Effect of an inquiry-based teaching sequence on secondary school students' understanding of wave optics

Maja Planinic,[1,*] Katarina Jelicic,[1] Karolina Matejak Cvenic,[1]
Ana Susac,[2] and Lana Ivanjek[3]

[1]*Department of Physics, Faculty of Science, University of Zagreb, Bijenicka 32, HR—10000 Zagreb, Croatia*
[2]*Department of Applied Physics, Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, 10000 Zagreb, Croatia*
[3]*School of Education, JKU Linz, Altenberger Straße 69, A-4040 Linz, Austria*

(Received 22 September 2023; accepted 30 May 2024; published 24 June 2024)

Wave optics is a mandatory part of Croatian secondary school physics curriculum for students in the final year of secondary school (age 18–19). Many physics education research studies have shown that it is a difficult physics topic for both university and secondary school students. An inquiry-based teaching sequence on wave optics, designed for eight 45-min teaching periods, was developed by the authors. The sequence included four investigative students' experiments on the topics of interference, diffraction, and polarization of light, as well as several teacher demonstrations. The experimental group included six classes of students from six different Croatian urban secondary schools, who underwent the teaching intervention with the new inquiry-based sequence on wave optics, whereas the control group consisted of six classes from the same schools, taught in a predominantly lecturing way. Both groups were post-tested with the same instrument, the Conceptual Survey on Wave Optics (CSWO), to evaluate the research hypothesis that the new sequence might improve students' conceptual understanding better than the traditional teaching. The results of the experimental and control groups were analyzed and compared using the Rasch analysis. The results show that the experimental group outperformed the control group in four out of five conceptual areas probed by the CSWO, suggesting that the new inquiry-based teaching sequence may contribute to stronger development of secondary school students' conceptual understanding of wave optics, especially concerning typical wave optics patterns, reasoning from experiments, and explaining basic wave optics phenomena. A questionnaire on attitudes toward the teaching intervention was administered to students and it was found that students generally liked the inquiry-based teaching intervention and expressed positive attitudes to interactive, experimental, and collaborative aspects of physics teaching. The results are very promising, but their generalization may be limited by the selection of the students, as well as by the short duration of the teaching intervention and the relatively small breadth of the covered topics.

DOI: 10.1103/PhysRevPhysEducRes.20.010156

I. INTRODUCTION

A. Wave optics in physics education research

Wave optics is a challenging topic for students, which was investigated in several studies, conducted either at university or secondary school level [1–15]. Many student difficulties with understanding interference, diffraction, and polarization of light have been identified and reported in those studies. According to a recent summary of student difficulties with interference and diffraction [15], and polarization [12], the most common student difficulties include not distinguishing between geometrical and wave optics and the areas of their application [1,4–7,15], creating hybrid models [1,4,5,9], treating every slit (regardless of its width) as a single point source of light [1,5], confusing slits with polarizers [1,12], not properly understanding waves, their properties, and interactions [7,16], not understanding the role of path length difference in interference conditions [1,2,5,9,12], and having trouble expressing distances in terms of wavelengths [2,17]. Once modern physics is introduced, students may also have difficulties linking the quantum model of light with wave optics phenomena [1,4].

To these specific difficulties, other more general difficulties can be added, such as difficulties with predicting, describing, and explaining wave optics patterns in basic experiments [15], the tendency to use simplified reasoning

*Contact author: maja.planinic@phy.hr

and avoiding complex explanations (attempting instead to reduce more challenging concepts to simpler ones), or a tendency to remember but misinterpret common schematic representations and analogies presented at school, such as, e.g., the mechanical analogy of a wave on the rope and two fences in the context of polarization of light [12,15].

In some studies, students were required to recognize or distinguish typical interference and diffraction patterns [14,18,19]. The recently developed Conceptual Survey on Wave Optics showed that the most difficult group of items for secondary school students concerned explanations and applications of wave optics phenomena and the second most difficult group was related to the recognition and distinguishing of wave optics patterns [14].

In some recent studies, secondary school students' recognition of typical interference and diffraction patterns was investigated using eye tracking [18,19]. It was found that distinguishing wave optics patterns typically is a complex and challenging task for students but that students who performed investigative experiments in wave optics had less difficulty with such tasks.

