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Improving Early Optics Instruction Using a Phenomenological Approach: A Field Study

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Abstract: Previous research has shown that phenomenological approaches in early optics education might be superior to traditional model-based instruction based on the light ray realm with regards to fostering students' conceptual understanding of basic optics topics. However, it remains open to date which learning difficulties students encounter when being introduced to optics following a phenomenological approach—in particular, in comparison to the learning difficulties that are widespread among students introduced to optics via traditional model-based instruction. With this article, we contribute to closing this gap: We report the results of a quasi-experimental field study with $N = 189$ secondary school students. We used ten items adapted from the literature in a pre-posttest design for an in-depth exploration of the conceptions of introductory optics topics acquired by $N = 89$ students introduced to optics following a phenomenological teaching-learning sequence and compare these students' conceptions to the ones acquired by $N = 100$ peers who participated in traditional model-based instruction covering the same content topics. The results of this study substantiate earlier findings according to which phenomenological teaching might be a fruitful endeavour for early optics education, in particular, when it comes to teaching and learning about image formation by converging lenses.

Keywords: optics; physics education; learning difficulty; phenomenology

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1. Introduction

The everyday life of secondary school students is rich in optical phenomena. In traditional introductory optics lessons at the secondary school level, mainly focused on geometrical optics, however, such phenomena frequently only play a limited role—the beauty of optical phenomena is often reduced to ray constructions and abstract models of light [1]. Physics education research has shown that this traditional model-based optics instruction can pose fundamental obstacles to student learning [2], particularly because the model nature of light rays is often not emphasized explicitly enough [3], leading, amongst other things, to students erroneously assigning haptic reality to light rays (cf. [4,5]). Hence, it is no surprise that in the literature numerous inconsistent conceptions have been shown to be prevalent among students regarding basic optics concepts that are not equivalent to the scientific point of view (cf. [6–8])—even after formal instruction. Such conceptions are (without valuation) referred to as student conceptions or, depending on the specific case, as misconceptions, and may be a source of learning difficulties among students.

A sensible alternative to traditional model-based instruction might be phenomenological approaches for teaching introductory optics. In a nutshell, the essence of all phenomenological educational pathways for teaching and learning about optics lies in phenomena being starting point and center for learning (see Section 2.2). Hence, in phenomenological teaching, knowledge about optics concepts is gained through the careful investigation of phenomena in order to uncover the conditions of their appearance (cf. [1]).

Prior research has provided empirical evidence according to which novice learners who had participated in a phenomenological approach to introductory optics outperformed their peers who had followed traditional model-based instruction in terms of conceptual understanding of basic optics topics [9]. The authors of Ref. [9] state that more empirical research is needed, e.g., in order to uncover the learning difficulties students encounter when being introduced to basic optics concepts following a phenomenological approach—in particular, in comparison to the learning difficulties that are widespread among students introduced to optics concepts via traditional model-based instruction.

This demand serves as a springboard for the study presented here: In this article, we report the results of a quasi-experimental field study with $N = 189$ secondary school students and we

1. provide an in-depth exploration of the conceptions of introductory optics topics such as the process of vision, refraction or image formation acquired by $N = 89$ students introduced to optics following a phenomenological approach, namely the Erlangen teaching-learning sequence of introductory optics (cf. [10], for an overview of this concept see Section 2.3 of this article) and
2. compare these students' conceptions to the ones acquired by $N = 100$ learners who participated in traditional instruction based upon the light ray realm.

This article is structured as follows: In Section 2, we provide an overview of the literature to contextualize our study against the backdrop of prior research. Our research question is presented in Section 3. In Section 4, we describe the design of our study and the methods used to analyse our data, before we report our findings in Section 5. We discuss our findings and derive implications for classroom practice in the discussion Section 6, before we conclude in Section 7.

2. Research Background

2.1. Students' Conceptions of Basic Optics Topics

A large number of earlier studies aimed at exploring students' conceptions of basic optics topics (cf. [11]), for example regarding the process of vision [12–16], properties of light [17–20], light propagation [21–23], color [24–27], refraction [28–30], or image formation [31–36]. In the following, we provide deeper insights into students' conceptions of (a) the process of vision, (b) refraction, and (c) image formation by converging lenses and a similar overview can also be found in Ref. [9].

2.1.1. Students' Conceptions of the Process of Vision

A frequently occurring conception of the process of vision is that of the active eye scanning the environment to register objects and images (cf. [11,12]). This conception can—at least to some extent—be drawn back to everyday language: For example, think of expressions such as "to throw a glance at something" [2] (p. 59). Science-Fiction-Figures actively scanning the surrounding via beams leaving the eyes are likely to be a further source for such conceptions among novices [23]. In addition, it has been found that some students believe that sunlight first has to reach the eye in order to enable vision [14].

That all objects are invisible in a completely darkened room poses further striking hurdles to learners and this learning difficulty is likely to stem from the widespread notion that light would possess substance-like properties and would fill the space surrounding light sources. As a consequence, many students believe that light sticks to objects it falls on making them bright that way [37] while the concept of light scattering remains unnoticed (cf. [38]).

2.1.2. Students' Conceptions of Refraction

Prior research has shown that refraction is frequently confused with other optical phenomena, e.g., diffraction [30] or reflection [39]. In contrast, some students believe that reflection and refraction are mutually exclusive [11]. One explanation for this observation could be that reflection and refraction are most often taught separately in optics classes, despite occurring simultaneously in real-world phenomena.

2.1.3. Students' Conceptions of Image Formation by Converging Lenses

Many students believe that the image of an object travels through the lens as a whole, whilst disregarding the underlying concept of the point to point principle [2]. This conception may result in further learning difficulties: For example, physics education research has revealed that many students think that an image is cropped by an aperture in front of the lens [40] and hence, apertures lead to reducing the size of the image [15]. Similarly, many students state that the image is cropped at the edges if the diameter of a lens is smaller than the object used in the experiment (cf. [35]). Furthermore, it has been found that many learners assign a preferred direction to an optical set-up: For example, the students think that the effect of an aperture on image formation depends on whether the aperture is located in front or behind the lens [31]. Last but not least, the left-right inversion of the image is often not noticed: As such, many students recognize the inversion of top and bottom only when asked about it [2] (p. 72) but do not consider that the image represents a point inversion of the object.

A major problem, especially for novice learners in introductory optics lessons, is the lack of clarity about the model character of light rays. This often leads to students mistakenly confusing light rays with haptic entities [4]. In contrast, a functional understanding of light rays is not widely disseminated (cf. [41,42]). In light of the aforementioned, it appears scarcely astonishing that students often lack sufficient conceptual understanding of optics topics notwithstanding formal instruction. To tackle the shortcomings of traditional model-based instruction sketched in this section on the one hand, and to bring everyday optical phenomena to the heart of optics teaching on the other, phenomenological educational pathways for introductory optics lessons have emerged from physics education research (cf. [10]). In such proposals, mechanistic models of light "are almost entirely replaced by the precise observation of images, the optical phenomena themselves" [10] (p. 2).

