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The World through My Eyes: Fostering Students' Understanding of Basic Optics Concepts Related to Vision and Image Formation

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Abstract: Prior research has shown that many secondary school students have a insufficient conceptual understanding of basic optics concepts even after formal instruction. In this paper, we empirically investigate whether a phenomenological approach might be a sensible alternative to traditional model-based instruction of introductory optics in early physics education. We report the results of a quasi-experimental field study to examine the effect of a phenomenological approach following the Erlangen teaching–learning sequence of introductory optics on $N = 42$ eight graders' acquisition of conceptual understanding related to (1) the process of vision, (2) refraction, and (3) image formation by converging lenses. We contrast the learning outcomes with those of $N = 55$ control group students who participated in traditional model-based instruction. The results of this study indicate that the phenomenological approach is superior to traditional (model-based) instruction in promoting students' conceptual understanding of basic optics concepts, in particular with regard to circumventing widespread learning difficulties related to image formation. Our results are further substantiated by a comparison of students' situational interest in optics between both groups. This adds further arguments in favor of the use of phenomenological approaches when it comes to teaching basic optics concepts in classroom practice.

Keywords: optics; vision; image formation; secondary school; phenomenology

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1. Introduction

Optics is a key element of physics education at the secondary school level. Topics in early secondary school education range from the observation of shadow phenomena and refraction to image formation by converging lenses. In traditional classroom teaching, it is common practice to introduce students to optics topics based on the ray model of light, e.g., in order to construct the image of an object (see Section 2.1). This model-based approach poses some well-researched learning difficulties that impede students' learning of introductory optics topics (see Section 2.2), e.g., because light rays are erroneously assigned a haptic ontology [1,2]. Phenomenological approaches provide a promising alternative to model-based instruction of introductory optics (see Section 2.3) since many authors regard these fruitful to (a) circumvent widespread learning difficulties and (b) foster students' interest in science topics (see Section 2.5). In this paper, we introduce a teaching–learning sequence that allows for a phenomenological approach to optics topics in early secondary school physics education (see Section 2.4). From Section 3 onward, we report and discuss the results of a quasi-experimental study comparing the effect of this phenomenological approach on students' conceptual understanding of introductory optics topics with traditional model-based instruction.

2. Research Background

2.1. Optics in Early Physics Education

The teaching of optics in early secondary school is confined chiefly to the field of geometrical optics [3]. The key tool for describing and explaining a wide variety of optical phenomena is the ray model of light, which enables geometric constructions, e.g., in the context of image formation: students learn about ray constructions, for example, in order to predict experimental results or to explain optical phenomena (see [4]).

In many school textbooks, a distinction is made between artificial and natural light sources, which "does not contribute to the understanding of the process of vision and [. . .] creates additional cognitive complexity" ([5], p. 12). However, traditional introductory optics instruction does not place sufficient emphasis on the process of vision [5], which is a crucial aspect of learning optics: for example, previous research has shown that an understanding of the process of vision can be considered a necessary prerequisite for developing a conceptual understanding of further optics topics [3,6].

In the course of traditional optics lessons, aspects such as reflection or refraction and image formation are treated based on the ray model of light (see [5]). Abstract representations are often complemented by formalization: for example, students are introduced to the lens equation. Prior research has questioned this tradition of introducing students to optics: for example, traditional optics instruction has been referred to as optics "for the blindman" (translated from [7], p. 2).

2.2. Widespread Learning Difficulties in Introductory Optics: A Brief Overview

Optical phenomena are omnipresent in students' everyday lives. Hence, teachers are confronted with a multitude of misconceptions about

- the process of vision (see [8–10]),
- the properties of light (see [4,11,12]),
- light propagation (see [13]),
- refraction (see [14,15]),
- image formation (see [4,13,15–19]),

even after formal instruction [4]. In the following, we provide more detailed insights into widespread learning difficulties regarding the process of vision (see Section 2.2.1) and image formation by converging lenses (see Section 2.2.2).

2.2.1. Learning Difficulties Regarding the Process of Vision

Regarding the process of vision, the notion of an active eye scanning objects has been repeatedly documented in previous research, see [8,20]. This conception is supported by expressions such as "looking at" or "casting a glance at something", which emphasize the activity of the eye in human vision ([4], p. 59). In addition, it was found that some students do not know that all objects are invisible in a completely darkened room. The reason for such ideas resides in the students' thinking that light had substance-like properties and filled the space around light sources: consequently, many students who possess the above-mentioned conception believe that objects appear bright because the light is incident onto them and then "stays" on them, while disregarding the concept of light scattering. It has further been shown that students believe that light of low intensity, in general, does not reach the human eye at all [21].

2.2.2. Learning Difficulties Regarding Image Formation by Converging Lenses

The variety of learning obstacles related to the properties of light (see [4,11,12]), light propagation (see [13]), and refraction (see [14,15]) consequently results in numerous learning difficulties on the topic of image formation (see [4,13,15–19]). For example, many students assume that the image of an object travels through the lens as a whole, while the underlying principle of point-to-point-imagining remains unheeded [4]. As a consequence, many students with the above difficulty postulate that

- the image would be cropped at the edges if the diameter of a lens is smaller than the object under investigation (see [22]),
- the diameter of the lens influences the image size (see [23]), or
- covering half of the lens would make half of the image disappear (see [24]).

