed (per set-up)	Total needed	Available	Condition	Deficit
A	52	Concave mirror	1	52	10	10 functional	42
		Screen	1	52	10	10 functional	42
		Mirror holder	1	52	5	5 functional	47
		Meter rule	1	52	3	3 functional	49
		Light source (incandescent)	1	52	10	10 functional	42
B	51	Concave mirror	1	51	17	17 functional	34
		Screen	1	51	15	15 functional	36
		Mirror holder	1	51	10	10 functional	41
		Meter rule	1	51	8	8 functional	43
		Light source (incandescent)	1	51	5	5 functional	46
C	49	Concave mirror	1	49	6	6 functional	43
		Screen	1	49	6	6 functional	43
		Mirror holder	1	49	0	-	49
		Meter rule	1	49	4	4 functional	45
		Light source (incandescent)	1	49	0	-	49

It can be seen from Table 4.5 that, across all three schools, the most significant deficits were in mirror holders and light sources, with school C having none of these tools. Meter rules, which are crucial for measuring distances accurately, were also in short supply, with school A having the highest deficit (49). Although school B had relatively better resources, the deficits across all tools indicate that none of the schools were adequately equipped to provide individual setups for students.

The last concept considered in this study was the determination of the focal length of a convex lens across the three schools, focusing on five major required tools, which are a convex mirror, a screen, a mirror holder, a meter rule and a light source (see Figure 4.5).

Figure 4.5: Experimental setup to determine the focal length of a concave mirror

The results for the availability of teaching and learning resources for the determination of the focal length of a convex lens across the three schools are presented in Table 4.6.

Table 4.6: Availability of Optical Teaching and Learning Resources for Determining the Focal Length of a Concave Lens in Nandom and Lawra Municipalities

School	Average class size	Required tools	Quantity needed (per set-up)	Total needed	Available	Condition	Deficit
A	52	Convex lens	1	52	20	20 functional	32
		Screen	1	52	10	10 functional	42
		Lens holder	1	52	5	5 functional	47
		Meter rule	1	52	3	3 functional	49
		Light source (incandescent)	1	52	10	10 functional	42
B	51	Convex lens	1	51	9	9 functional	42
		Screen	1	51	15	15 functional	36
		Lens holder	1	51	10	10 functional	41
		Meter rule	1	51	8	8 functional	43
		Light source (incandescent)	1	51	5	5 functional	46
C	49	Convex lens	1	49	5	5 functional	44
		Screen	1	49	6	6 functional	43
		Lens holder	1	49	0	-	49
		Meter rule	1	49	4	4 functional	45
		Light source (incandescent)	1	49	0	-	49

As shown in Table 4.6, across all three schools, deficits in the required tools for determining the focal length of a convex lens were glaring. The results indicate that convex lenses were in short supply, with deficits ranging from 32 in school A to 44 in school C. Screens and meter rules, though slightly better supplied in schools A and B, remained insufficient across all schools. Lens holders and light sources were particularly inadequate, with deficits of 41 to 49 across the three schools. These shortages were further exacerbated by the average class sizes, which required significant quantity of each tool to facilitate meaningful hands-on experiments.

4.2.2 Results for Research Question 2

Research question 2: What is the difference in students' conceptual understanding in geometric optics between students exposed to virtual laboratory and those exposed to real laboratory?

To answer research question 2, a statistical and qualitative approach, specifically an in- depth content analysis of students' responses to open-ended items were employed.

4.2.2.1 Quantitative Results for Research Question 2

The quantitative analysis was structured beginning with an assessment of the normality of the quantitative data, followed by the comparison of the pretest scores and posttest scores.

4.2.2.1.1 Normality Assessment

Before conducting any inferential statistical test, the normality of the data was assessed using both statistical and visual methods. The Kolmogorov-Smirnov test and the Shapiro- Wilk test were applied to determine whether the data followed normal distribution, and the results are presented in Table 4.7.

Table 4.7: Tests of Normality

		Kolmogorov-Smirnov			**Shapiro-Wilk**		
	Group	**Statistic**	**df**	**Sig.**	**Statistic**	**df**	**Sig.**
Pretest	Experimental	0.087	55	0.200*	0.964	55	0.103
	Control	0.094	54	0.200*	0.964	54	0.103
Posttest	Experimental	0.090	55	0.200*	0.964	55	0.094
	Control	0.080	54	0.200*	0.962	54	0.081

$^{*}P > 0.05$

The results presented in Table 4.7 indicate that both Kolmogorov-Smirnov and Shapiro-Wilk tests yielded non-significant results (p>0.05) for all groups at both pretest and posttest levels. Specifically, the experimental group's pretest scores showed a Kolmogorov-Smirnov statistic of 0.087 (p = 0.200) and a Shapiro-Wilk statistic of 0.094 (p = 0.103). The control group's pretest scores had a Kolmogorov-Smirnov statistic of 0.094 (p = 0.200) and Shapiro-Wilk statistic of 0.964 (p = 0.103).

Similarly, for the posttest scores, the experimental group had a Kolmogorov-Smirnov statistic of 0.090 (p = 0.200) and a Shapiro – Wilk statistic of 0.964 (p = 0.094), while the control group yielded a Kolmogorov – Smirnov statistic of 0.080 (p = 0.200) and a Shapiro-Wilk statistic of 0.962 (p = 0.081). These results indicate that the distributions of the pretest and the posttest scores for both groups do not significantly deviate from normality, thereby satisfying the assumption of normality required for parametric tests.

In addition to the statistical tests, visual inspection of histograms (see Appendices E1 to E4), box plots, and Q-Q plots confirmed that the data for all groups appeared approximately symmetrical and bell shaped. The box plots (see Appendices F1 and F2) showed no extreme outliers, while the Q-Q plots (See Appendices G1 to G4) demonstrated that the data points closely aligned with the diagonal reference line, further supporting the normality assumption. Based on the results of the Kolmogorov-Smirnov test, the Shapiro-Wilk test, and visual inspection, it can be concluded that the pretest and posttest scores for both the experimental and control groups were normally distributed. This validation justifies the use of parametric statistical methods for subsequent analyses.

4.2.2.1.2 Pretest Analysis (Students' Conceptual Understanding before Intervention)

The analysis began with a comparison of the pretest scores of the experimental group (exposed to virtual laboratories) and the control group (exposed to real laboratories) to ascertain whether there were any significant differences in students' conceptual understanding of geometric optics prior to the intervention. An independent sample t-test was employed for this purpose, providing a statistical basis for determining the baseline equivalence of the two groups. This comparison ensured that any observed differences in the posttest results could be attributed to the intervention and not to pre-existing disparities in conceptual understanding. As an assumption, the variances in the pretest scores were determined to ensure that they were equal for both groups. This assumption, known as homogeneity of variances (Pallant, 2011), was tested and the results are presented in Table 4.8.

Table 4.8: Results for Homogeneity of Variances in Pretest Scores

		Levene's Test Statistic	
		F	**p**
Pretest	Equal Variances Assumed	3.706	0.057

From Table 4.8, the variances in the pretest scores of the experimental and control groups were equal, since Levene's statistic, F, was not significant (F = 3.706, p = 0.057 > 0.05). Consequently, the assumption of homogeneity of equal variances was not violated, further validating the conduction of the independent sample t-test on the pretest scores, and the results are presented in Table 4.9.

Table 4.9: Independent Sample T-test on Pretest Scores

Group	N	Mean	SD	t	df	p
Experimental	55	11.80	3.946	0.905	107	0.368
Control	54	11.19	3.090			

df – degrees of freedom

As indicated in Table 4.9, there was no statistically significant difference between the pretest scores of the experimental group (M = 11.80, SD = 3.946) and the control group (M = 11.19, SD = 3.090; $t_{(107)} = 0.905$, p = 0.368). The p-value of 0.368 was greater than α – level of 0.05, and therefore, it can be concluded the two groups were equivalent in their conceptual understanding of geometric optics prior to the intervention.

4.2.2.2 Qualitative Results for Research Question 1

A content analysis was also conducted on students' answers to the open-ended items. This qualitative approach provided deeper insights into the students' conceptual understanding of geometric optics, beyond what could be inferred from the numerical data alone. While the independent sample t-test revealed no significant difference in pretest scores, the content analysis of students' written responses allowed for a more nuanced understanding of their initial conceptions and misconceptions regarding the various concepts of geometric optics considered in this study. Illustrative examples from student responses to sample items are provided below to highlight the range of conceptual understandings exhibited by students prior to the intervention.