2.2. Phenomenological Approaches in Science Education

By the term *phenomenology* one understands the "attempt to get to the truth of matters, to describe phenomena, in the broadest sense as whatever appears in the manner in which it appears, that is as it manifests itself to consciousness, to the experiencer. As such, phenomenology's first step is to seek to avoid all misconstructions and impositions placed on experience in advance, whether these are [. . .] from everyday common sense, or, indeed, from science itself. Explanations are not to be imposed before the phenomena have been understood from within" [43] (p. 4).

In science education, phenomenological approaches have a long history and have frequently been traced back to Goethe whose "writings often show some aspects that resonate with the phenomenological attitude of the primacy of qualitative aspects and lived experience" [44] (p. 42). Phenomenological teaching is characterized by a focus on asking questions, carefully observing phenomena, and describing, interpreting as well as reflecting on own experiences [45]. This characterization is further substantiated by Dahlin in his 2001 paper [46], stating that the phenomenological approach "brings aesthetic perception (in its original sense) into the formal and objective aspect of both learning and research in science. More precisely, it establishes an internal, dialectic relation between the personal, subjective aspect, and the formal, objective one" [46] (p. 468). In this way, phenomenological approaches are aimed at tackling shortcomings of traditional instruction, such as students' decreased awareness towards phenomena [45] while still aiming at bridging observation and theory [47]. Not least due to optical phenomena being omnipresent in our everyday life it seems natural to use phenomenological approaches for teaching basic optics concepts. Rather, the description of optical phenomena by means of abstract models in early physics education even represents a detour that poses obstacles to student learning: The students see "no refraction of rays, but bending shadow edges" (translated from [48])

(p. 155). However, this does not imply phenomenological and model-based approaches to be incompatible in (early) optics instruction since teaching "may be phenomenon-based and model-oriented" [49] (p. 8). In the next Section 2.3, we sketch the key ideas of a phenomenological teaching-learning sequence developed for early optics education [10].

2.3. The Erlangen Teaching-Learning Sequence of Introductory Optics

The key ideas of the Erlangen teaching-learning sequence of introductory optics [10] date back to the well-known phenomenological concept "Optics of visual experience" by Maier [50,51] and to the work of von Mackensen [52] who transferred Maier's ideas to school teaching. The Erlangen teaching-learning sequence of introductory optics is aimed at early optics education at the secondary school level (grade 7/8). A time frame of ten school lessons à 45 min is required to implement the teaching concept in classroom practice. In terms of content four chapters are covered:

1. Vision and brightness,
2. Refraction,
3. The look through a prism, and
4. Image formation by converging lenses.

The teaching proposal is described in detail in the earlier contributions [9,10] and hence, in the following subsections, we only sketch the main aspects of the learning pathway.

2.3.1. Learning Pathway of the Erlangen Teaching-Learning Sequence

In the introduction, the distinction between vision and the tactile sense is highlighted. For example, using the example of the smoothness of different types of wool, the youngsters experience that there are things that can be felt but not seen or vice versa: there are also things that can be seen but that can not be felt, e.g., the image of a mirror. After the learners have become conscious of the distinction between vision and the tactile sense, the sequence focuses on the sender-receiver-emitter concept to explain the process of vision [3]: In this context, the students get to know different sources of light, namely emitting sender and re-emitting sender. Furthermore, the students "vary the visual contact between each other and conclude that light always travels in a straight direction—at least, this turns out to be the case for only one surrounding medium" [10] (p. 6).

In the second chapter, the behavior of light at the interface between two transparent media is investigated: Therefore, the students conduct the well-known experiment where a coin is observed in a water basin [53,54]. The coin is not hit when targeting with a skewer through a straw placed at an angle on the edge of the basin. From this experiment, the pupils get further insights into the relationship between vision and tactile sense [55]. Finally, the students observe the change of light's direction at the water surface in an aquarium via the kink of a shadow edge. This leads to the concept of light refraction at the end of this second chapter.

In the teaching concept's third chapter, each student tinkers his or her own prism corpus, which can be filled with water afterwards. For a manual as to how the prism corpus can be fabricated best see Ref. [10]. The students explore the water prisms by looking through them and observe that the image of an object behind the prism gets shifted towards one of the edges, the so-called towing edge (cf. [10]). More precisely, the students derive that the shift of the image enlarges if (a) "one moves the object backwards and away from the prism" [10] (p. 9), or if (b) "one enlarges the angle at the towing edge by turning the prism" [10] (p. 9). The final step towards optical imaging is taken putting together two water-prisms: this is done in pairs of students and leads to so-called double prisms. The double prism can be regarded a functional approximation of a plano-convex-lens: just like in the case of looking through a converging lens, the image "is pulled apart and travels towards the edges of the double prism" [10] (p. 9) as the distance of an object behind the double prism is increased.

The last chapter is the centerpiece of the teaching-learning sequence. At the beginning, the students tinker their own optics inventory, including liquid lenses (cf. [56]) made "out of a plane overhead film and a piece of curved surface of a plastic bottle” [10] (p. 4), a slide made from a cable duct [57], apertures and translucent screens. As a light source, the students are provided with nine-LED-torches [58]. The torch’s LEDs can be easily colored to create an asymmetrical object that can be used for imaging.

The approach taken in this chapter foregrounds a typical procedure for phenomenological teaching, namely, the smooth transition from (a) the experimenters being part of the experiment (the students are looking through the lens) in a first step to (b) the experiment standing alone and detached from the experimenters in a second step: in the first phase, the students explore their liquid lenses by looking through them, before they get the task to explore the conditions under which a sharp image of the sender appears at the screen using the self-made liquid lenses without any further guidance. It is noteworthy that the type of experiments conducted within the educational pathway presented here can be referred to as *exploratory experiments* [59,60] which “are driven by the desire to seek empirical regularities and the proper concepts and classifications that may be the underlying causes of those regularities” [44] (p. 53). From the experimental results gathered within this course, it may be concluded that in order to obtain sharp images, a certain object distance g needs to go along with a specific image distance b for a given lens. After exploring the impact of different apertures on image formation by converging lenses, in a last step, image formation is connected to human vision discussed at the very beginning of the teaching-learning sequence: Therefore, the students use self-made liquid lenses with variable curvature as suggested in Ref. [61] to explore the eye’s accommodation.