Accordingly, the use of apertures is thought to decrease the size of the image [25]. Lastly, the left-right reversal of the image often remains unnoticed: many students only are aware of a reversal of top and bottom when being asked ([4], p. 72) while not having in mind that the image represents a point inversion of the object. Many of the above-mentioned difficulties are probably caused by abstracting too early in introductory optics classes since prior research has indicated that

- the introduction of the ray model of light (and corresponding ray diagrams) from the beginning, and
- the focus on a mathematical description at too early a stage of teaching

often results in students struggling with different optics concepts. For instance, refraction and reflection become blurred for many students ([20], p. 280). As a result, reflection is claimed to be the reason for image formation by converging lenses, rather than students recognizing refraction as a possible cause [3].

A common difficulty for students is that the model character of light rays does not become obvious. Thus, students often mistakenly assign haptic ontology to light rays [1]. The subsequent introduction of wave or particle models of light in physics classes is likely to result in hybrid models among learners as a result [26]. Given the above, it hardly seems surprising that students often have a poor conceptual understanding of optics topics despite formal instruction. Therefore, alternative approaches to introducing optics to youngsters in early secondary education taking into account the above-mentioned difficulties have been published (see [5]). In particular, some authors have even proposed (mainly) model-free approaches in which models of light "are almost entirely replaced by the precise observation of images, the optical phenomena themselves" ([27], p. 2). A known representative of such phenomenological teaching concepts on optics is *An Optics of Visual Experience* by Maier [28,29].

2.3. Phenomenological Approaches in Science Education

The meaning of the term "phenomenological approach" in teaching contexts is broad and its use is heterogeneous. The description of open-ended, preconceptual, and phenomenon - oriented science teaching unifies all ideas about this term [30]. Phenomenological approaches relate learning directly to the observation and analysis of phenomena: "Phenomenology [. . .] emphasises 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" ([31], p.4).

Phenomenological approaches have a long tradition and represent a possible response to widespread problems in science education: proponents of phenomenological teaching often demand more time for (1) observations, descriptions, or reflections on what students have experienced and (2) subsequent discussions of students' various interpretations [30]. It is criticized that traditional teaching in science subjects, especially in physics, often mainly leads to reproduced technical language or formulas, conceptual misunderstandings (especially with regard to models), or reduced sensitivity to natural phenomena [30]. In contrast, in phenomenological approaches, teaching is based on asking questions, considering all possible answers formulated by the students, and carefully perceiving phenomena. Phenomenological approaches have been pursued for a long time. For example, already Wagenschein [32] (see English translation [33]) demanded phenomena to stand at the beginning of learning science, unimpeded by technical language, mathematization, or models.

From the pedagogical point of view, a step-by-step abstraction only makes sense if the preceding results are sufficiently well-founded [32,33]. In this context, it is noteworthy that phenomenological and model-based instruction are not mutually exclusive: Instead, in the course of teaching "the teacher can move along that continuum, guiding students from exploratory to more theory-laden experiments, from inductive to deductive reasoning, from descriptive to explanatory modeling, and from their everyday world to the world of physics. Thus, physics instruction may be phenomenon-*based* and model-*oriented*" [34] (p. 8).

In the context of teaching and learning optics, prime examples for the use of phenomenological ideas can be found and the essentials of phenomenological teaching approaches can easily be understood considering optics teaching (see [27–29,35]). Grebe-Ellis, an author of key contributions to this field [7,36], sees a break in the explanation of phenomena in traditional classroom instruction, e.g., by means of light rays that are deflected, reflected, or scattered. The students see "no refraction of rays, but bending shadow edges" (translated from [36], p. 155). Phenomenological optics, in contrast, is guided by questions such as "what do we see?" and "what are the conditions for what we see?". Hence, despite the phenomenon being at the center of the lesson, phenomenological approaches also enable us to link theory and practice in science education [37]. In particular, it has been shown that "phenomenology and science education meet most fruitfully when phenomenology is *done*, when it is turned into actual efforts for understanding and promoting learning" ([30], p. 115).

The use of phenomenology in teaching practice seems particularly natural in the context of optics. In Section 2.4, we present a phenomenological teaching–learning sequence for introductory optics in which learners explore phenomena in optics in a hands-on way, and which aims to circumvent learning difficulties that are widespread among students who have participated in (model-based) traditional teaching (see Section 2.2).

2.4. A Phenomenological Approach to Introductory Optics: The Erlangen Teaching–Learning Sequence

The "Erlangen teaching–learning sequence of introductory optics" [27] is a phenomenological teaching concept developed for introductory optics education in secondary school (grade 7/8, depending on national curricula). The teaching concept can be taught in at least ten school lessons of 45 min or five lessons of 90 min and is divided into four chapters: (i) Vision and brightness, (ii) Refraction and apparent depth, (iii) The look through a prism, and (iv) The images of a converging lens. A detailed overview of the teaching–learning sequence is provided in [27]. Hence, we only sketch the key ideas in the following.

2.4.1. Vision and Brightness

The pupils are introduced to optics by the distinction between optical and haptic perceptions of the human senses. They become aware that the visual and the tactile sense do not always coincide. The transmitter–emitter–receiver concept is established to explain the visual process [5] based on this: on the one hand, the students learn to distinguish two different sources of light (emitting sender and re-emitting sender). On the other hand, "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" ([27], p. 6). In addition, the students realize "that brightness varies as they move through the room" ([27], p. 5) and "the conditions that make a surface appear bright and in a certain colour to us are discussed" ([27], p. 6).