Item 1: Describe what happens to the angle between the incident ray and the reflected ray when a plane mirror is rotated twice the angle of incidence.

Experimental Group Responses

Response 1:

> *"The angle between the incident ray and the reflected ray doubles when the mirror rotates twice the angle of incidence."*

Analysis:

This response demonstrates a misconception. The student assumes a linear doubling relationship between the mirror's rotation and the angle between the rays, which is incorrect. The error lies in misunderstanding that the reflected ray moves by twice the angle of the mirror's rotation relative to the normal, not the incident ray. This response reflects a partial grasp but reveals gaps in the understanding of angular relationships in reflection.

Response 2:

> *"When the mirror rotates, the angle between the rays increases, but it is not always double the rotation of the mirror."*

Analysis:

This response indicates partial understanding. The student correctly identifies that the angle changes as the mirror rotates but avoids overgeneralising the relationship. However, the explanation lacks specificity and fails to outline the doubling effect or mention the geometric dependency. This shows a grasp of the concept but with limited depth.

Response 3:

> *"The reflected ray moves twice the angle by which the mirror is rotated, so the total angle changes accordingly."*

Analysis:

This response suggests a reasonable understanding. The student identifies that the reflected ray shifts by twice the angle of rotation. Although this is accurate, the answer could be improved with a calculation or a geometric diagram to explicitly show the resulting angular change. This reflects a solid foundation with room for enhancement.

Response 4:

> *"If the mirror is rotated twice the angle of incidence, the angle between the rays changes depending on how the rays strike the mirror."*

Analysis:

This response demonstrates a misconception. The student introduces unnecessary dependency on the orientation of the incident ray, which is typically fixed. They fail to connect the mirror's rotation to the doubling effect on the reflected ray. This reflects a lack of clarity in understanding the relationship.

Response 5:

> *"The angle increases because the mirror affects both the incident and reflected rays equally."*

Analysis:

This response shows misconception. The student mistakenly assumes that the mirror's rotation directly affects the incident ray, which is incorrect. This misconception indicates a lack of understanding of the basic principles of reflection.

Control Group Responses

Response 1:

"The angle doubles because the mirror rotates more, so the rays reflect farther apart."

Analysis:

This response reflects a misconception. The student assumes a direct doubling effect without recognising the geometric principle that the reflected ray moves by twice the mirror's rotation relative to the normal. This suggests limited understanding of angular relationships.

Response 2:

> *"When the mirror rotates, it affects the angle of the reflected ray, but I think it also depends on the angle of incidence."*

Analysis:

This response indicates partial understanding. The student correctly identifies that the reflected ray is affected but incorrectly introduces dependency on the angle of incidence. This reflects an incomplete understanding of the independence of the incident ray's angle in this scenario.

Response 3:

"The angle between the rays increases when the mirror rotates, but I don't know by how much."

Analysis:

This response suggests partial understanding. The student correctly identifies the relationship between mirror rotation and the angle change but lacks quantitative clarity. This indicates a limited but developing grasp of the concept.

Response 4:

> *"If the mirror rotates, the angle changes because the rays bounce at different points."*

Analysis:

This response demonstrates a misconception. The student confuses the concept of reflection, implying that the rays "bounce" at different points as the mirror rotates. This reflects a lack of understanding of the geometric principles of reflection.

Response 5:

> *"The angle changes depending on how the mirror is turned, but it's hard to explain why."*

Analysis:

This response reflects partial understanding. The student acknowledges the relationship between mirror rotation and angular change but cannot articulate the geometric principles involved. This highlights a need for further conceptual clarity.

Item 2: In what situation does light pass into a medium without refracting?

Experimental Group Responses

Response 1:

"Light does not refract when it hits the medium perpendicularly."

Analysis:

This response demonstrates partial understanding. The student correctly identifies that refraction does not occur when light enters perpendicularly (normal incidence). However, they do not explain why this happens, which reveals a lack of depth in their understanding.

Response 2:

"Refraction does not occur if the angle of incidence is zero degrees."

Analysis:

This response reflects partial understanding. While the statement is accurate, it is repetitive of Response 1 and lacks depth. The student fails to elaborate on why zero incidence angle prevents refraction, which limits the response's completeness.

Response 3:

"When light travels at an angle, it refracts, but if it’s straight, it doesn’t."

Analysis:

This response reflects a misconception. The student incorrectly generalizes that refraction only occurs at angles other than zero. This shows a lack of clarity about the dependency of refraction on the angle of incidence.

Response 4:

"Light doesn’t refract if the surface of the medium is flat."

Analysis:

This response demonstrates a misconception. The student confuses the surface's shape with the phenomenon of refraction, failing to understand the role of refractive indices and angles. This highlights a foundational gap in knowledge.

Control Group Responses

Response 1:

"Light will not refract if it enters the medium straight on."

Analysis:

This response reflects partial understanding. The student identifies the scenario of zero incidence angle (normal incidence) but does not provide any explanation of the principle behind it. The response is accurate but lacks depth.

Response 2:

"When light moves between two materials with the same properties, there is no refraction."

Analysis:

This response demonstrates good understanding. The student accurately describes that refraction does not occur when the refractive indices are equal. However, the term "same properties" is vague and should be clarified to refer specifically to the refractive index.

Response 3:

"Refraction does not happen if the light is going straight and the two substances are similar."

Analysis:

This response reflects partial understanding combined with some confusion. The student combines two concepts – normal incidence and equal refractive indices – but does not clearly differentiate between them. The response is correct but lacks precision and clarity.

Response 4:

"Light passes without refracting when it doesn't bend as it enters the new material."

Analysis:

This response reflects a misconception. The student's statement is tautological—they describe the phenomenon without identifying the conditions under which it occurs, such as normal incidence or equal refractive indices. This indicates a lack of conceptual understanding.

Response 5:

"If the light enters the medium at a flat angle, it won't refract."

Analysis:

This response demonstrates a misconception. The student confuses the concept of the angle of incidence with the surface orientation, failing to correctly identify normal incidence or matching refractive indices as the key factors. This reflects a fundamental misunderstanding of refraction.

The quantitative and qualitative pretest results indicate a comparable baseline understanding between the experimental and control groups. Both groups exhibited a mix of partial understanding and misconceptions prior to the intervention, with a few students demonstrating a thorough grasp of the concepts. This suggests limited conceptual understanding of geometric optics concepts considered in this study. These findings validated the need for intervention using virtual laboratory (for the experimental group) and real laboratory (for the control group).

Following the intervention, students' scores and responses to the posttest items were also analysed quantitatively and qualitatively to ascertain the effect of the intervention by determining the difference between the posttest results and pretest results. Quantitative analysis was done using an independent sample t-test on the overall posttest scores of students. Similar to the pretest, the assumption of homogeneity of variances was tested and the results are presented in Table 4.9.

Table 4.9: Results for Homogeneity of Variances in Posttest Scores

		Levene's Test Statistic	
		F	**p**
Posttest	Equal Variances Assumed	0.025	0.875

As indicated in Table 4.9, the variances in the posttest scores of the experimental and control groups were equal, since Levene's statistic, F, was not significant (F = 0.025, p = 0.875 > 0.05). Accordingly, the assumption of homogeneity of equal variances was not violated, further validating the conduction of the independent sample t-test on the pretest scores, and the results are presented in Table 4.10.

Table 4.10: Independent Sample T-test on Posttest Scores

Group	**N**	**Mean**	**SD**	**t**	**df**	**p**
Experimental	55	19.55	3.896	-0.295	107	0.768
Control	54	19.76	3.660			

df – degrees of freedom

The results as indicated in Table 4.10 indicate that there was no statistically significant difference between the posttest scores of the experimental group (M = 19.55, SD = 3.896) and the control group (M = 19.76, SD = 3.660; $t_{(107)} = -0.295$, p = 0.768). The two groups demonstrated equivalent conceptual understanding of geometric optics after the intervention. An effect size, which describes the magnitude of the difference in mean scores between the two groups, was also determined using Cohen's d (see Appendix G) for the formula), which produced a value of 0.06, indicating a moderate effect according to Pallant (2011).

To support the quantitative results, students' answers to sampled items were analysed qualitatively using content analysis, to reveal how students demonstrated conceptual understanding after exposure to the intervention. The content analysis was done using the same items and students selected for the content analysis in the pretest. Illustrative examples from student answers to sample items are provided below to highlight the conceptual understandings exhibited by students after the intervention.

Posttest Analysis for Item 1

Item 1: Describe what happens to the angle between the incident ray and the reflected ray when a plane mirror is rotated twice the angle of incidence.