2.3.2. Empirical Findings

A quasi-experimental field study was conducted to investigate the effect of a phenomenological approach following the Erlangen teaching-learning sequence of introductory optics on $N = 42$ grade eight students’ conceptual understanding of basic optics concepts such as the process of vision, the concept of refraction, and image formation by converging lenses [9]. The learning outcomes were compared to those of $N = 55$ peers in a control group who experienced traditional model-based optics instruction. The two interventions did neither differ in terms of content nor with regards to further design features such as the use of media. In addition, the same amount of time was used for optics teaching in both groups. The findings of this study revealed that the phenomenological approach might be superior to model-based traditional instruction with regards to fostering students’ conceptual understanding of basic optics concepts (medium effect size $d = 0.56$).

However, the findings of this study need to be substantiated further beyond the investigation of mere learning gains. For instance, it constitutes a research desideratum to date to clarify (a) which widespread learning difficulties may indeed be circumvented efficiently in phenomenological optics teaching or (b) which new learning difficulties may arise among students in such learning settings (cf. [9]).

3. Research Question

In this contribution, we approach a clarification of the following research question: *Which learning difficulties regarding the basic optics concepts*

- *vision and brightness,*
- *refraction, and*
- *image formation by converging lenses*

Can be observed among students who have been introduced to optics following a phenomenological approach compared to students who have participated in traditional model-based instruction?

4. Methods

4.1. Study Design and Sample

We conducted a quasi-experimental field study to compare the conceptions of basic optics topics acquired by students introduced to optics via the Erlangen phenomenological teaching-learning sequence (intervention group, IG) with those acquired by students who participated in a traditional model-based teaching sequence (control group, CG). A detailed description of the interventions included in the control and intervention groups, respectively, is provided in Section 4.2. Participating teachers and their classes were randomly assigned to either the control or the intervention group. To ensure a standardised approach the participating teachers were briefed prior to the intervention. A pretest was conducted at the beginning of the study in order to check for differences regarding control and intervention group students' prior knowledge. The instrument used in our study is described in detail in Section 4.3. After the interventions, a posttest was conducted to examine the effects of the interventions on students' conceptions of basic optics concepts and to investigate differences in control and intervention group students' learning difficulties.

The sample comprised a total of $N = 189$ students from eight classes (grade 8) of German secondary schools. A detailed overview of the study sample is provided in Table 1.

Table 1. Overview of the study sample.

	Total Sample	**IG (Phenomenological Approach)**	**CG (Traditional Instruction)**
Students	189	89	100
Gender			
males	101	40	61
females	78	47	31
not specified	10	2	8
Teachers	7	3	4
Classes	8	4	4

Students' and teachers' participation in our study was voluntary and not financially recompensed. The students were also informed about the anonymity and the processing of their data and asked for their consent to participate.

4.2. Interventions

The intervention consisted of ten school lessons of 45 min for the control group (model-based traditional instruction) as well as the intervention group (phenomenological approach via the Erlangen teaching-learning sequence, cf. Section 2.3). The use of instructional design features such as media and formulated tasks was equaled in both interventions. The same introductory optics topics were covered in both interventions (process of vision, refraction, apparent depth, and image formation by the converging lens). However, the two interventions differed in terms of the approach taken to convey these optics concepts: While the students in the intervention group explored experiments with self-made liquid lenses following a phenomenological approach, namely the Erlangen teaching-learning sequence of introductory optics (cf. Section 2.3), in the control group the same experiments were conducted in the light ray realm using ray boxes and lenses. In Table 2, a summary of further differences and commonalities regarding the key ideas of both interventions is provided.

Table 2. Conceptual differences and commonalities regarding the key ideas of the two interventions used in this study (see [9]).

Phenomenological Approach to Optical Concepts (IG)	**Traditional Optics Teaching (CG)**
Process of vision as a key idea along the entire sequence.	The process of vision as an introductory topic.
Transmitter-receiver concept of vision.	Transmitter-receiver concept of vision.
Experimental exploration of apparent depth, refraction and image formation.	Model-based explanation of apparent depth, refraction and image formation using the ray model of light.
Experimental exploration of dependencies between object distance, image distance and focal length of a converging lens	Mathematical description of image formation using the thin lens formula.

4.3. Instrument

We used a concept inventory consisting of a total of ten two-tier single-choice items to explore students' conceptions of basic optics topics. The items of our instrument have been adapted from prior research into teaching and learning optics [62–65]. Cronbach's Alpha as a measure for our instrument's internal consistency has been found to be satisfactory ($\alpha = 0.74$). In tier one of each item, the students had to choose precisely one out of four answer options (for one item, only two answer options were provided). The distractors, i.e., the incorrect answer options, have been formulated based on widespread student conceptions of basic optics topics (see Section 2.1). In tier two, the students were asked to rate their confidence with the given answer on a five-point rating scale (1 = very confident, . . . , 5 = guessed). A point was assigned to the student if and only if (a) the correct answer option was chosen in tier one, and (b) the answer was given confidently or very confidently. This not only minimizes the effect of guessing but also allows for an investigation of students' conceptions as we will elaborate on further in Section 4.4. A total of ten points could be achieved in our concept inventory. In the study presented in this article, we made use of

1. the students' pretest scores to check for differences between control and intervention group students with respect to prior knowledge regarding introductory optics topics.
2. the combination of answer option chosen in tier one, and students' answer certainty provided in tier two in order to detect learning difficulties as explained in the data analysis Section 4.4.

Thematically, the instruments' items can be categorized into three domains as shown in Table 3.

Table 3. Description of content domains covered in the concept inventory used in this study and the corresponding items.

Domain		Descriptors	Items
1	Vision and brightness	Light propagation, visibility of objects, sender-emission-receiver concept	1, 2, 3, 4
2	Refraction and apparent depth	Apparent depth, definition of light refraction, distinction between refraction and reflection	5, 6, 7
3	Images by converging lenses	Real images by the converging lens, image size, brightness of images	8, 9, 10

With the items assigned to domain 1, *Vision and brightness*, we explore students' conceptions of the process of vision, including the visibility of objects and the sender-emission-receiver concept. A sample item for content domain 1 is provided in Table 4.

With the items assigned to domain 2, *Refraction and apparent depth*, we explore students' conceptions of the refraction of light. The main focus of this domain lies in the change of light propagation at a plane interface between two transparent media. Furthermore, the items address the differentiation between refraction and reflection. A sample item for content domain 2 is provided in Table 5.

Table 4. Item 2 of the test covering the visibility of objects (translated from [65] (p. 28)).

Item 2: Which of the following objects/animals can you see in a completely darkened room?				
☐ A glowing firefly.				
☐ A white sheet of paper.				
☐ A bicycle reflector.				
☐ The eyes of a cat.				
☐ Very sure	☐ Sure	☐ Undecided	☐ Unsure	☐ Guessed

Table 5. Item 7 of the test covering straight light paths, refraction and reflection (adopted from [63] (p. 28)).