2.4.2. Refraction and Apparent Depth

The second chapter focuses on the principle of light refraction. The students approach this topic by performing experiments on apparent depth: they observe a coin in a basin of water by means of a straw, which they place obliquely on the edge. Pushing a skewer through the straw the coin is not hit. In this way, the pupils derive further evidence of the discrepancy between visual and tactile space. The explanation for what has been observed can be summarized using the principle of light refraction: for this purpose, the students observe the kink shadow on the boundary surface of an aquarium. Finally, they formulate preconditions for the occurrence of the optical phenomenon of light refraction.

The explanation for what is seen is summarized in the principle of light refraction. For this purpose, the pupils observe the bending shadow at the boundary surface of an aquarium. Finally, they formulate requirements for the optical phenomenon of light refraction to occur.

2.4.3. The Look Through a Prism

In this chapter, the students build water prisms themselves using overhead film and a glass slide. A description of how to build these water prisms can be found in [27]. Looking through the water prisms held at different distances and different observation angles from an object, the pupils recognize a shift in the image of varying magnitude. In partner work, two oppositely oriented prisms are put together—this constellation paves the way towards the introduction of the converging lens in the last chapter of the teaching–learning sequence.

2.4.4. The Images of Converging Lens

At the beginning of this last chapter, the students produce their own self-made optics inventory according to craft instructions provided by [27]—hands-on from low-cost everyday materials. Among others, they fabricate self-made liquid lenses, apertures, and optical benches made from a cable duct [27,38].

In a first exploration, the students take a look through their self-made lenses slowly varying object distance. In this way, the students anticipate principles underlying image formation by the converging lens. As is common in phenomenological teaching concepts, the transition from the experimenter's being part of the experiment (students' view through the lens) to the experiment being detached from the experimenter is made subsequently: "the students are asked to map a sharp image of the sender that is (a) in original size, (b) enlarged and, lastly, (c) downsized" ([27], p. 9) and the experimental results may be used to derive that "an object width g is always coupled with a certain image width b in order to get a sharp image" ([27], p. 9). In the following, the students produce and use different apertures to investigate the relations between object, lens, and image and to further elaborate on the conditions, under which sharp and bright images can be observed on the screen. Finally, the connection is made to the introduction of the process of vision discussed in chapter one: using a self-made lens with variable curvature according to the proposal of [39], the eye's accommodation is explored. This brings us full circle to the introduction of the Erlangen teaching–learning sequence of introductory optics.

In summary, the Erlangen teaching–learning sequence of introductory optics is a hands-on phenomenological approach aimed at introductory physics education in secondary schools. As such, it meets the condition formulated in [30] according to which doing phenomenology is likely to be conducive to learning. The extent to which this (model-free) phenomenological teaching concept to optics actually implies stronger learning efficacy than traditional (model-based) instruction is empirically investigated in this paper (see Section 3 onward). However, despite fostering students' understanding of introductory optics the hands-on approach also seems promising in terms of fostering students' situational interest in science in general, and in optics in particular. We elaborate more on this in Section 2.5 just below.

2.5. Situational Interest

For the situational interest, we follow Ref. [40] and conceive it as a "short term preference which can be generated by particular conditions such as a demonstration of a discrepant event or a novel hands-on experiment"([40], p. 2153). Situational interest has already been researched extensively and three key statements have emerged from this research: first, situational interest shows a positive correlation with students' attention. Second, it is positively correlated with learning outcomes in general, and third, students' situational interest is influenced by a variety of different factors, e.g., students' prior knowledge in a given domain, see [41].

A number of authors have already observed high situational interest in a given topic among students who have learned within learning environments that foster students' experience of autonomy, e.g., by providing students with choices and control over their work [42]. Palmer [43] showed that students' situational interest was higher when they were involved in the observation, performance, and explanation phases of experimentation. Furthermore, hands-on experiments have been found likely to lead to a high situational interest in a topic under investigation among students [40,43]. The findings from Blankenburg [44] and Swarat [45] further support these results, since both authors have found higher situational interest among students who worked on hands-on experiments. The question remains as to whether or not a phenomenological approach to introductory optics according to the Erlangen teaching–learning sequence may lead to a higher situational interest in optics among students than traditional instruction (see Section 3).

3. Research Questions

The purpose of this study is to examine the extent, to which a phenomenological (model-free) approach to introductory optics in early secondary school physics following the Erlangen teaching–learning sequence, can help (1) improve students' conceptual understanding of introductory optics topics and (2) lead to a higher situational interest in optics compared to traditional (model-based) instruction. Hence, in this study, we approach a clarification of the following research questions (RQs):

RQ1: How does the phenomenological teaching approach to introductory optics affect students' situational interest in optics compared to traditional instruction?

RQ2: Which differences appear in students' learning gains regarding the conceptual understanding of introductory optics topics, namely:

(a) the process of vision,
(b) refraction and apparent depth, and
(c) image formation,

when comparing the phenomenological teaching approach and traditional instruction in German secondary schools?

4. Methods

4.1. Study Design and Sample

We conducted a field study aimed at contrasting the effect of the phenomenological approach via the Erlangen teaching–learning sequence (intervention group, IG) on student learning of introductory optics in early physics education in secondary schools in Germany with that of the model-based traditional instruction (control group, CG). A detailed description and comparison of the intervention in both groups is provided in Section 4.2. The study took place in the natural school setting to optimize the transferability of the empirical findings to classroom practice. Therefore, we opted for cluster randomization [46], meaning that whole school classes were randomly assigned to either the intervention group (phenomenological approach) or the control group (traditional instruction). The classes were taught by their regular teachers. The teachers were briefed prior to the study to ensure a standardized approach. The study followed a pre–post test design to analyze learners' (a) situational interest (for the scale used in this study see Section 4.3.1), and (b) conceptual understanding of optics (for the instrument see Section 4.3.2), in IG and CG at pre-test, and post-test points in time (see Figure 1).