Experimental Group:

Response 1:

> "*When a plane mirror is rotated by an angle, the angle between the incident ray and the reflected ray doubles. So, if the mirror is rotated by twice the angle of incidence, the angle between the rays will quadruple*."

Analysis: This response demonstrates a full understanding of the concept. The student accurately describes the relationship between the rotation of the mirror and the resulting angles without misconceptions or ambiguities.

Response 2:

> "*If the mirror rotates by twice the angle of incidence, the angle between the incident and reflected rays becomes four times the original angle of incidence*."

Analysis: The student correctly identifies the proportional relationship. This response indicates that the student has mastered the geometric relationship between the mirror's rotation and the angle changes.

Response 3:

> "*The angle between the incident ray and reflected ray will be four times the rotation of the mirror, which is twice the angle of incidence*."

Analysis: The response reflects an understanding of the concept, with clarity in how the angles interact. There is no evidence of the prior misconception of equating mirror rotation to incident angle changes.

Response 4:

> "*The angle doubles every time the mirror is rotated, so when it is rotated twice the angle of incidence, the resulting angle quadruples*."

Analysis: This response shows mastery of the concept. The explanation is logical, precise, and avoids prior errors or omissions.

Response 5:

> "*When the mirror is rotated by twice the angle of incidence, the resulting angle becomes four times the original. This is because the reflected ray follows the rotation of the mirror but is multiplied by two*."

Analysis: This response demonstrates full conceptual understanding, using accurate terminology to explain the geometric relationship.

Control Group:

Response 1:

> "*If a mirror is rotated twice the angle of incidence, the angle between the incident and reflected rays becomes four times the angle of incidence*."

Analysis: The student demonstrates a thorough understanding of the concept. The response is concise and free of misconceptions.

Response 2:

> "*The rotation of the mirror causes the angle between the rays to double each time, so for twice the angle of incidence, the angle quadruples*."

Analysis: This response is accurate and reflects a clear grasp of the relationship between the mirror's rotation and angle changes.

Response 3:

> "*Rotating the mirror doubles the angle between the rays. If the rotation is twice the angle of incidence, the angle will be multiplied by four*."

Analysis: The response demonstrates conceptual clarity and correctly applies the rule governing the interaction of angles.

Response 4:

> "*The angle between the incident ray and the reflected ray will be four times the angle of incidence when the mirror is rotated twice the angle*."

Analysis: This response indicates a complete understanding of the concept and avoids previously observed misconceptions.

Response 5:

> "*When the mirror rotates twice the angle of incidence, the angle between the rays becomes four times that of the initial angle. This happens because each rotation doubles the effect*."

Analysis: This response shows mastery of the concept, with logical reasoning that connects the mirror's rotation to the resulting angle changes.

Posttest Analysis for Item 2

Item 2: In what situation does light pass into a medium without refracting?

Experimental Group:

Response 1:

> "*Light does not refract when it enters a medium at an angle of 90° to the surface, called normal incidence*."

Analysis: This response demonstrates full understanding by identifying the correct condition (normal incidence) and providing an accurate explanation without any ambiguity or misconception.

Response 2:

> "*If the light strikes the surface perpendicularly, it travels straight through without bending, which means no refraction occurs*."

Analysis: The explanation accurately captures the principle of normal incidence and shows the student has mastered this concept.

Response 3:

> "*When the refractive indices of the two media are the same, light passes without refracting because there is no change in speed*."

Analysis: This response reflects a clear understanding of the second condition under which refraction does not occur. The student demonstrates conceptual clarity about matching refractive indices.

Response 4:

> "*Light does not refract when it travels normally to the surface or when the two media have equal refractive indices*."

Analysis: This response integrates both conditions where refraction does not occur, indicating a complete grasp of the concept.

Response 5:

> "*If the refractive indices of the two media are equal or the light enters at 90°, it does not refract because there is no bending*."

Analysis: This response highlights both scenarios accurately and avoids previous misconceptions or incomplete explanations.

Control Group:

Response 1:

> "*Light passes straight without refracting when it enters a medium at a 90° angle to the surface*."

Analysis: The response clearly identifies the condition of normal incidence and reflects complete understanding.

Response 2:

> "*No refraction happens if the light travels perpendicularly or the refractive indices of the media are the same*."

Analysis: This response demonstrates full conceptual understanding, addressing both scenarios of no refraction with precision.

Response 3:

> "*If the light is perpendicular to the surface, it will go through without bending, which means no refraction occurs*."

Analysis: The explanation captures the principle of normal incidence and demonstrates mastery of the concept.

Response 4:

> "*When light enters at normal incidence or the two media have the same refractive index, it does not refract because there is no change in speed*."

Analysis: This response reflects a thorough understanding of the two main conditions under which refraction does not occur.

Response 5:

> "*Light does not refract when the angle of incidence is 90° or when the media have equal optical densities*."

Analysis: This response demonstrates full comprehension of both conditions and effectively applies the correct terminology.

The posttest results from the quantitative and qualitative analysis show that students in both the experimental and control groups fully understood the geometric optics concepts considered in this study. Compared to the pretest, students in both groups could now provide accurate; precise explanations and use proper terminology to describe concepts; correctly and precisely identify the concepts of normal incidence and matching refractive indices without any misconceptions; and accurately describe the behaviour of light rays and provide correct ray diagrams to illustrate their explanations. This means that the interventions successfully enhanced conceptual understanding of geometric optics concepts considered in this study.

4.2.3 Results for Research Question 3

How do students develop conceptual understanding of geometric optics through virtual laboratory?

To answer this research question, qualitative data was collected through one-one-one semi-structured interviews with 15 participants from the experimental group who were exposed to virtual laboratory. A thematic analysis was conducted, identifying key themes that reflect how students developed conceptual understanding in geometric optics. Participants' direct quotes are included to provide evidence for each theme.

Theme 1: Interactive Simulations Enhance Engagement and Understanding

A frequent theme in participant's responses was the role of interactive simulations in engaging students and helping them visualise abstract concepts. Some participants reported that the ability to manipulate variables and observe immediate outcomes helped them better understand the principles of geometric optics. As an example, participant 3 said that:

> "*When I adjusted the angle of incidence in the simulation and saw the reflected ray move in real time, it made me realise how the angle of reflection always equals the angle of incidence. It clicked instantly*."

Similarly, participant 14 added that:

> "*The simulation made it easier to understand how refraction works. I could see how the light bends depending on the refractive indices, and that visual representation stayed on my mind*."

In another voice, participant 8 articulated that:

> "*The interactive nature of the virtual lab kept me engaged. I could do the experiment several times without worrying about breaking any equipment, and that gave me confidence to try out different scenarios*."

From the participants’ responses, the interactive nature of the virtual laboratories appeared to promote active learning, allowing students to construct knowledge by engaging directly with the material.

Theme 2: Visual Representations Aid Conceptualisation of Abstract Ideas

Students consistently highlighted the effectiveness of the visual representations provided in the virtual laboratory in helping them grasp difficult concepts, such as the behaviour of light rays during reflection and refraction. For instance, in their own voice, participant 6 highlighted that:

> “*Seeing the ray diagrams drawn automatically on the screen as I moved the object or mirror really helped me understand how concave mirrors can produce both real and virtual images*.”

Also, participant 12 stated that:

> “*I always struggled with understanding critical angle and total internal reflection, but watching the light completely reflect when the angle was larger than the critical angle helped me make sense of it*.”

Participant 1 also added that:

> “*The diagrams in the simulation showed me exactly where the focal point is and how it affects the image. It’s something I could never visualise properly before*.”

These responses underscore the importance of visualisation tools in virtual laboratories, which help students move from rote memorisation to conceptual understanding.

Theme 3: Opportunities for Independent Exploration Foster Deeper Understanding

Some participants expressed that the freedom to explore and experiment in the virtual laboratories contributed to their learning. Unlike real laboratories, where time constraints and the need for supervision might limit experimentation, virtual laboratories allowed for unrestricted exploration. For example, participant 5 explained that:

> "*I liked that I could repeat the experiments as many times as I wanted. This helped me understand things I didn't get the first time*."

In addition, participant 9 said that:

> "*In the virtual laboratory, I could test my own ideas, like changing the medium or the angle of light, and see if I was right. It helped me learn through trial and error*."

Furthermore, participant 11 stated that:

> "*I spent extra time experimenting with how lenses work. By the end, I could confidently explain how convex lenses focus light to form real and virtual images*."

This theme supports the idea of self-regulated learning, where students take control of their learning process. The virtual laboratories provided an environment where students could pace their learning and experiment independently, leading to deeper understanding.