Item 7: What can you say about the light path at the intersection form air to another transparent medium (e.g., glass or water)?				
☐ The light reaches to the middle of the other medium and makes it shine.				
☐ The light changes its direction as soon as it reaches the other medium.				
☐ The light only reaches the intersection and is absorbed there.				
☐ The light does not change its direction, it propagates in a straight line.				
☐ Very sure	☐ Sure	☐ Undecided	☐ Unsure	☐ Guessed

With the items assigned to domain 3, *Image formation by a converging lens*, the students are asked how the image of an object changes if the light source is moved, or if parts of the lens are covered by an aperture. A sample item for content domain 3 is provided in Table 6.

Table 6. Item 9 of the test covering the image of a half occluded lens (translated from [65] (p. 30)).

Item 9: In an experimental setting, a light bulb, a converging lens and a screen are set up in a way that an enlarged, reversed, sharp image of the filament can be seen. What happens if the lower half of the lens is covered?				
☐ The upper half of the image is cut off.				
☐ The lower half of the image is cut off.				
☐ The image becomes darker.				
☐ The image becomes smaller.				
☐ Very sure	☐ Sure	☐ Undecided	☐ Unsure	☐ Guessed

4.4. Data Analysis

Firstly, the students' pretest scores were assessed to check for potential differences in prior knowledge between control and intervention group students. Hence, we conducted an independent-samples t-test to check for statistical significance in the pretest scores of the control and the intervention group.

Secondly, the students' answer certainty provided in the items' second tiers (see Section 4.3) can be used to detect learning difficulties via the Certainty of Response Index (CRI) established by Hasan et al. [66]. The CRI of an answer option is given by the value of certainty that an answer option has been chosen with (1 = very confident, ..., 5 = guessed). For example, if an answer option has been selected very confidently (=1) 30 times and was guessed (= 5) 50 times, the average CRI of this answer option is calculated to

$$\langle \mathrm{CRI} \rangle = \frac{30 \cdot 1 + 50 \cdot 5}{50 + 30} = 3.5.$$

In other words, an answer option with a high average CRI indicates a tendency towards guessing and a low average CRI indicates a tendency towards confidence. Hasan et al. [66] used this coefficient to detect learning difficulties by analysing wrong answer options that were selected confidently (i.e., having an average CRI shifted towards the lower end of the scale) and this approach has further been supported, e.g., by Lemmer [67] and Leppavirta [68]. An overview of the resulting scheme to code answer options is provided in Table 7.

Table 7. Coding scheme for identifying learning difficulties using the average CRI (see [69]).

	High CRI ($\geq$3)	Low CRI ($\leq$3)
Correct Answer	Correct answer and high CRI *Lack of knowledge*	Correct Answer and low CRI *Knowledge of scientific concept*
Wrong Answer	Wrong answer and high CRI *Lack of knowledge*	Wrong answer and low CRI *Learning difficulty*

As highlighted in [69], cases can be constructed where apparent learning difficulties cannot be identified from the data using the average CRI alone. Thus, we further analyzed the relative number of confident (CRI = 2) and very confident (CRI = 1) responses for each wrong answer option as has been done in prior research (cf. [70]). We follow [69] by setting the threshold in this respect to 10% of the number of total respondents who must have chosen a wrong answer option (very) confidently in order for a striking learning difficulty to be identified.

Conversely, if only one participant selected a wrong answer option and did so very confidently, the average CRI of this option will be 1, indicating a learning difficulty according to Table 7 even though this answer pattern was only observed a single time. To account for this sensitivity for outliers, we only considered answer options that were selected (very) confidently by at least 5% of the participants.

In summary, in this study, learning difficulties were identified from student responses if at least one of the following two criteria applied:

1. At least 10% of the students selected a wrong answer option confidently or very confidently.
2. The average CRI of an answer option is below 3 and at least 5% of students selected this answer option confidently or very confidently.

It is noteworthy, that applying these criteria to the respondents' posttest data one cannot detect all student conceptions and learning difficulties of basic optics concepts apparent among learners. However, the criteria ensure that striking learning difficulties that several students encounter when being introduced to optics are identified—this procedure allows for contrasting the effect of the phenomenological approach with the one of traditional model-based instruction on students' conceptions. Further limitations that come along with the methods used in this study and possibilities to tackle them in future research are outlined in the limitations Section 7.1.

5. Results

5.1. General Overview

No systematic difference in the pretest scores was observed between the control ($m = 2.70$, SD = 2.02) and intervention group students ($m = 2.46$, SD = 1.56), as indicated by a t-test for independent samples ($t(169) = 0.86$, $p = 0.39$). Thus, it can be assumed that there was similar prior knowledge of introductory optics topics in both groups before the intervention. In the following, we therefore solely focus on the posttest results.

For each item and answer option of our concept inventory, the average CRI and the relative number of students who selected the answer option confidently or very confidently are presented in Table 8. The answer choices that, according to our criteria outlined in Section 4.4, can be considered indicators of striking learning difficulties among students in at least one of the groups are highlighted in red. In the following Section 5.2, we present the respective items and the learning difficulties identified in more detail and we discuss our findings in Section 6.

Table 8. Posttest response patterns for both intervention and control group students. Shown are the average CRI and the relative proportion of students who selected the respective answer option (very) confidently. Correct answer options are highlighted in green while answer options that may be regarded as indicators for striking learning difficulties among the students of at least one of the groups according to our criteria outlined in Section 4.4 are highlighted in red.

	Answer Option 1				**Answer Option 2**				**Answer Option 3**				**Answer Option 4**			
Item	**CRI**		**Relative #**		**CRI**		**Relative #**		**CRI**		**Relative #**		**CRI**		**Relative #**	
	IG	CG	IG	CG	IG	CG	IG	CG	IG	CG	IG	CG	IG	CG	IG	CG
1	2.00	2.57	3%	4%	1.37	1.50	95%	81%	-	-	-	-	-	-	-	-
2	1.81	1.71	79%	58%	-	3.00	0%	1%	3.00	1.88	0%	7%	2.00	2.06	3%	17%
3	2.40	2.18	45%	58%	3.00	3.40	0%	1%	3.67	3.71	0%	0%	2.84	2.40	9%	4%
4	3.14	2.78	3%	3%	-	3.50	0%	1%	3.70	3.60	3%	5%	2.42	2.19	44%	40%
5	1.92	2.10	62%	36%	2.64	3.67	7%	5%	3.00	3.39	0%	9%	2.50	3.83	1%	0%
6	2.67	3.33	5%	2%	2.25	2.12	40%	48%	3.00	5.00	1%	0%	2.68	2.33	13%	14%
7	3.33	3.11	1%	5%	2.00	2.41	55%	39%	3.83	3.83	1%	3%	2.09	2.63	8%	8%
8	1.97	2.52	60%	36%	3.33	3.83	1%	5%	4.50	3.73	0%	1%	2.80	2.87	1%	5%
9	2.74	3.19	8%	11%	3.36	3.00	3%	19%	1.88	3.00	41%	8%	2.33	3.00	3%	1%
10	2.86	3.36	3%	8%	1.72	3.43	69%	4%	2.75	2.79	1%	20%	1.67	3.43	4%	3%

5.2. *Exploration of Student Conceptions*

In this subsection, we apply the criteria defined in the data analysis Section 4.4 to identify learning difficulties based on students' response patterns in the items of the posttest used in our study (for a descriptive overview, see Table 8). While we

- provide a description of the answer choices that point to learning difficulties, and
- specify the differences and commonalities between students in the intervention and control groups with respect to these potential learning difficulties based on descriptive statistics,

We elaborate on the underlying learning difficulties (a) in light of prior research, and (b) with an eye toward the implications of our findings for (phenomenological) optics instruction in the discussion Section 6.