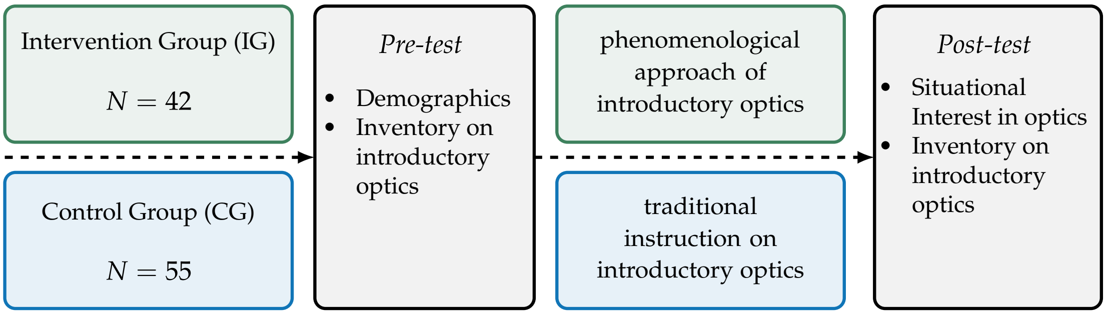

Figure 1. Overview of the study design. For a detailed description of all scales, see Section 4.2.

The sample comprised a total of $N = 97$ eight graders from four classes of German secondary schools. A detailed overview of the study sample in terms of IG and CG is given in Table 1.

Table 1. Overview of the study sample. See text for detils.

	Total Sample	Intervention Group (IG) (Phenomenological Approach)	Control Group (CG) (Traditional Instruction)
Students	97	42	55
Teachers	3	2	1
Classes	4	2	2
Gender			
males	51	19	32
females	40	22	18
not specified	6	1	5

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 interventions in both IG (phenomenological approach according to Erlangen teaching–learning sequence; for a description, see Section 2.2) and CG (model-based traditional instruction) comprised a total of ten school lessons (45 min each). In both interventions, the same introductory optics topics were covered: vision, refraction, apparent depth, and image formation by the converging lens—hence, the interventions did not differ in terms of content. In addition, design features such as the use of media and the way tasks are formulated were kept constant in order to highlight the difference between the model-based and phenomenological approaches.

However, of course, the two interventions examined in our study differ with regards to the approach taken to introduce students to the topics covered: the Erlangen teaching–learning sequence of introductory optics used in the IG follows a (mainly model-free) phenomenological approach. In contrast, traditional instruction is based on an early use of the ray model of light and corresponding geometrical and mathematical abstractions, e.g., based on students completing hands-on experiments using ray boxes and lenses.

While the visual process in traditional teaching is usually only used as an introduction, in the phenomenological teaching concept it is at the core of teaching optics. Still, the transmitter–receiver concept for explaining human vision may be regarded as the conceptual interface between the two approaches. Table 2 provides a summary of the differences between and similarities of the two interventions used in IG and CG.

Table 2. Conceptual differences between and similarities of the two interventions used in this study.

Phenomenological Approach to Optical Concepts, IG	**Traditional Optics Teaching, CG**
Consistent treatment of the process of vision along the entire sequence.	The process of vision as an introductory topic.
Transmitter–receiver concept of vision.	Transmitter–receiver concept of vision.
Model-free treatment of apparent depth, refraction, and image formation.	Use of the ray model of light for the explanation of light refraction and for geometrical construction of image positions.
Experimental determination of dependencies between object width, image width, and focal length of a converging lens	Mathematical description of image formation using the thin lens formula.

4.3. Instrument

The questionnaire completed by the students consisted of two parts, P1 and P2:

P1: Scale to assess students' situational interest in optics (only post-test); for details, see Section 4.3.1.

P2: Concept inventory to assess students' conceptual understanding of introductory optics topics (pre-test and post-test); for details, see Section 4.3.2.

4.3.1. Assessment of Students' Situational Interest

We adopted a 5-point rating scale (1 denotes the lowest trait level, 5 denotes the highest trait level) comprising nine items to assess students' situational (optics) interest from [47]. A sample item of the scale reads: "I would like to learn more about optics". Cronbach's alpha [48] serves as a measure for the scale's internal consistency and was found to be $\alpha = 0.90$ in this study, where values above 0.7 are considered acceptable (cf. [49]).

4.3.2. Assessment of Students' Conceptual Understanding of Introductory Optics

We used a concept inventory consisting of a total of 15 two-tier single-choice items to assess students' conceptual understanding of introductory optics topics. The items used in this study have been adapted from the literature [47,50,51] and have already been used in prior empirical research into teaching and learning introductory optics.

For each item, the students are asked to choose exactly one out of four answer options in tier one. Furthermore, the students are asked to rate their confidence in the given answer on a 5-point rating scale (1 reserved for "guessed", . . ., 5 for "very confident"). A point is awarded to the respondent for a specific test item if and only if (a) the correct answer option was chosen in tier one and (b) the answer was given with confidence, meaning that 4 or 5 had to be marked on the rating scale in tier two. This coding scheme ensures to minimize the effect of guessing [52–55], and hence, is "useful for gauging the quality of students' understanding" ([55], p. 3). Cronbach's alpha as a measure for internal consistency has been found to be satisfactory ($\alpha = 0.71$).

In terms of content, the items of the concept inventory are arranged in three content 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. See text for details.