Theme 4: Real-Time Feedback Improves Accuracy and Understanding

Participants emphasised the importance of real-time feedback provided by the virtual laboratory, which helped them identify and correct their misconceptions during the learning process. For instance, participant 2 voiced out that:

> "*Whenever I made a mistake, like placing the object in the wrong position, the simulation immediately showed me how the image formed incorrectly. That response helped me understand the correct concept*."

In the same vein, participant 13 noted that:

> "*The hints and explanations provided in the simulation after each step were helpful. They explained why something happened the way it did, which made learning easier*."

Also, participant 7 expressed that:

> "*I realised that I did not understand how refractive index works, but the simulation corrected me by showing the calculations and the light ray's behaviour*."

Real-time feedback aligns with formative assessment theory, which highlights the importance of timely feedback in helping earners adjust their understanding and improve performance.

Theme 5: Increased Confidence in Applying Concepts

Some participants noted that their experiences in the virtual laboratory improved their confidence in explaining and applying geometric optics concepts to real-world scenarios. For instance, according to participant 4:

> "*Before the virtual lab, I couldn't explain how mirrors form images, but now I feel confident drawing ray diagrams and explaining the concepts to others*."

Also, according to participant 10:

> "*The virtual lab gave me the confidence to solve problems on my own. I now understand why lenses are used in glasses and how they work*."

Participant 14 also added that:

> "*I struggled with ray diagrams before, but after using virtual lab, I was able to draw them perfectly during the second test. It was a big boost on my confidence*."

The thematic analysis of students' responses from the interview highlights how virtual laboratories foster conceptual understanding of geometric optics through interactive simulations, visual representations, opportunities for independent exploration, real-time feedback, and increased confidence. These themes emphasise the potential of virtual labs to provide effective, engaging, and supportive learning environments that promote deep understanding and active engagement with abstract geometric optics concepts.

4.3 Discussion of Results

This section presents the discussion of the results, which is also organised based on the research questions.

4.3.1 Discussion of Results for Research Question 1

The analysis of the availability of teaching and learning resources across all concepts (verification of the laws of reflection, determination of the number of images formed by inclined mirrors, verification of Snell's law, determination of the focal length of a concave mirror, and determination of the focal length of a convex lens) revealed significant resource deficits in all three participating schools (A, B, and C). Across board, essential tools such as plane mirrors, triangular prisms, concave and convex mirrors, lens holders, drawing boards, optical pins, meter rules, and light sources were grossly inadequate, with some schools lacking critical resources entirely. The deficits ranged from moderately inadequate (e.g. school B's availability of certain items) to severe shortages (e.g. school C's lack of lens holders and light sources for some concepts).

These shortages significantly limit students' ability to perform experiment independently or even in small groups, reducing the overall quality of the teaching and learning experience (Niyitanga et al., 2021). Practical lessons, according to Antwi et al. (2021), are vital for developing students' understanding of abstract scientific concepts, such as geometric optics. The lack of resources likely impedes students' ability to engage in experiential learning, which is essential for fostering critical thinking, problem-solving skills, and scientific inquiry (Pareek, 2019). Furthermore, the disparities in resource allocation among the schools suggest inequities in educational provisioning, which could lead to the variations in educational provisioning, and ultimately leading to variations in students' learning outcomes. Schools with more acute deficits, are particularly disadvantaged, and students in such environments may lag in their conceptual understanding compared to peers in better-equipped schools.

This finding highlights the urgent need for interventions to address these deficiencies. A solution proposed by the Ministry of Education (2023) is the use of virtual laboratory simulations, which can offer a cost-effective alternative for teaching complex optics concepts in resource-constrained settings. The ensuing consequence is that students' understanding of optics concepts is improved, which in turn affect their overall academic performance in optics.

4.3.2 Discussion of Results for Research Question 2

Research question 2 aimed to assess the whether there is a difference in students' conceptual understanding of geometric optics between students exposed to virtual laboratory and those exposed to real laboratory. Quantitatively, an independent sample t-test showed no significant difference between the conceptual understanding of students in the experimental group (exposed to virtual laboratory) and those in the control group (exposed to real laboratory). The qualitative findings, derived from students' answers to the open-ended items, corroborate the quantitative analysis. Students in both the experimental and control groups demonstrated full understanding of key geometric optics such as the laws of reflection and refraction, and image formation in concave mirrors, amongst others, concepts after the intervention, which they demonstrated partial understanding and misconceptions prior to the intervention. Students, after the intervention, provided clear and accurate explanations, demonstrating their ability to apply theoretical principles to practical scenarios, such as drawing ray diagrams and explaining image formation in concave mirrors.

This suggests that both types of laboratory exposure resulted in comparable improvements in students' understanding of geometric optics. The lack of a significant difference can be explained by the fact that both methods engage students in active learning. Real laboratories allow students to manipulate physical materials and observe real-world results, which has been shown to improve conceptual understanding (Lehesvuori et al., 2023). However, virtual laboratories are increasingly recognised for their potential to provide visual and interactive experience that can foster deeper understanding of abstract concepts, especially in physics (Ali et al., 2022; Hamed & Aljanazrah, 2020). According to Wörner et al. (2022), virtual laboratories enable students to engage with complex concepts through simulations and interactive tasks, which Ali et al. (2022) argue that, in some cases, may even surpass the capacity of real laboratories in terms of accessibility and safety.

The absence of a significant difference between the two groups may also be attributed to the effectiveness of both methods in supporting constructivist learning, which underpins both virtual and real laboratory approaches in this study. According to Vygotsky (1978), learning is most effective when students actively work in solving problem and interact with their environment. Both real and virtual laboratories, by providing opportunities for students to engage with scientific concepts actively, support this form of learning. It is therefore plausible that, regardless of the medium, whether students engage with physical materials in real laboratory or interactive simulations in a virtual laboratory, both methods appear to offer the potential to support deep, conceptual learning. This means that both real and virtual laboratories can be designed to foster inquiry, problem-solving, and critical thinking, all of which are essential components of the learning process.

This finding is consistent with previous research that has explored the effectiveness of virtual laboratories in teaching scientific concepts. Studies including, but not limited to those conducted by Burkett and Smith (2016), Kapici et al. (2019), Hamed and Aljanazrah (2020), Faour and Ayoubi (2018), as well as Santos and Prudente (2022), have demonstrated that virtual laboratories can provide students with experiences that are equivalent to, if not better than, those provided by real laboratories, particularly in contexts where access to physical laboratory materials is limited. However, some researchers including Lynch and Ghergulescu (2017), Colthorpe and Ainscough

(2021), and Asare et al. (2023), have suggested that virtual laboratories may not fully replicate the hands-on experience offered by real laboratories, particularly in terms of physical manipulation of materials. This current study, however, found no significant difference between the two, suggesting that when both methods are used effectively, the outcome in terms of student conceptual understanding can be similar.

The fact that both virtual and real laboratories produced similar learning outcomes suggests that virtual laboratories could serve as cost-effective and accessible alternative to traditional real laboratories. According to Asare et al. (2023), virtual laboratories provide the flexibility of remote access and the potential to simulate a wide variety of optical experiments that may be difficult or impossible to replicate in real laboratory. Accordingly, for schools with limited resources or large student populations, incorporating virtual laboratories into the curriculum could be an effective way to enhance the teaching and learning of geometric optics while maintaining standards of the teaching and learning of geometric optics.

At the same time, the findings do not diminish the value of real laboratories. Rather, they suggest that when both real and virtual laboratories are used appropriately, they can complement each other, offering a well-rounded educational experience. For instance, real laboratories, could be used for activities requiring physical manipulation of materials, while virtual laboratories could be used for simulations and exploration of theoretical concepts.

4.3.3 Discussion of Results for Research Question 3

Research question 3 sought to determine how students develop conceptual understanding of geometric optics through virtual laboratory. The findings from research question 3 revealed five major themes: interactive simulations enhancing engagement, visual representations aiding conceptualisation, opportunities for independent exploration fostering deeper understanding, real-time feedback improving accuracy, and increased confidence in applying concepts. Students were captivated and given the opportunity to actively play with the concepts of geometric optics owing to the interactive simulations in the virtual laboratories. Students stated that they were able to close the gap between theoretical understanding and real-world application by manipulating variables like the refractive index or the angle of incidence and seeing the outcomes in real time. These results are consistent with constructivist learning theory, which holds that knowledge is actively created through task completion and concept investigation (Poonam, 2017). The virtual lab provided a learning environment where students could investigate “what if” scenarios, a hallmark of constructivist teaching.