5.2.1. Vision in Complete Darkness

In item 2, the students had to chose between objects and animals that can be seen in the dark (cf. Table 4). Answer option 4 hints at a learning difficulty with a striking difference between intervention and control group students (cf. Figure 1): While 17% of the control group students have answered (very) confidently that cat eyes are visible in complete darkness (average CRI = 2.06), this was the case for only 3% of the intervention group students (average CRI = 2.00).

Furthermore, in the control group, 7% of students (very) confidently selected answer option 3, indicating that bicycle reflectors would be visible in complete darkness (average CRI = 1.88). In contrast, none of the intervention group students were of that opinion—this is further underlined by an average CRI = 3.00 (cf. Figure 1).

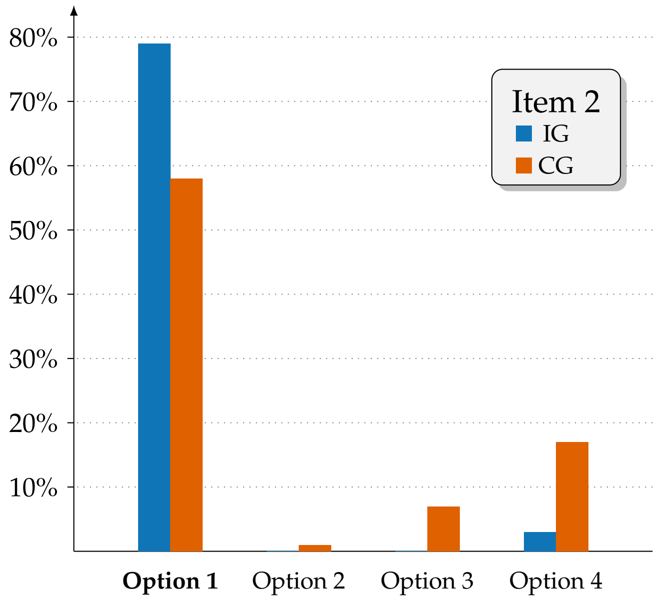

Figure 1. Relative frequencies of confident answers for item 2. The correct option is in bold font.

5.2.2. The Influence of Bright Walls on Overall Brightness

In item 3, the students were asked if dark or bright wallpapers would have an impact on the brightness in a room (cf. Table 9).

Table 9. Item 3 of the concept inventory (translated from [65] (p. 28)).

Item 3: Does it affect the brightness in a room whether it has bright or dark wallpaper?					
☐	Yes, because bright wallpapers scatter more light which than can fall into the eye, than a dark wallpaper.				
☐	No, because dark wallpapers do not change the brightness in a room.				
☐	Yes, because more light will remain lying on the bright wallpaper.				
☐	No, the brightness depends on the lamp in the room or the sunlight that falls through the window, not on the brightness of the wallpaper.				
	☐ Very sure	☐ Sure	☐ Undecided	☐ Unsure	☐ Guessed

A learning difficulty among intervention group students can be identified from answer option 4 in item 3: In the intervention group, the average CRI for this answer option was found to be 2.84 and 9% of the intervention group students have chosen this answer option (very) confidently stating that brightness in a room would only depend on the primary light source (cf. Figure 2). In contrast, only 4% of the control group students were (very) certain that this would be the case (average CRI = 2.40).

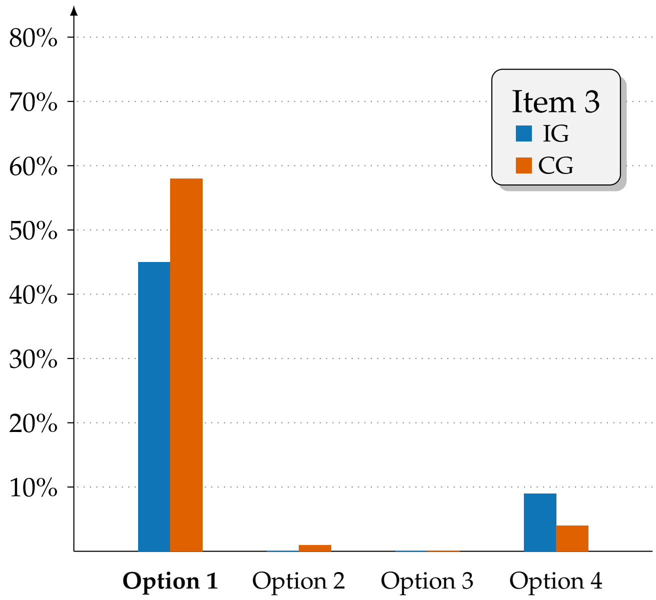

Figure 2. Relative frequencies of confident answers for item 3. The correct option is in bold font.

5.2.3. Refraction versus Reflection

In item 5, the students were asked to provide their understanding of the term *light refraction* (cf. Table 10).

Table 10. Item 5 of the concept inventory (translated from [62]).

Item 5: Please select what you understand by refraction of light.				
☐ Change of direction of the light path when light reaches another transparent medium.				
☐ Change of direction of the light path when light reaches a non-transparent medium.				
☐ Change of direction of the light path when light is redirected at a mirror.				
☐ Propagation of light without a change of direction of the light path.				
☐ Very sure	☐ Sure	☐ Undecided	☐ Unsure	☐ Guessed

In the control group, 9% of the students (very) confidently have chosen answer option 3 (average CRI = 3.39), stating that refraction would be the change in the direction of the light propagation when the light is deflected at a mirror (cf. Figure 3)—in contrast, none of the intervention group students have chosen this answer option with (high) answer certainty (average CRI = 3.00). Accordingly, the correct answer option 1 was selected (very) confidently by 62% of students in the intervention group in the posttest, but only by 36% of the students in the control group.

This observation is closely related to the observed answer pattern in item 6 where refraction and reflection were addressed as well. In item 6, the participants were given a picture of the corner of an aquarium. In the picture an orange and a silver fish could be seen through both glass walls of the aquarium alongside some black fish. The students were then asked to choose between one of four statements (cf. Table 11).