Domain	Descriptors	Items
Process of vision	Light propagation, visibility of objects, sender-emission-receiver-concept, shadow.	1, 2, 3, 4, 14, 15
Refraction and apparent depth	Apparent depth, definition of light refraction, distinction between refraction and reflection.	5, 6, 7, 8, 9
Image formation by a converging lens	Real images of the converging lens, image size, brightness of images.	10, 11, 12, 13

The items corresponding to the content of domain 1 (Process of vision) address the visual process and focus on light propagation. In addition, different light sources are dealt with, especially with respect to a distinction between emitting and re-emitting senders. The last item of this domain covers shadow formation. A sample item for content domain 1 is shown in Table 4.

Table 4. Item 2 of the test covering the visual process (see Table 3).

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

The items corresponding to content domain 2 (Refraction and apparent depth) deal with the topic of light refraction. The main focus of the items is on the change of light propagation at an interface. Moreover, the distinction between refraction and reflection is addressed. A sample item for content domain 2 is shown in Table 5.

Table 5. Item 9 of the test covering straight light paths, refraction, and reflection (see Table 3).

Item 9: Comment on the following statement of a classmate: I do not believe that light propagates in a straight line. If light falls obliquely on a water surface, its direction of propagation changes.
☐ I agree with the classmate. Light does not propagate in a straight line.
☐ I do not agree with the classmate. When light hits a water surface, it is reflected.
☐ I agree with the classmate. When light hits a water surface, it always passes through in a straight line.
☐ I do not agree with the student. The light is refracted at the water surface, but then it propagates in a straight line again.
☐ Very sure ☐ Sure ☐ Undecided ☐ Unsure ☐ Guessed

The items corresponding to content domain 3 (Image formation by a converging lens) are used to examine students' understanding of image formation using converging lenses. In particular, students are asked to what extent the image of an object changes when the lens aperture changes or part of the lens is occluded. A sample item for content domain 3 is shown in Table 6.

Table 6. Item 10 of the test covering the real image of a converging lens (see Table 3).

Item 10: What can you say about the image of an object produced by a converging lens on a screen?				
☐ The image is upside down and side-inverted.				
☐ The image is upright and real.				
☐ The image is upside down and black and white.				
☐ The image is upright and in color.				
☐ Very sure	☐ Sure	☐ Undecided	☐ Unsure	☐ Guessed

4.4. Data Analysis

We provide an overview of IG and CG students' situational interest and conceptual understanding of introductory optics topics for both pre- and post-test points in time, using descriptive statistics such as median, mean value μ, and standard deviation (SD). We calculate non-parametric Mann–Whitney U-tests to test differences between IG and CG students for statistical significance (for our research questions, see Section 3) due to deviations of our data from a normal distribution. These nonparametric tests perform at up to 95% of the test power of their parametric equivalents [56]. We report the Mann–Whitney U-test statistics according to the APA (American Psychological Association) standards as

$$U(N) = (U, z, p),$$

where U is the test-statistic, N is the number of observations, z is the z-score, and p is the p-value; for details, see Ref. [57]. Each effect is considered statistically significant when the p-value was below the 5% threshold, while p-values below the 10% threshold indicate statistical significance by trend. We also report the effect of size measure in terms of the biserial rank correlation, r, to judge the magnitude of statistically significant effects. Note that for all statistics applied to our data, we only used data from those students who completed all items of the corresponding instrument or scale, respectively.

In addition, we use Hake's g [58] calculated as

$$g = \frac{\text{postscore\%} - \text{prescore\%}}{1 - \text{prescore\%}}, \tag{1}$$

to compare IG and CG students' pre-test and post-test results [59] in the optics concept inventory. While the difference between post-test and pre-test scores does not provide a reliable measure for students' learning achievement at both ends of the scale, i.e., for high and low performers [60], Hake's normalized gain g is not biased by students' pre-test results, see [59]. The normalized gain g takes values below 1, while values of $0.30 \leq g \leq 0.70$ may be associated with a medium learning gain ([58], p. 65).

It is noteworthy that our study design, by including a cluster-randomized controlled trial, implies that students' learning process may be influenced by the social groups the students belong to. We calculated the intraclass correlation coefficient (ICC) to quantify the influence of students' aggregation in classes by the proportion of variance explained at the class level and found that only a small proportion of the variance is localized at the class level (ICC = 0.05). Since (1) the ICC lays well below the threshold of 0.10 ([61], p. 544) and (2) our sample only comprises two classes for intervention and control group, respectively, we have refrained from multilevel analysis for our study.

5. Results

5.1. Results regarding RQ1

The situational interest averaged $\mu = 3.58$ (SD = 0.84) with a median of 3.56 for the IG and $\mu = 2.82$ (SD = 0.90) with a median of 2.89 for the CG. A boxplot of the data is provided in Figure 2. The difference in both groups was further verified to be statistically highly significant by means of a Mann–Whitney U-test ($U(76) = 379$, $z = 4.10$, $p < 0.001$). The effect size $r = 0.47$ is regarded medium according to [62].