By presenting difficult ideas in an approachable, interactive manner, the interactive simulations probably decreased unnecessary cognitive strain from the standpoint of cognitive load theory. Students were guaranteed to concentrate on germane cognitive load, which is crucial for deep learning, because of the instant visual feedback. Students explained, for instance, how they were able to comprehend relationships such as the angle of incidence equaling the angle of reflection by watching real-time changes in reflected or refracted rays. This active participation is consistent with research that highlights the value of interactive learning resources in fostering understanding. (e.g., Haleem et al., 2022; Kharki et al., 2021).

Students’ understanding of abstract concepts like ray diagrams and picture generation was greatly aided by the visual aids that the virtual labs offered. The focal points of mirrors and the bending of light during refraction were two ideas that participants found difficult to understand previously, but the simulations helped them visualise. According to the cognitive load theory (Sweller, 2019), visual aids lessen intrinsic cognitive load and promote meaningful learning by breaking down complicated ideas into simpler components. Furthermore, the constructivist emphasis on visualisation as a tool for knowledge construction lends credence to this finding. For instance, virtual laboratories gave students scaffolded experiences that matched their zone of proximal development by combining guided exploration with real-time visualisations (Vygotsky, 1978). The results of the posttest showed that this type of scaffolding assisted students in progressing from a partial comprehension to complete mastery of ideas. These findings are supported by research by Udin et al. (2020), and Gunawan et al. (2018) which shows that students’ understanding and application of scientific concepts are enhanced by the use of visual aids in virtual laboratories.

The freedom to explore concepts independently was another theme that emerged from the interviews. Virtual laboratory allowed students to engage in trial-and-error learning, enabling them to test hypotheses and discover principles on their own. This approach aligns with constructivist learning theory, which emphasises the importance of active, self-directed exploration in constructing knowledge (Waite-Stupiansky, 2022). Students reported that the ability to experiment without time or material constraints encouraged deeper engagement and persistence in solving problems. From a cognitive load theory perspective, independent exploration allows learners to manage their own cognitive load effectively (Kirschner et al., 2018). Without the pressure of real-world laboratory constraints, students could focus entirely on the learning task, experimenting with different scenarios to develop a thorough understanding of the concepts. This finding resonates with Zimmerman’s (2002) theory of self-regulated learning, which highlights the importance of autonomy and self-paced learning in fostering academic success.

The real-time feedback provided by the virtual laboratory was also a crucial feature that supported corrective learning and conceptual clarity. Participants described how the immediate feedback helped identify and rectify misconceptions, reinforcing accurate understanding of geometric optics principles. In the context of cognitive load theory (Sweller, 2019), the real-time feedback minimised extraneous cognitive load by directly addressing students’ errors and misconceptions, preventing them from expanding unnecessary cognitive resources on incorrect pathways. This immediate feedback loop enabled learners to focus on the essential cognitive processes required for conceptual understanding, a key factor in fostering meaningful learning as outlined by Sweller (1994).

Another theme that emerged was the increased confidence students gained in applying geometric optics concepts after using virtual laboratories. Students reported feeling more competent in explaining concepts and solving problems independently. From a constructivist perspective, this increased confidence reflects the success of active, inquiry-based learning approaches, where students construct knowledge through hands-on experiences (Efgivia et al., 2021). This finding also aligns with studies such as those by Peechapol (2021) and Gungor et al. (2022) which demonstrate that virtual laboratories enhance students' self-efficacy by providing safe, repeatable, and engaging learning environments.

The findings from research question 3 are consistent with previous research emphasizing the efficacy of virtual laboratories in improving conceptual understanding. Studies by Wenk et al. (2023) and Liu et al. (2022) have highlighted the role of interactive simulations and visualizations in promoting active learning and reducing cognitive load. Similarly, increased confidence and autonomy reported by students in this study resonate with the findings of research on self-regulated learning in virtual environments (Al-Duhani et al., 2024; Reginald, 2023). However, this study provides new insights into specific mechanisms through which virtual laboratories contribute to conceptual understanding, such as the role of real-time feedback in minimising cognitive load and fostering corrective learning. These findings underscore the potential of virtual laboratories as a complement to traditional teaching methods, particularly in contexts where access to physical laboratories is limited.

CHAPTER FIVE

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.0 Overview

This chapter concludes the study by providing a summary of key findings. The chapter also presents the conclusions drawn from the findings, and highlights practical recommendations for stakeholders. Finally, it offers suggestions for future research to address the limitations of this study.

5.1 Summary of Findings

This study aimed to assess the integration of technology in the teaching and learning of geometric optics by comparing the effects of virtual and real laboratories on SHS physics students' conceptual understanding of geometric optics. In this study, a mixed-method approach was adopted, combining quantitative and qualitative analyses to answer research questions. Key findings from the study are summarised as follows:

1. **Availability of teaching and learning materials for geometric optics**: the study revealed significant deficits in the availability of essential optical instruments required for teaching and learning geometric optics in SHSs across the Nandom and Lawra Municipalities. Schools lacked sufficient plane mirrors, drawing boards, paper clips, optical pins, and other essential tools, making it challenging for students to engage in hands-on experiments. Even the resources available were unevenly distributed and often in poor condition.
2. **Effectiveness of virtual and real laboratories**: the comparison of students' conceptual understanding, as measured by pretest and posttest scores, showed that both virtual and real laboratories improved students' conceptual

understanding of optics at equivalent levels with no significant difference observed. This finding underscores the potential of virtual laboratories to enhance students' conceptual understanding of geometric optics, especially when resources for traditional laboratories are limited.

3. **Students' Perceptions of Virtual Laboratories**: the qualitative data highlighted students' positive perceptions of virtual laboratories. Participants appreciated the accessibility, interactive nature, and opportunity to explore complex geometric optics concepts in a risk-free environment.

5.2 Conclusions

The study concluded that:

1. SHSs across Nandom and Lawra Municipalities who offer physics lack sufficient teaching and learning materials for geometric optics, hindering students' conceptual understanding of concepts.
2. Furthermore, it was concluded that while real laboratories remain important for experiential learning, the findings suggest that virtual laboratories can serve as a viable alternative or complement in enhancing SHS physics students' conceptual understanding in geometric optics, especially in settings such as Nandom and Lawra Municipalities, where physical resources are insufficient.
3. Moreover, SHS physics students' express positive perceptions of virtual laboratories highlighting their potential as effective tools for fostering active learning in the development of conceptual understanding of geometric optics concepts.

5.3 Recommendations

Based on the findings of the study, the following recommendations are proposed:

1. The Ghana Education Service and other stakeholders should prioritise the provision of adequate teaching and learning materials for geometric optics SHSs across Nandom and Lawra Municipalities.
2. SHS physics educators within Nandom and Lawra Municipalities should incorporate virtual laboratories as a supplementary tool to traditional laboratory experiments with the aim of improving students' conceptual understanding in geometric optics. Platforms like PhET simulations can be used to provide interactive learning experiences, particularly in under – resourced schools.
3. SHSs within the Nandom and Lawra Municipalities should provide orientation programmes to help students navigate virtual laboratory tools effectively. This will ensure students maximise the benefits of simulations and maximise initial challenges.

5.4 Suggestions for Further Research

To build on the findings of this research, the following areas are suggested for further studies:

1. Expanding the study to other regions in Ghana could provide a broader understanding of the challenges and opportunities associated with integrating technology into physics education.
2. Similar studies could be conducted to evaluate the effectiveness of virtual laboratories in teaching other challenging physics concepts.

3. Also, future replicated studies should consider the selection and assignment of participants via randomisation to minimise the effect of extraneous variable that might have affected the results of this study.

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APPENDICES

Appendix A

Optics Concept Test

1. Describe what happens to the angle between the incident ray and the reflected ray when a plane mirror is rotated twice the angle of incidence.
2. In what situation does light pass into a medium without refracting?
3. What does it mean when a material has a refractive index greater than 1?
4. How does the magnification produced by a rear-view mirror in vehicles compare to 1?
5. Explain the scientific principle behind why the word “ambulance” is mostly written in an inverted manner on the front of ambulances.
6. Describe one practical application of the laws of reflection in everyday life, explaining how these principles enhance the functionality of the application.
7. Using a ray diagram, explain how you would determine the focal length of a concave lens.
8. Using a ray diagram, explain how a concave mirror can produce both real and virtual images.

Appendix B

Marking Scheme to Optics Concept Test

1. When a plane mirror is rotated through a certain angle, the reflected ray rotates through twice that angle. Therefore, when the mirror is rotated twice the angle of incidence, the angle between the incident and reflected rays increases by four times the angle of incidence. This occurs because the angle of reflection always equals the angle of incidence, and a mirror rotation causes the reflected ray to deflect through double the rotation angle.