B. Inquiry-based teaching and learning

Inquiry-based learning (IBL) is an educational approach that emphasizes the active and student-centered exploration of knowledge. It involves posing questions, problems, or scenarios that encourage students to investigate and seek solutions through their own observations, research, and critical thinking skills. Instead of relying solely on direct instruction from teachers, inquiry-based learning promotes a more hands-on and collaborative learning environment [20–22]. It is based on constructivist philosophy of learning [23]. The core components from the learner's perspective are Refs. [24,25]:

1. Learner engages in scientifically oriented questions,
2. Learner gives priority to evidence in responding to questions,
3. Learner formulates explanations from evidence,
4. Learner connects explanations to scientific knowledge;
5. Learner communicates and justifies explanations, and
6. Learner designs and conducts investigations.

There is less consensus, however, on how IBL should be translated into the teaching of scientific disciplines, how much teacher guidance it should include, or how the work in the classroom should be organized. There exist three main types of classroom inquiry, which involve different levels of teacher guidance: open inquiry, guided inquiry, and structured inquiry. In open inquiry, students pose their own research questions and choose their own methods of investigation to answer those questions. However, open inquiry is usually not well suited for class investigation, because of practical concerns regarding the organization of class work within the constraints of limited time and sometimes also resources. In structured inquiry, the teacher presents both the research questions and the investigation procedures, leaving little autonomy in the investigation to students. In the physics education community, the most accepted and promoted is the middle level of inquiry, the guided inquiry [26], in which the teacher provides the research questions but students investigate on their own and come to their conclusions, which are then discussed and negotiated with the whole class.

Inquiry-based teaching has long been recognized as a teaching strategy that can contribute to better teaching outcomes, although it is not always easy to experimentally establish its efficacy, and studies sometimes give mixed findings. One meta-analysis on science teaching [27] reviewed 62 experimental and quasiexperimental studies. The authors found an effect size of 0.65 for the subset of studies that included inquiry strategies, defined as those that are student-centered and in which students answer scientifically oriented research questions. Another meta-study included 138 studies [25], including qualitative, experimental, quasiexperimental, and nonexperimental studies. The authors identified a subset of 42 comparative studies that compared inquiry-based teaching with other approaches. They did not calculate an effect size for the subset of these studies but reported the following findings [25]:

- collaborative work with peers increased the conceptual learning of students, compared to independent work,
- higher levels of inquiry, especially those that included hands-on investigation and emphasis on student responsibility for learning did statistically significantly better in comparative studies than treatments with lower amounts of inquiry,
- there exists a clear and consistent trend indicating that instruction with an emphasis on active thinking and within the investigation cycle that includes the generation of questions, designing experiments, collecting data, drawing conclusions from the data, and communicating findings is associated with students' improved learning of concepts,
- hands-on activities are important but do not appear to be enough to produce improved understanding alone—it is crucial that students can construct and refine the meaning of content through class discussion, so pairing experimental activities with teacher-guided activities and class discussion may be a more productive way to organize instruction.

One of the important goals of inquiry-based teaching is the development of students' scientific reasoning. Scientific reasoning includes types of reasoning that are used in science for investigation, conducting experiments, evaluation of arguments, and forming explanations and conclusions. Lawson [28,29] suggests that scientific reasoning is mostly hypotheticodeductive in its nature and includes different aspects, such as proportional reasoning, control of variables, probabilistic and correlational reasoning, and forming and testing of hypotheses. It includes abilities necessary for designing scientific experiments and forming conclusions based on the results of experiments. Inquiry-based physics teaching relies very much on experimental investigation and is therefore very suitable for developing scientific reasoning. But even though experimental work is important for physics teaching, inquiry-based teaching requires much more than just the use of hands-on experiments or experimental kit-based instructional materials. It is true that using these materials may focus students' thinking and promote learning in the right sequence. However, even the use of the best materials does not necessarily engage students in full-on inquiry mode nor does it guarantee students' active learning. A key feature of IBL is a skilled teacher who guides students carefully through the process of inquiry. This was emphasized in a systematic review of research on secondary school science programs [30]. The outcomes of the review seem to support the use of programs with a strong focus on professional development, technology, and support for teaching, rather than materials-focused innovations.