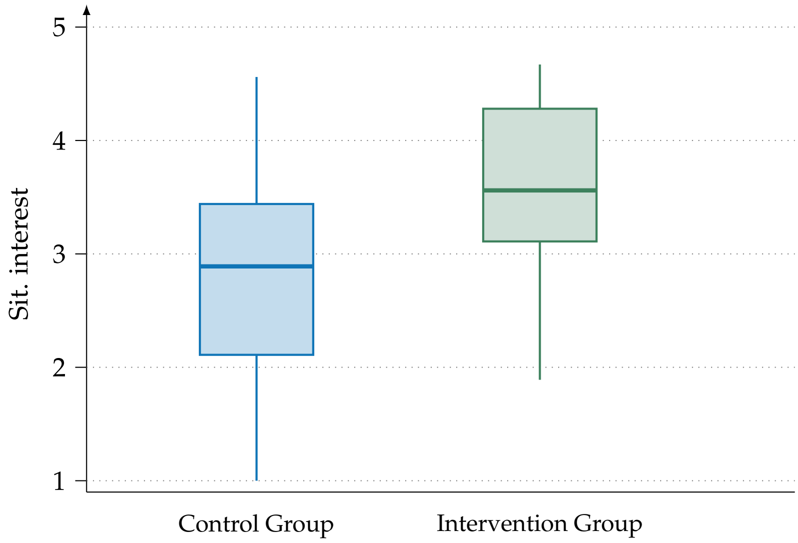

Figure 2. Boxplot of the situational interest for the intervention and control group (1 denotes the lowest trait level, 5 the highest trait level). The two minima indicate the lowest data points in the set and the maxima the highest. The boxes range from the 25th percentile to the 75th percentile while the horizontal line indicates the median.

5.2. Results regarding RQ2

The pre-test score averaged $\mu = 4.73$ for CG and $\mu = 4.24$ for IG, while the post-test score averaged $\mu = 6.62$ for CG and $\mu = 7.93$ for IG. A visualization of the change in μ for both groups is provided in Figure 3. The median pre-test and post-test scores are provided in Table 7 alongside the statistics of two Mann–Whitney U-tests confirming that (a) the groups' pre-test scores did not differ statistically significant ($p = 0.47$) and (b) there is a significant difference by trend between the groups' post-test scores.

Here, it is noteworthy to reiterate that a point was awarded in the post-test if and only if the correct answer option was selected and additionally confident (rating scale 4) or very confident (rating scale 5) was selected on the certainty scale. If uncertain (rating scale 3) but correct answers are awarded a point as well, the difference in the groups' average scores becomes even more pronounced with $\mu = 10.24$ (SD = 2.96) for IG and $\mu = 8.12$ (SD = 2.70) for CG ($U(55) = 210$, $z = 3.29$, $p < 0.01$; $r = 0.44$).

Table 7. Descriptive statistics on pre-test and post-test scores for the intervention group (IG) and the control group (CG). The maximum achievable score in the test was 15 points. See text for deatails.

	Group	Median	SD	Mann–Whitney-U	*p*	*r*
Pre-test	CG	5.00	2.54	$U(55) = 334$,	0.47	-
	IG	4.00	2.49	$z = 0.85$		
Post-test	CG	7.00	3.02	$U(55) = 276$,	<0.1	0.27
	IG	8.00	3.24	$z = 2.00$		

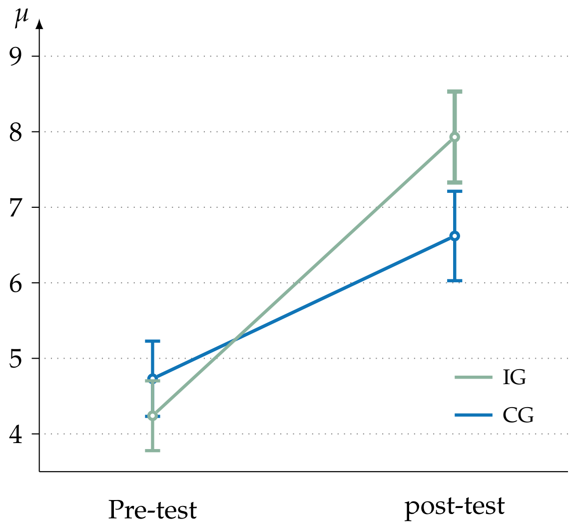

Figure 3. Change in average test score, μ, for the intervention group (IG) and the control group CG). The error bars indicate three times standard error.

Figure 4 shows the students' score distribution in the post-test for IG as well as CG.