   States that reflected ray rotates twice the mirror angle – **2 marks**

Explains that angle between incident and reflected rays increases by four times the mirror rotation (or twice the mirror angle on each side) – **2 marks**

2. Light passes into a medium without refraction when it enters perpendicularly (normally) to the surface separating the two media. In this situation, the angle of incidence is 0°, so the light continues in the same straight-line direction without bending.

   Mentions perpendicular or normal incidence – **2 marks**

   States that there is no bending or change in direction – **1 mark**

3. A refractive index greater than 1 means that light travels slower in that medium than in a vacuum (or air approximately). It indicates that the medium is optically denser than air, causing light to bend toward the normal upon entry.

   States light travels slower in the medium – **2 marks**

   Identifies the medium as optically denser / bends light toward the normal – **1 mark**

4. The magnification produced by a rearview mirror (a convex mirror) is less than 1. This means the images formed are diminished (smaller than the object) but upright and virtual, allowing the driver to see a wider field of view.

   Identifies the mirror as convex – **1 mark**

   States magnification is less than 1 – **1 mark**

   Explains that image is diminished but gives wider view – **1 mark**

5. The word "AMBULANCE" is written in laterally inverted (mirror image) form so that when drivers ahead view it through their rearview mirrors, the word appears upright and readable. This uses the law of reflection which states that the angle of incidence equals the angle of reflection, causing lateral inversion in mirrors.

   Identifies that the word is written laterally inverted – **1 mark**

   Mentions viewing through rearview mirrors – **1 mark**

   States that it appears upright and readable in the mirror – **1 mark**

   Relates to the law of reflection / lateral inversion principle – **1 mark**

6. One practical application is in periscopes used in submarines or by soldiers. Periscopes employ two plane mirrors placed parallel at 45° angles to the line of sight. The law of reflection (angle of incidence = angle of reflection) ensures that light from an object reflects successively from both mirrors to the observer's eye, allowing them to see over obstacles while remaining hidden or submerged.

   Identifies periscope (or other valid example like rearview mirrors) – **1 mark**

   Describes mirror arrangement or setup – **2 marks**

   States use of law of reflection – **1 mark**

   Explains how it helps functionality (seeing over obstacles) – **1 mark**

7. Ray Diagram (should include):

   Procedure and Explanation:

   Place a concave lens on an optical bench.

   Use a plane mirror behind the lens and direct parallel rays of light toward the lens.

   Adjust the distance between the lens and mirror until the reflected rays retrace their paths (indicating they pass through the focal point).

   Measure the distance between the lens and the mirror – this equals the focal length (f) of the concave lens.

   Parallel incident rays striking concave lens.

   Diverging rays reflecting off the mirror and converging back through the lens.

   Indication of focal point at mid-distance.

   Proper setup with lens and mirror – **2 marks**

   Correct explanation of reflected rays retracing paths – **2 marks**

   Accurate determination of focal length as lens-to-mirror distance – **1 mark**

   Correct and labeled ray diagram – **1 mark**

8. Explanation:

   A concave mirror forms:

   Real images when the object is placed beyond the focus (F). The reflected rays converge to form an inverted real image in front of the mirror.

   Virtual images when the object is placed between the focus (F) and the mirror. The reflected rays diverge, but their extensions appear to meet behind the mirror, forming an upright, magnified, virtual image.

   Ray Diagram (should include):

   One diagram showing object beyond F → real, inverted image.

One showing object between F and mirror → virtual, upright image.

Correct description of real image condition – **2 marks**

Correct description of virtual image condition – **2 marks**

Clear, correctly labeled ray diagram for both cases – **2 marks**

Appendix C

Geometric Optics Instruments Inventory

This inventory focuses on the availability, quantity and condition of geometric optics teaching and learning instruments. Please write the quantity of the available instrument and state the availability and condition by providing a tick in the corresponding boxes of options provided.

Instrument	Availability		Quantity	Condition		
	Yes	No		Excellent	Good	Poor
Concave lens						
Convex lens						
Plane mirrors						
Lens holder						
Mirror holder						
Concave mirrors						
Convex mirrors						
Screen						
Meter rule						
Optical pins						
Paper clips						
Drawing boards						
Light Sources (Laser, LED, Incandescent)						
Prisms						

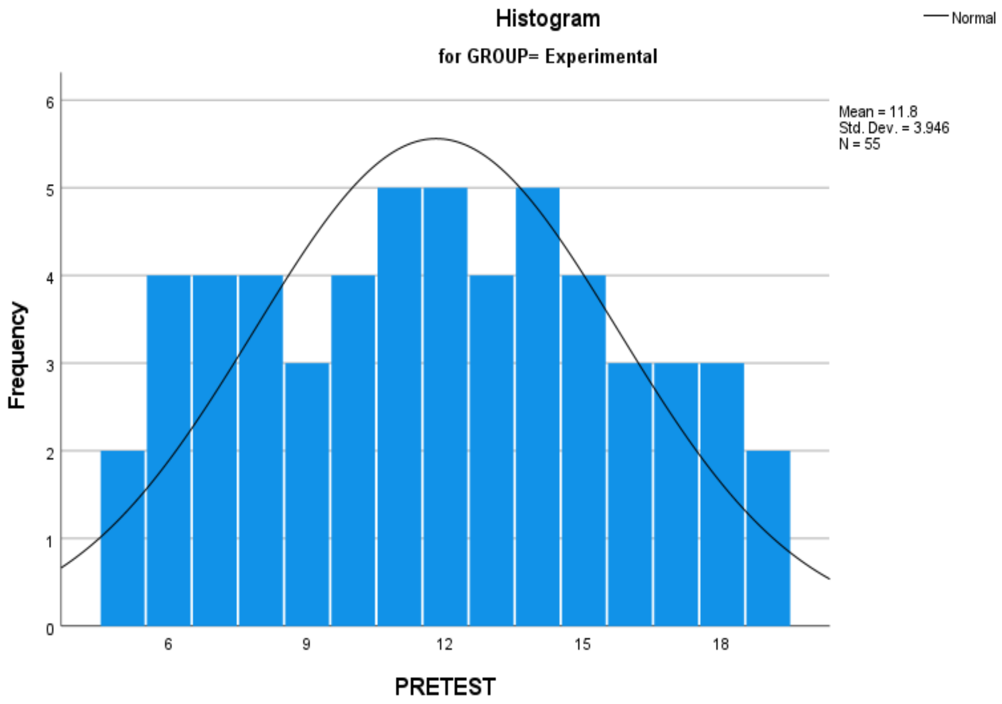
Appendix D

Semi-Structured Interview Guide

1. How did the learning activities influence your motivation to learn optics concepts?
2. Reflecting on your experiences with the learning activities, how did it impact your ability to work effectively in groups?
3. How do you believe instructional approach helped you develop your ability to approach complex optics problems?
4. Describe any changes you noticed in your confidence in solving optics problems after engaging in the learning activities.
5. Reflecting on your overall learning experience, how has the instructional approach contributed to your ability to apply optics knowledge beyond the classroom?