Another meta-study [31] reviewed 37 experimental and quasi-experimental studies on inquiry-based teaching, published between 1996 and 2006, and found an overall mean effect size of 0.50. The authors defined inquiry in terms of two dimensions: the cognitive and social activities of the student and the guidance provided to students by their teacher, their peers, or curriculum. For the cognitive and social part, they relied on Duschl's [32,33] identification of three categories of inquiry that included:

(1) conceptual structures and cognitive processes of scientific reasoning,
(2) epistemic frameworks in development of scientific knowledge, and
(3) social interactions that guide communication and representation of knowledge.

To these three, they added the fourth category, which they called procedural. It comprises the posing of scientifically oriented questions, designing experiments, executing procedures, and creating data representations [31]. The guidance dimension of inquiry distinguishes on a continuum between teacher or student leading the activity, with the traditional teacher-led instruction on one end and completely open discovery learning on the other, and the teacher-guided inquiry in the middle. The results not only indicate a positive effect of inquiry-based teaching on student learning of science but also suggest the importance of the role of the teacher in actively guiding student activities in the context of IBL. Once again the authors emphasize that inquiry-based teaching should not be equated with completely open and unguided student investigation (e.g., discovery learning) and that adequate teacher guidance is an important element of success in inquiry-based learning, which was demonstrated by the fact that studies in their analysis, which contrasted guided inquiry with traditional instruction, had the mean effect size of 0.65, and those that contrasted student-led inquiry with traditional instruction only had the mean effect size of 0.25.

Inquiry-based teaching has found its place in the Croatian physics curriculum prescribed by the Croatian Ministry of Education [34], in line with many research study results and educational institutions' suggestions that incentivize inquiry-based teaching and learning and provide practical guidelines on its implementation in classrooms [35–39]. Research has shown overall that inquiry-based teaching can be an effective teaching method for science courses and is considered an extremely beneficial teaching strategy for helping students conceptualize basic concepts and apply science process skills in their daily lives [40]. Inquiry-based learning has also been associated with students' positive attitudes toward science [41], as well as fostering motivation [37,42], mastery goal orientation [43], enhancing learning of women and low-achieving groups of students, with no harm done to other groups [44] and increasing standardized achievement test gains [45].

C. Some inquiry-based programs developed through physics education research

There exist multiple programs employing inquiry in physics teaching, developed through physics education research, but those that are probably best known and that have partly inspired our new sequence on wave optics are Physics by Inquiry, Tutorials in Introductory Physics, and Investigative Science Learning Environment (ISLE).

Physics by Inquiry [26] is a set of laboratory-based modules that guides students in the formation of basic physics concepts through the in-depth study of selected simple physical systems. It also attempts to introduce students to the process of science and to develop their scientific reasoning skills. It is based on students' experimental investigations in small groups and discussions with the instructor and peers. Students work experimentally in small groups, investigating, forming concepts, hypotheses, and ideas about basic physics phenomena, and then testing and discussing them. Physics by Inquiry does not cover the topic of wave optics but provides a general framework for developing a conceptual understanding of physics phenomena and concepts and student scientific reasoning through guided inquiry.

Tutorials in Introductory Physics [46] is a set of supplemental instructional materials that promote the intellectual engagement of students in the process of learning physics and aim at developing the reasoning necessary to construct and apply physics concepts. Inquiry is focused here mostly on building and refinement of functional conceptual understanding. The learning takes place in small groups, with the help of an instructor who circulates among groups and helps students with Socratic questioning, intended to promote reasoning. The set provides tutorials for wave optics, starting from the analysis of wavefronts on water, formation of interference pattern, and relating the pattern and interference conditions on the water surface to the pattern observed in Young's experiment. Tutorials that follow lead students to multiple-slit pattern and optical grating and then introduce a model for single-slit diffraction based on multiple-slit interference. Students are then guided to develop and apply a conceptual model for combined interference and diffraction and afterward to explore the thin film interference. Polarization of light tutorial includes exploring the behavior of polarizing filters and analyzing incident and transmitted electric fields. Although tutorials are intended for university introductory physics courses, some selected parts can be applied in secondary school physics teaching, when trying to deepen student understanding of basic concepts in an interactive small group setting. Tutorials for wave optics were tested on university student populations and shown to be effective in improving students' conceptual understanding [2].