Based on the student answers to option 4 in item 6, we identify a learning difficulty which seems to be apparent among learners from both groups: It was selected with (high) certainty by 13% of the intervention group (average CRI = 2.68) and by 14% of the control group students (average CRI = 2.33), respectively (cf. Figure 3). This indicates that the a substantial part of the students in both groups tend to mix up the concepts of refraction and reflection erroneously as we elaborate on in more detail in the discussion

Section 6. Accordingly, the proportion of correct answers (answer option 2) given with (high) confidence is similar in both groups (40% in the IG and 48% in the CG).

Table 11. Item 6 of the concept inventory (translated from [62]).

Item 6: You want to count the number of fishes in the aquarium [picture shown to students]. Which statement do you agree with?				
☐ In the aquarium are two orange, two silver and some black fish.				
☐ The refraction at the edge of the aquarium is deceiving. In reality there are only one orange, one silver and some black fish.				
☐ In the aquarium are four orange fish, but because of refraction you can see only two.				
☐ The orange fish is reflected on the wall of the aquarium, that is why it looks like there are two orange fish.				
☐ Very sure	☐ Sure	☐ Undecided	☐ Unsure	☐ Guessed

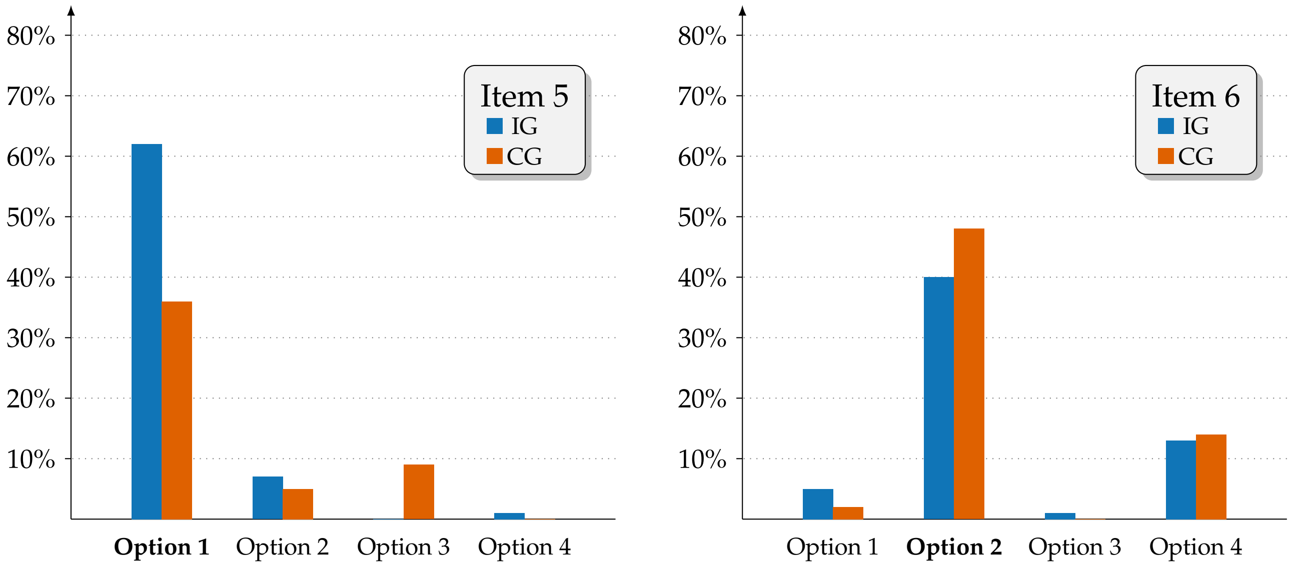

Figure 3. Relative frequencies of confident answers for items 5 (**left**) and 6 (**right**). The correct options are in bold font.

The above difficulty is further underpinned by the response patterns to item 7 (see Table 5): 8% of the students in both groups (very) confidently chose answer option 4 (cf. Figure 4), which states that the light would not change direction at the interface between air and another transparent medium such as glass or water. The average CRI for this answer option has been found to be 2.09 in the intervention group and 2.63 in the control group.

In this item, however, we still observe a striking difference between intervention and control group students regarding the correct answer option 2: While 39% of the control group students are (very) certain that light changes its direction at the intersection between two transparent media, even 55% of the intervention group students are (very) certain that this is true.

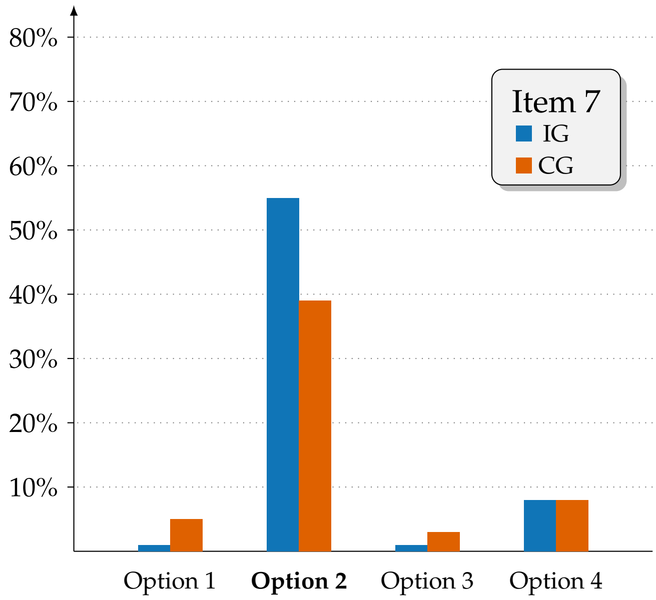

Figure 4. Relative frequencies of confident answers for item 7. The correct option is in bold font.

5.2.4. Image Formation by Converging Lenses

The most pronounced differences between the learning difficulties encountered by intervention and control group students can be observed from items 9 and 10 of the concept inventory addressing image formation by converging lenses: In item 9 (cf. Table 6), 11% of participants in the control group have chosen answer option 1 with (high) certainty stating that the upper half of the image is cut off if the lower half of the lens is covered (average CRI = 3.19). The same is true for 8% of the intervention group students (average CRI = 2.74). In addition, 19% of the control group students answered (very) confidently that the lower half of the image is cut off when the lower half of the lens is covered (average CRI = 3.00), while only 3% of the intervention group students chose this response option with (high) confidence (average CRI = 3.36). The differences between intervention and control group students are further substantiated analysing the proportion of students who have chosen the correct answer option 3 which states that the image becomes darker if the lower half of the lens is covered: While 41% of the intervention group students chose this response option with (high) certainty (average CRI = 1.88), this is the case for only 8% of the control group students (average CRI = 3.00). Figure 5 provides a graphical summary of these observations and the students responses to item 10 (cf. Table 12) substantiate them even further.