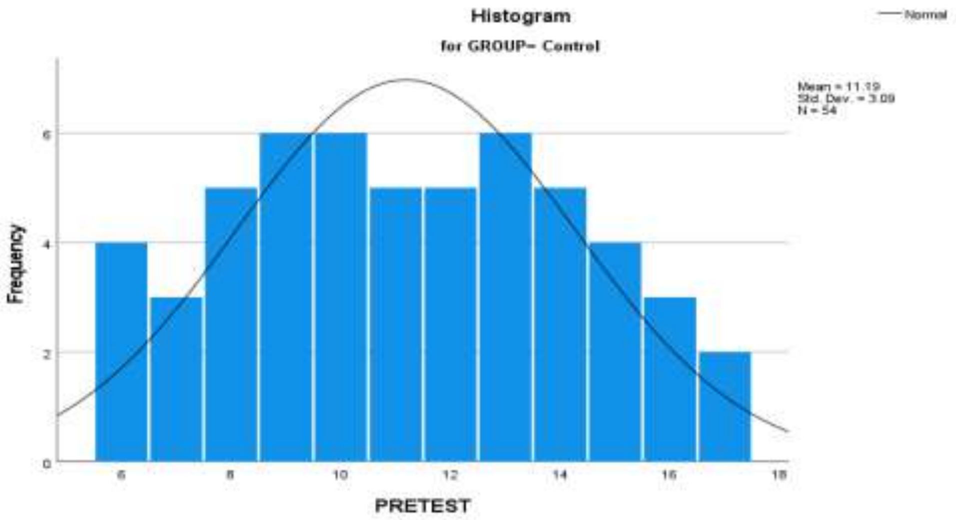
Appendix E1

Histogram Distribution for Pretest Scores of Experimental Group



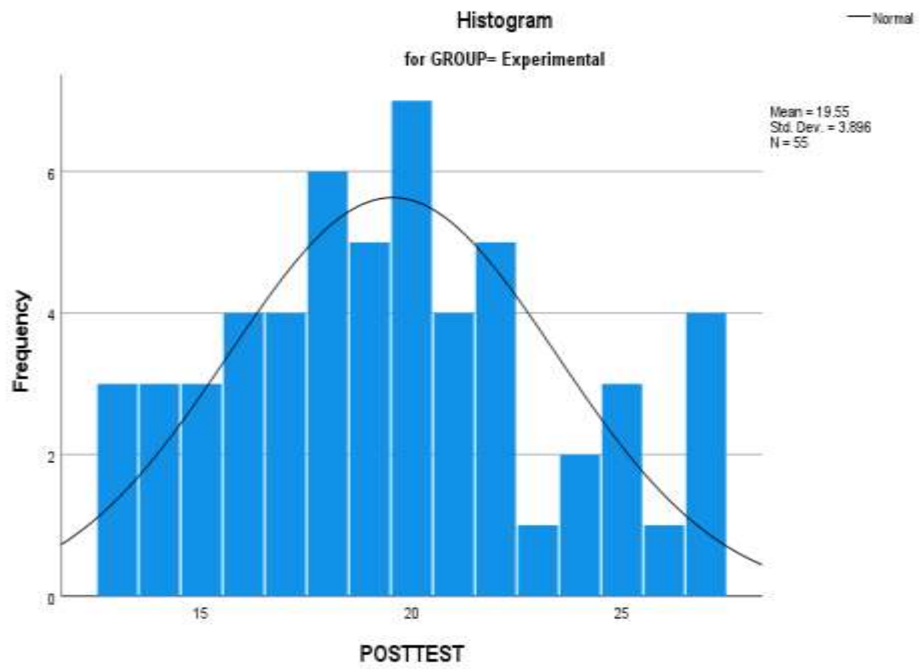
Appendix E2

Histogram Distribution for Pretest Scores of Control Group



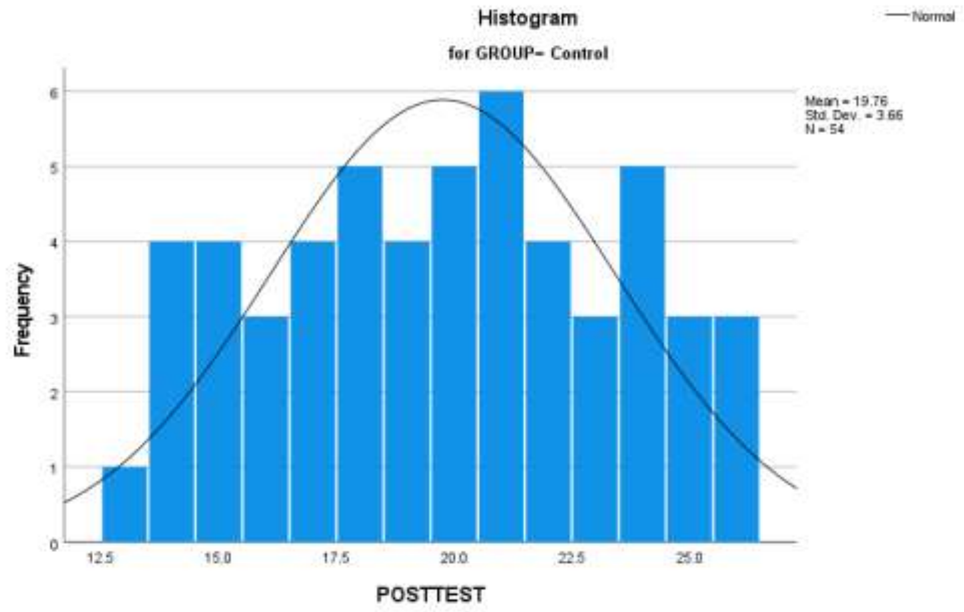
Appendix E3

Histogram Distribution for Posttest Scores of Experimental Group



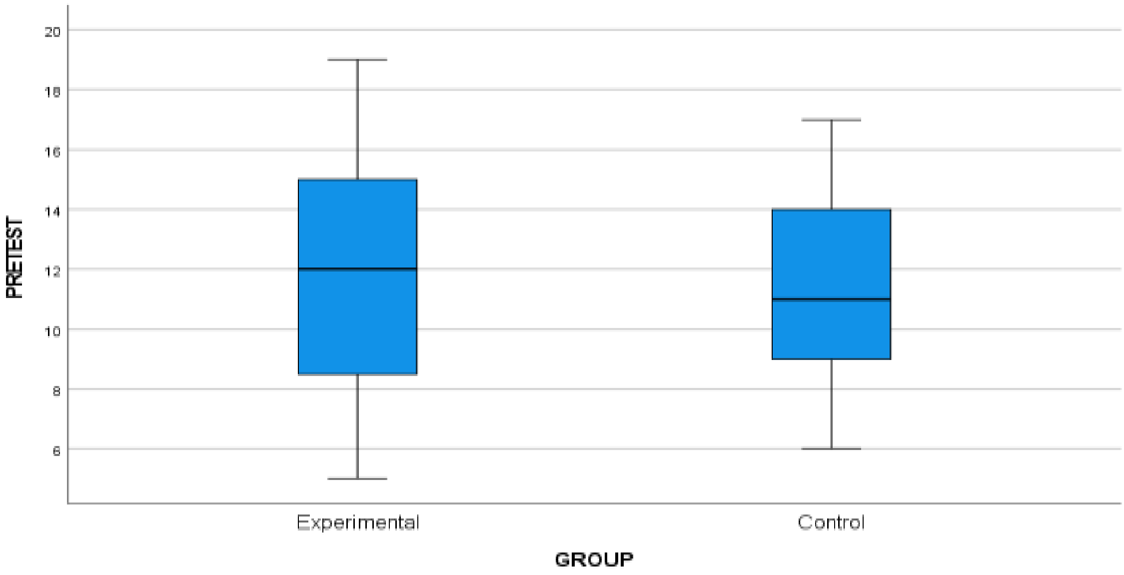
Appendix E4

Histogram Distribution for Posttest Scores of Control Group



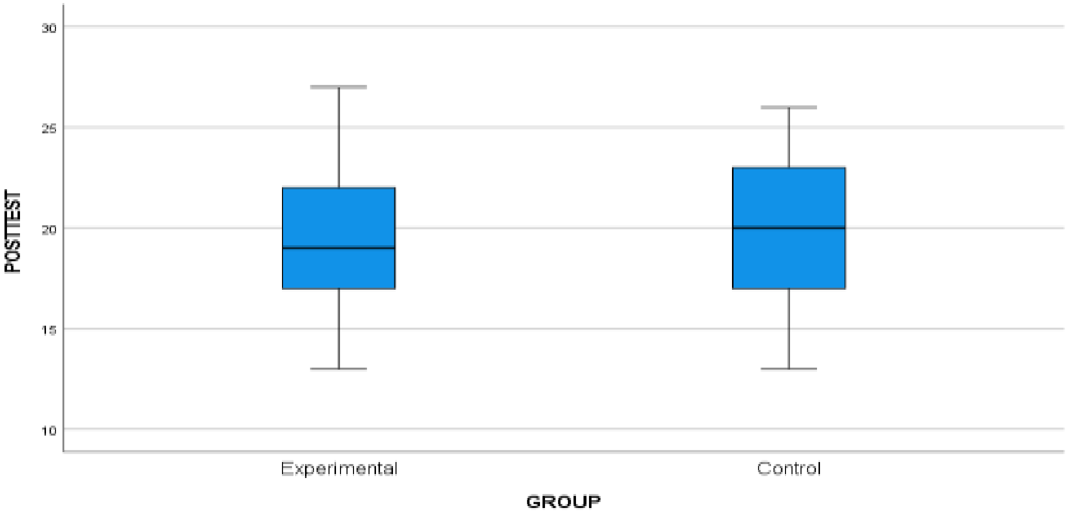
Appendix F1

Box Plots of Pretest scores for Experimental and Control Groups



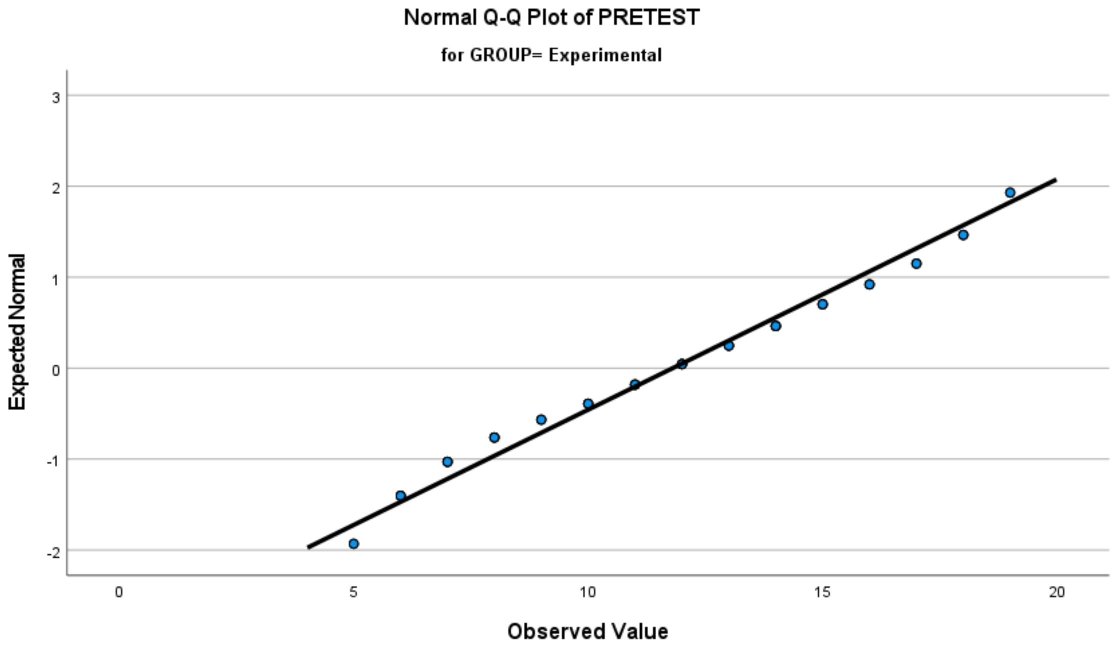
Appendix F2