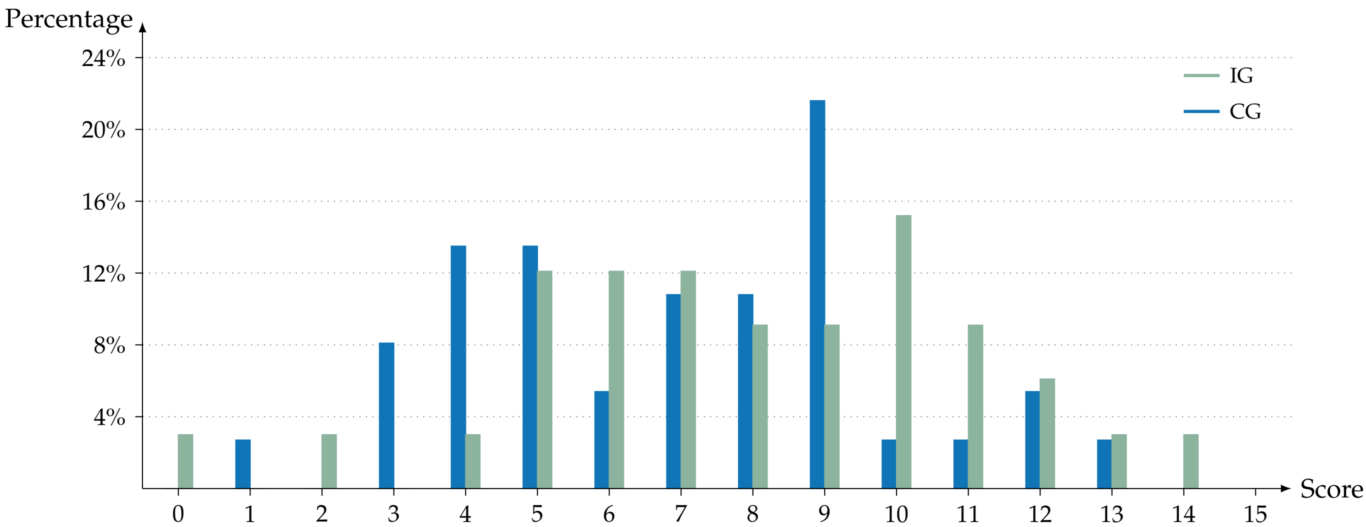

Figure 4. The students' score distribution in the post-test for the intervention group (IG) and the control group (CG).

The students' learning gains for each of the three domains (see Table 3) as well as the total learning gain expressed by Hake's g are provided in Table 8. A Mann–Whitney U-test further verifies that the groups statistically differ regarding g_{total} and g_{image} while the difference is not statistically significant in the first two domains (see Table 8).

Table 8. Normalized learning gains g_{vision}, $g_{\text{refraction}}$ and g_{image} regarding the different domains such as process of vision (domain 1), refraction and apparent depth (domain 2), and image formation by a converging lens (domain 3), respectively. See Table 3 and text for details.

	g_{vision}	$g_{\text{refraction}}$	g_{image}	g_{total}
μ (CG)	0.08	0.21	0.11	0.17
μ (IG)	0.27	0.30	0.47	0.36
Median (CG)	0.20	0.25	0.00	0.24
Median (IG)	0.25	0.29	0.50	0.39
Mann–Whitney U	$U(56) = 320$, $z = 1.30$, $p = 0.27$	$U(61) = 432$, $z = 0.55$, $p = 0.64$	$U(61) = 182$, $z = 4.73$, $p < 0.001$	$U(55) = 229$, $z = 2.91$, $p < 0.05$
r	-	-	0.61	0.39

In Figure 5, the difference in the groups' learning gains is illustrated by a boxplot for each domain.

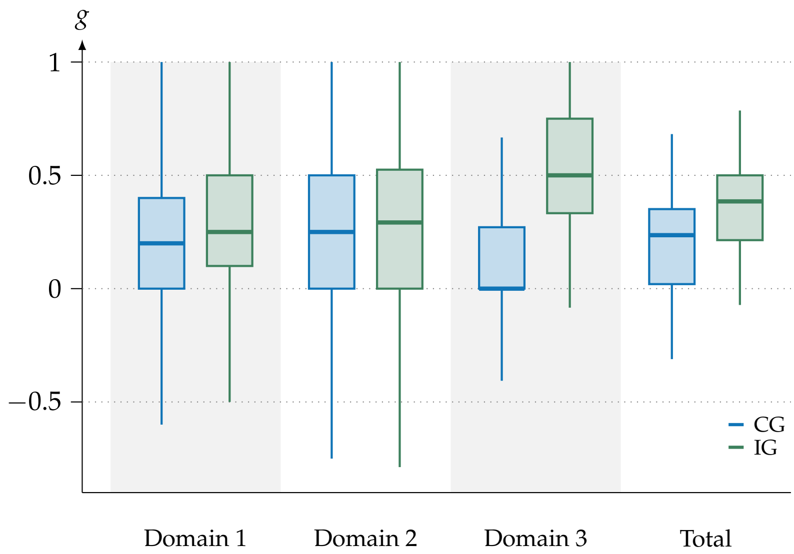

Figure 5. Boxplots of the learning gain (Equation (1)) for each of the three domains (see Table 3) as well as the total learning gain for the intervention group (IG) and the control group (CG).

6. Discussion

6.1. Discussion of RQ1

We observed a statistically significant difference in students' situational interest in optics between IG and CG ($U(74) = 276$, $z = 4.10$, $p < 0.001$; $r = 0.47$). In both interventions, the same topics have been covered, and hence, this result is not an artifact of different topics. However, it seems that the (model-free) phenomenological approach using hands-on experiments in the intervention group (following the Erlangen teaching–learning sequence of introductory optics [27]) indeed led to higher situational interest among students than traditional model-based instruction. In this respect, the findings presented in this study add further evidence according to which students' situational interest may be increased by hands-on experiments [44,45,63]. This is of particular interest for science introduction since "regular experiences of situational interest in a subject may eventually lead to the development of individual interest in that subject" ([64], p. 731).

6.2. Discussion of RQ2

No significant difference between the pre-test results of the IG and CG students was found ($p = 0.47$). After instruction, an increase in students' conceptual understanding of basic optics topics was observed in both groups. However, the IG students (median = 8.00, $\mu = 7.93$, SD = 3.24) outperform the CG students (median = 7.00, $\mu = 6.62$, SD = 3.02). This difference is statistically significant by trend ($U(55) = 276$, $z = 2.00$, $p < 0.1$; $r = 0.27$). This result has been obtained by only awarding points in the concept test if and only if the correct answer option was selected with (high) confidence. By loosening up this coding scheme, this finding can become even more prominent: the difference in post-test scores between IG and CG students is found to be highly significant if points are also awarded for correct answers where the students state to be undecided ($U(55) = 210$, $z = 3.26$, $p < 0.01$; $r = 0.44$).