Table 12. Item 10 of the test covering the image of a half occluded lens (adpoted from [65] (p. 31)).

Item 10: In an experimental setting, a light bulb, a converging lens and a screen are set up in a way that an enlarged, reversed, sharp image of the filament can be seen. What happens if the the lens is covered by a cardboard with a small hole?				
☐ The image becomes smaller.				
☐ The image becomes darker.				
☐ The edges of the image are cut off circularly.				
☐ The image becomes brighter.				
☐ Very sure	☐ Sure	☐ Undecided	☐ Unsure	☐ Guessed

In item 10, 20% of participants in the control group have chosen answer option 3 with (high) certainty stating that the edges of an image are cut off circularly if the lens is covered by a cardboard with a small hole (average CRI = 2.79). The same is true for only 1% of the intervention group students (average CRI = 2.75). The difference between intervention and control group students are further substantiated analysing the proportion of students who have chosen the correct answer option 2 which states that the image becomes darker if the lens is covered by a cardboard with a small hole: While 69% of the intervention group students chose this response option with (high) certainty (average CRI = 1.72), this is the case for only 4% of the control group students (average CRI = 3.43). Again, a graphical summary of these results can be found in Figure 5.

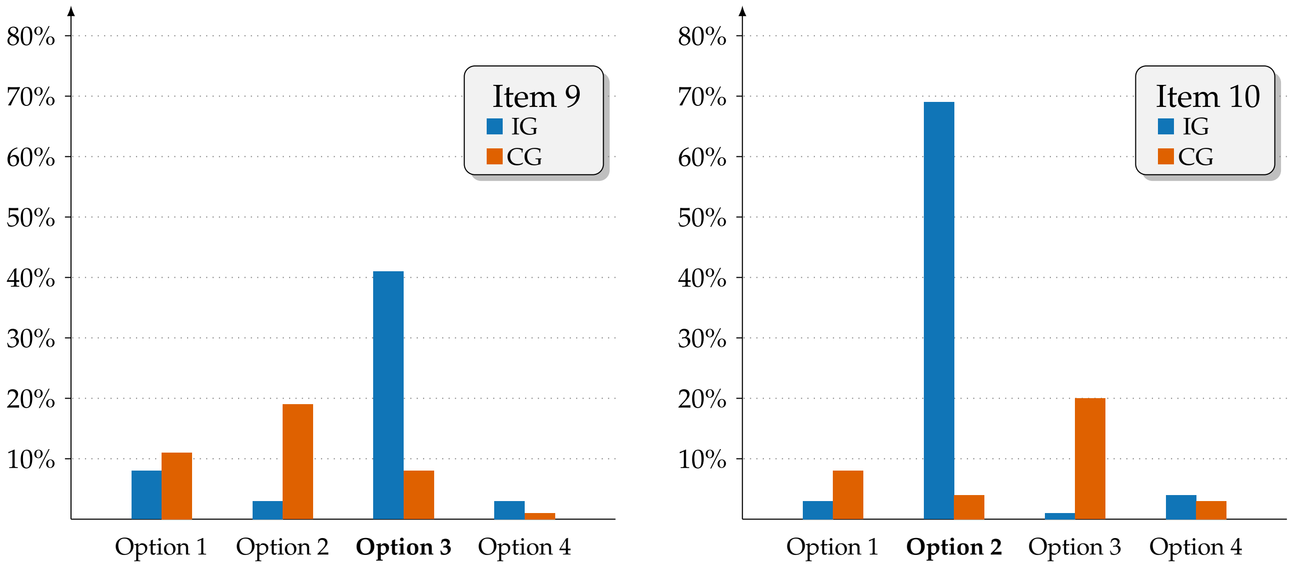

Figure 5. Relative frequencies of confident answers for items 9 (**left**) and 10 (**right**). The correct options are in bold font.

6. Discussion

Throughout Sections 5.2.1–5.2.4, we identified five learning difficulties encountered by a subset of the study participants which we address individually in the following. Table 13 provides an overview of the learning difficulties and how they can be categorized according to the content domains established earlier in this article (cf. Table 3).

Table 13. Overview over the learning difficulties found among the study participants from particular items of the concept inventory. The numbers in the IG and CG columns show the relative frequency of intervention and control group students, respectively, who chose that answer option confidently.

	Domain	Learning Difficulty	Item	Answer Option	IG	CG
1	Vision and Brightness	"Cat eyes can be seen in absolute darkness"	2	4	3%	17%
		"Illuminated objects do not send out light"	3	4	9%	4%
2	Refraction and apparent depth	"Refraction = Reflection"	5	3	0%	9%
			6	4	13%	14%
		Confusion about the concept of refraction	7	4	8%	8%
3	Images by converging lenses	"An aperture in front of a converging lens crops the image"	9	1	8%	11%
			9	2	3%	19%
			10	3	1%	20%

6.1. Learning Difficulties Regarding Vision and Brightness

6.1.1. "Cat Eyes Can Be Seen in Absolute Darkness"

The first learning difficulty is linked to item 2. Overall, 17% of the students in the control group confidently stated that cat eyes can be seen in complete darkness, with an average CRI of 2.06. This learning difficulty has been described in the literature as "seeing works without light" by Chu et al. [37]. While many students with this misconception can relate to seeing a cat in the darkness and noticing their seemingly glowing eyes, the students can not differ between the darkness they have experienced and absolute darkness, since absolute darkness is something one can hardly experience in everyday life. This learning difficulty is likely to be induced by a lack of differentiation between primary and secondary light sources (emitting senders and re-emitting senders, respectively). In the intervention group, only 3% of students gave the respective answer (very) confidently indicating the potential of phenomenological optics instruction following the Erlangen teaching-learning sequence to circumvent this misconception. This observation is underpinned by answer option 3 of item 2, as mentioned in Section 5.2.1: Here, 7% ($\langle \mathrm{CRI} \rangle = 1.88$) of the control group students confidently answered that bicycle reflectors can be seen in the dark while 0% of intervention group students did.

6.1.2. "Illuminated Objects Do Not Send Out Light"

The above described lack of differentiation between emitting senders and re-emitting senders also expresses itself in a further learning difficulty observed among a subset of our study participants: With an average CRI of 2.84, 9% of the students in the intervention group confidently stated that only emitting senders such as lamps or the sun would have an impact on the brightness in a room (item 3, answer option 4). In the control group, this was the case for only 4% of the students ($\langle \mathrm{CRI} \rangle = 2.40$). These students did not seem to understand that all objects serve as re-emitting senders when illuminated depending on their surface characteristics. Light and brightness are only noticeable for these students if an emitting sender is strongly luminous (cf. [12]).