Box Plots of Posttest scores for Experimental and Control Groups



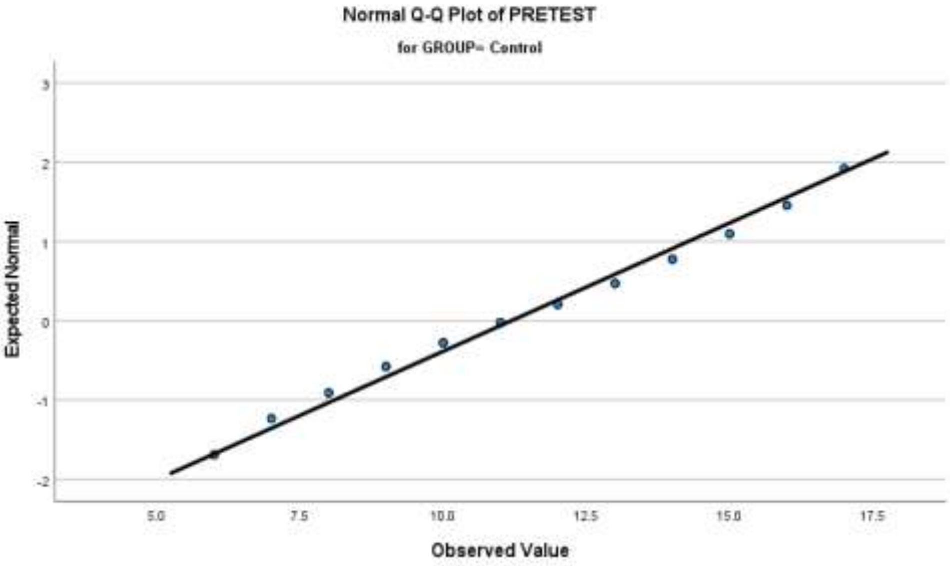
Appendix G1

Normal Q-Q Plot of Pretest Scores for Experimental Group



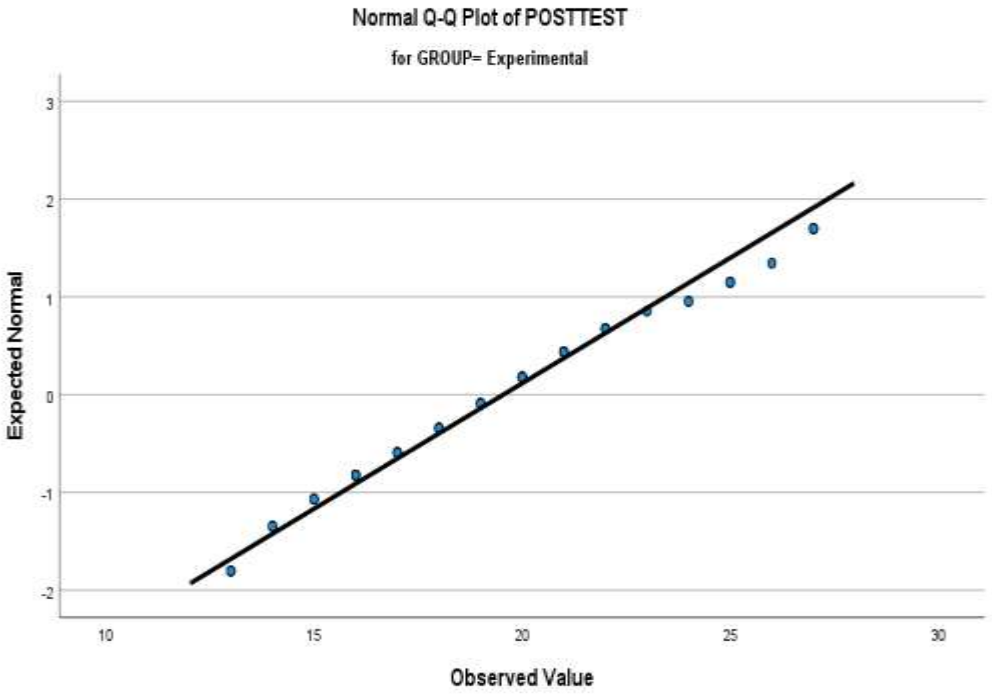
Appendix G2

Normal Q-Q Plot of Pretest Scores for Experimental Group



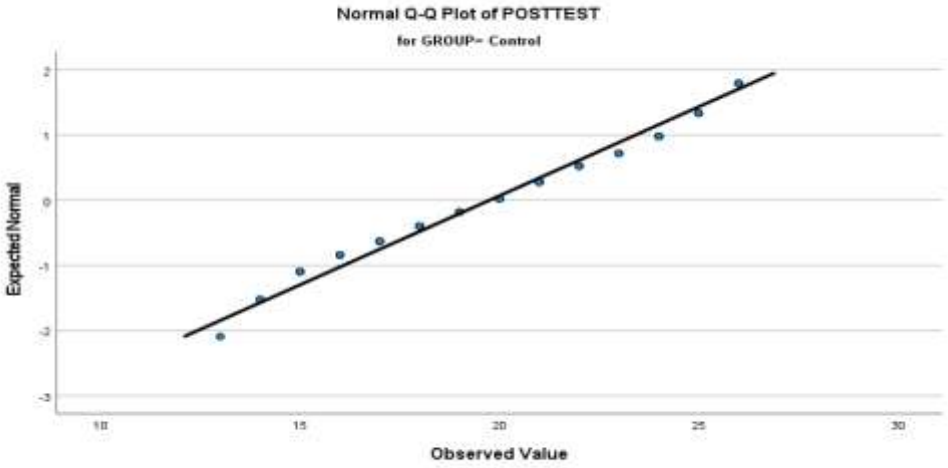
Appendix G3

Normal Q-Q Plot of Posttest Scores for Experimental Group



Appendix G4

Normal Q-Q Plot of Posttest Scores for Control Group



Appendix H

Formula for Cohen's d

d = $\frac{M_1 - M_2}{SD_{pooled}}$

where M_1 = Mean score for experimental group

M_2 = Mean score for control control group

SD_{pooled} = pooled standard deviation = $\sqrt{\frac{SD_1^2 + SD_2^2}{2}}$