The total normalized gain among the IG students was $g_{\text{Total}} = 0.36$ (SD = 0.24). Specifically, the difference to the one in the CG at $g_{\text{Total}} = 0.17$ (SD = 0.31) is statistically significant ($U(55) = 229$, $z = 2.91$, $p < 0.05$; $r = 0.39$). The normalized learning gain in the IG can be regarded medium and comparable to the ones found in prior projects using similar research designs in different contexts (cf. 0.40 ± 0.21 in [60] (p. 8), 0.48 ± 0.14 in [58] (p. 66)). Hence, our study reveals a positive impact of the phenomenological (model-free) approach to introductory optics (following the Erlangen teaching–learning sequence) on students' conceptual understanding of basic optics concepts—in particular, in comparison to traditional (model-based) instruction.

Analyzing the normalized learning gains for the three content domains, namely process of vision (domain 1), refraction and apparent depth (domain 2), and image formation (domain 3), we found the following: no statistically significant difference could be found for the first two. In contrast, the average normalized learning gain regarding image formation by converging lenses among the IG students ($g_{\text{Image}} = 0.47$, SD = 0.30) was higher than among the CG students ($g_{\text{Image}} = 0.11$, SD = 0.31). This difference has been found to be highly statistically significant ($U(61) = 182$, $z = 4.73$, $p < 0.001$; $r = 0.61$) with a large effect size according to [62].

To substantiate this finding qualitatively, it is worth analyzing students' answers to the corresponding items in more detail. For example, in item 12 (see Table 3) of the concept inventory, the students were asked what happens with the image if the lower half of the converging lens is covered. While no significant differences in the IG and CG students have been revealed at the pre-test point in time, in the post-test, we observe the following: among the CG students, 15.38% were certain that the upper half of the image will be cut off. In the IG that was the case for only 12.12% of the students. Another 20.51% of the CG students were certain that the lower half of the image will be cut off—none of the IG students voiced this opinion. However, 39.39% of the IG students gave the correct answer with certainty: the image becomes darker. Only 10.26% of the CG students were certain that this would be the correct answer option.

Similar observations are made when analyzing students' answers regarding item 13 (see Table 3). In this item of the concept inventory, the students were asked what happens with the image if an aperture with a very small diameter is placed in front of the lens. While again no significant differences in IG and CG students have been revealed at the pre-test point in time, in the post-test, we observe the following: among the CG students, 12.50% were certain that the image becomes smaller. In the intervention group, that was the case for none of the students. Another 25.00% of the CG students were certain that the edges of the image would be cut off circularly, while only 3.03% of the IG students were of that opinion. In contrast, 75.76% of the IG students gave the correct answer with certainty: also, in this case, the image becomes darker. Only 5.00% of the CG students were certain that this would be the correct answer option.

It is noteworthy that the above-given differences in students' answers may not be drawn back to differences in the interventions in both groups, since they did not differ in terms of content, tasks, or media used. However, our results support the implication that a phenomenological (model-free) approach is superior to traditional (model-based) instruction in circumventing widespread learning difficulties related to image formation by a converging lens among learners (see [4,13,15–19]).

7. Conclusion

7.1. Limitations

The study presented in this paper has some limitations that need to be tackled in follow-up projects. First, our study was conducted in the field and we used a quasi-experimental design. It is widely accepted that field studies lead to high external validity and low internal validity compared to a experimental lab study, which is characterized by a randomized distribution of the study participants between intervention and control groups. Thus, in the case of experimental studies, it can be assumed that there is a neutralization of person-specific confounding variables, such as self-concept, motivation, or interest [65]. In contrast, in the case of quasi-experimental studies, there is a risk that such confounding variables do not balance out between the comparison groups. As a result, the different study groups may differ systematically. The (significant) differences found in a study with regard to the dependent variables can then no longer be conclusively attributed to differences in the independent variables. As a result, a quasi-experimental study has a lower internal validity compared to an experimental study.

Second, to get in-depth insights into the success of the Erlangen teaching–learning sequence of introductory optics, the analysis of more covariates from the participating students, classes, and teachers seems valuable. Specifically, we believe that taking into account interactions of student learning and students' affective characteristics, so-called aptitude–treatment interactions [66], might influence the learning effectiveness of the intervention. Furthermore, in our study the gender distribution among the study participants was unbalanced. Hence, we believe that future research should take particular attention to the gender sensibility of our proposed teaching approach.

Third, in this study, we explored the advantages of the phenomenological approach for teaching introductory optics in early physics education exclusively with respect to students' learning gain and students' situational interest. Although we found evidence that this new approach is superior to traditional model-based instruction in this respect, further research is needed with respect to the students' conceptions acquired about introductory optics topics. Therefore, we believe qualitative methods will enable comprehensive insights into student thinking. In particular, we are interested as to whether our phenomenological approach will help circumvent learning difficulties documented in the literature that are widespread in traditional model-based instruction (see Section 2.2).

7.2. Outlook

In this study, we found empirical evidence for a phenomenological approach in teaching introductory optics being superior to traditional model-based instruction with regards to fostering (a) students' conceptual understanding and (b) students' (situational) interest. Despite being restricted to the context of optics, i.e., not being generalizable to other subjects, the study results presented in this paper support previous research results according to which phenomenological (hands-on) teaching might serve as a fruitful endeavor for science education in general (see Section 2.5). In future research, we aim at delving deeper into the conceptions acquired by students' introduced to introductory optics in the course of the phenomenological approach proposed in this article, in particular, compared to the ones acquired by students participating in traditional model-based instruction.

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

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