6.2. Learning Difficulties Regarding Refraction

6.2.1. "Reflection = Refraction"

The answer pattern regarding item 5 substantiates findings from prior research, e.g., from [30,39]: 9% of the control group students confused reflection and refraction, stating that refraction of light is "the change of direction of the light path when light is redirected at a mirror" (item 5, answer option 3). The fact that none of the intervention group students selected this answer option suggests that the phenomenological approach following the Erlangen teaching-learning sequence might be superior to traditional model-based instruction when it comes to learning about refraction in early optics education.

However, in item 6, a share of roughly 14% in both groups struggled with transferring their knowledge about refraction to more practical questions: Hence, we conclude that in neither teaching approach the students' were protected from confusing refraction and reflection sufficiently.

6.2.2. General Confusion about the Concept of Refraction

The students' observed difficulties with light refraction can also be observed analysing the responses to item 7: Here, 8% of both, the control ($\langle \mathrm{CRI} \rangle = 2.63$) and intervention group students ($\langle \mathrm{CRI} \rangle = 2.09$) confidently stated that light does not change its direction but travels in a straight line at the intersection between air and another transparent medium. This is in line with findings from the literature: In the 2010 study by Keawkhong et al. [30], many students completely ignored refraction and would draw straight line paths across intersections of two different media. As this learning difficulty can be observed equally in both groups we further verify the above statement that neither teaching approach under investigation in this study seemed suitable in circumventing this misconception.

6.3. Learning Difficulties Regarding Images by Converging Lenses

The most pronounced learning difficulties were observed in the context of image formation by converging lenses. Prior research, e.g., by Goldberg et al. [31], Galili et al. [2] and Uwamahoro et al. [40], has shown that students exhibit a tendency to think the produced image will be cropped by an aperture before or behind the lens. We addressed this finding with the items 9 (cf. Table 6) and 10 (cf. Table 12) of our concept inventory.

In item 9, 8% of the intervention group and 11% of the control group students (very) confidently stated that covering the lower half of the lens leads to the upper half of the image being cut off. A more convincing difference in both groups is revealed with the second answer option, stating that the lower half of the image is being cut off. While only 3% of intervention group students selected this option (very) confidently a striking 19% of control group students did. Taken together, 11% of the intervention group students held the opinion that covering one half of the lens leads to the image being cut in half while 30% of control group students did.

This observation can be further substantiated with item 10 where 20% of the control group students (very) confidently stated that a lens being covered by a cardboard with a small hole leads to the edges of the image being cut off circularly. In the intervention group, however, only 1% selected this answer option with a high answer certainty, marking a huge difference in both teaching approaches. We conclude that (a) traditional model-based instruction focusing on the light ray realm exhibits a substantial lack regarding the topic of image formation by converging lenses, and that (b) the phenomenological approach following the Erlangen teaching-learning sequence of introductory optics seems to be a sensible alternative for early optics education which allows to tackle the observed misconceptions in a way that might be more conducive to student learning as has already been indicated in prior research (cf. [9]).

7. Conclusions

Taken together, the majority of the students participating in the phenomenological approach following the Erlangen teaching-learning sequence of introductory optics seem to have acquired conceptions of image formation by converging lenses that match the scientific views. In contrast, a significant proportion of the students participating in traditional model-based instruction seem to encounter various serious learning difficulties in this area. Hence, the Erlangen teaching-learning sequence seems to serve as a sensible alternative to traditional model-based teaching methods for early optics education—in particular regarding the topic of image formation by converging lenses. However, though finding several hints that the phenomenological approach also might be superior to traditional model-based instruction with regards to supporting students building coherent mental models regarding the process of vision or the concept of light refraction, the empirical evidence provided by the study presented in this article is heterogeneous overall. Hence, further research is needed to provide more empirical evidence (cf. Section 7.2). In particular, there are some limitations of our study that need to be tackled in future projects in order to confirm and extend the results reported in this article (cf. Section 7.1).

7.1. Limitations

The study presented in this article has some limitations that must be considered: Our study was conducted in a real school setting which leads to high external validity. However, a quasi-experimental design was used for our study due to organisational boundary conditions at the participating schools—this limits internal validity compared to an experimental study design (cf. [71]) where students are randomly assigned to experimental groups leading to a balancing of person-specific variables potentially influencing the study results, such as students' subject-specific interest [72]. In our study sample, we observe an asymmetric gender distribution between the intervention and control groups: While around two-thirds of the students in the control group were males, the gender distribution in the intervention group was about equal. Such systematic differences may impact the findings described in this paper and further research is needed in this respect.

Another limitation of this study relates to the chosen methodology: In order to enable a comprehensive and robust comparison of learning difficulties of students who were introduced to optics either following traditional model-based instruction or a phenomenological approach via the Erlangen teaching-learning sequence, we aimed for a large sample. To meet this requirement, we sought, on the one hand, a data collection method that met the established quality criteria of empirical research. On the other hand, we intended to collect data in a way that was compatible with the limited time constraints of regular school settings. Therefore, we have used a concept inventory consisting of ten two-tier single-choice items adopted from the literature to explore students' conceptions of basic optics topics prior and post the interventions because the administration of this test only required very little extra time. To ensure that widespread learning difficulties regarding basic optics topics could be detected with this instrument, the items' distractors have carefully been formulated based on a comprehensive review of the literature (cf. Section 2.1) or have been adopted from earlier studies. However, of course, the instrument does still not cover all conceivable learning difficulties—this is an important limitation of our study. In addition, one must be aware that the closed answer format may influence students' answers: For example, if none of the answer options fit to participant's natural reaction (cf. [73]). To tackle these limitations in future research a transition to qualitative research seems sensible: The obvious solution would be to conduct interviews with students who had participated in either traditional model-based instruction or a phenomenological approach before. However, note that interview questions themselves "can awaken mental connections in the respondent that would not have been expressed without prior input" [74] (p. 2). Therefore, we believe that asking study participants to create mind maps or concept maps of optics concepts under investigation might be more edifying with regards to getting in-depth insights into student thinking (cf. [75]).

Finally, it is noteworthy that the results obtained in this study should not be treated independent from the specific interventions that we have implemented. In particular, differences and similarities observed regarding learning difficulties apparent among students who have been introduced to optics following either the Erlangen teaching-learning sequence of introductory optics (phenomenological approach) or traditional model-based instruction may not be transferred to phenomenological optics education in general without further ado.

7.2. Outlook

As already mentioned in Section 7.1, the transition to qualitative research might add value to the results presented in this paper, for example conducting an interview study or applying the mind map method to delve deeper into student thinking about basic optics concepts. In this way, further insights into teaching and learning basic optics concepts following phenomenological approaches in early physics education can be obtained.

In order to favour the implementation of the Erlangen teaching-learning sequence in physics education at secondary schools, the incorporation of practitioners' feedback might be of value in order to be able to address the teachers' needs in a revised version of the teaching concept (cf. [76]): Hence, we suggest to conduct a survey of physics teachers' practical experiences with this phenomenological teaching concept in the future.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study to publish this paper.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

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