Investigative Science Learning Environment, ISLE [47,48], is a learning environment that attempts to help students learn physics by engaging them in the processes that mirror scientific practice. It also aims at developing student perseverance, growth mindset, and physics identity. The key elements of the ISLE approach, as listed in Ref. [47] are as follows:

- observing phenomena and looking for patterns,
- developing explanations for these patterns,
- using these explanations to make predictions about the outcomes of testing experiments,
- deciding if the outcomes of the testing experiments are consistent with the predictions,
- revising the explanations if necessary, and
- encouraging students to represent physical processes in multiple ways.

This is applied to every conceptual unit, including wave optics. The special emphasis of the approach is the use of multiple representations in teaching and helping students develop capacities for qualitative reasoning and problem solving. The general outline of the ISLE approach to wave optics [49] includes analysis of Young's double slit experiment and introduction of interference of light, followed by interference on optical grating, the application of interference phenomenon to thin films, and diffraction of light. Polarization of light is treated separately from wave optics, at the end of the unit on electromagnetic (EM) waves. ISLE relies mostly on hypothesis testing, which strongly promotes students' scientific reasoning but may be difficult to follow exclusively in some secondary school settings, due to time and equipment constraints. However, ISLE is very helpful for shaping the inquiry-based teaching cycle, introducing different roles of experiments in it (observational, testing, and application experiments), and for its emphasis on active learning and multiple representations which promote the development of students' deeper understanding of physics and scientific reasoning.

D. Research questions

Even though it is prescribed by the national physics curriculum, the inquiry-based approach to physics teaching is still not very widespread in Croatian secondary schools (the situation is better in elementary schools, where physics is a compulsory subject in grades 7 and 8). Some physics teachers, inclined to traditional teaching, are skeptical about the applicability and advantages of the inquiry-based approach. This study is an attempt to investigate how teachers can be helped in their efforts to transition to inquiry-based teaching and what benefits can be expected if the transition is made. We developed a new inquiry-based teaching sequence on wave optics, which was applied by six secondary school physics teachers in six schools in Zagreb, Croatia, and compared its effects on students' conceptual understanding of wave optics to the effects of a traditional lecture-based approach. We were also interested in students' attitudes toward this type of instruction. Our hypothesis was that the new sequence would result in a better student conceptual understanding of wave optics than the traditional lecture-based teaching.

With this study, we aimed to answer the following research questions:

RQ1. How does a new inquiry-based teaching sequence affect students' conceptual understanding of wave optics in comparison to traditional teaching?

RQ2. What aspects of student understanding are improved through the new teaching sequence?

RQ3. What are students' attitudes toward the new teaching sequence?

II. METHODS

To answer our research questions, we conducted a five-year research project from 2018 to 2023 [50], with the following outline:

(1) Qualitative investigation of secondary school student difficulties with wave optics.
(2) Selection of the participating physics teachers.
(3) Development and validation of the diagnostic instrument in wave optics.
(4) Testing of the control group.
(5) Development and testing of the inquiry-based teaching sequence on wave optics including selection of experimental equipment for wave optics school experiments.
(6) Training of the participating teachers.
(7) Implementation of the new teaching sequence by the participating teachers.
(8) Testing of the experimental group.

(9) Evaluation of the teaching sequence and of the testing results.

These steps are described further in this section, except for steps 4 and 8 which are described in Sec. III B. Since steps 1 and 3 were already described in detail in our previous publications [12,14,15,19], we bring here only a summary of their results.

A. Qualitative investigation of secondary school student difficulties with wave optics

We investigated student difficulties with wave optics through demonstration interviews with 27 secondary school students and through one eye-tracking study [12,15,18]. Interviews were held with students who volunteered to participate, after the regular school instruction on wave optics, which included all the phenomena probed in the interviews. Interviews were audiotaped, transcribed, and analyzed to identify common difficulties. In the 45-min interviews, students were presented with some common school demonstration experiments from wave optics (double-slit, optical grating, and single-slit experiments) and asked to predict the patterns on the screen, describe their observations after the demonstration, and provide an explanation of the observed patterns [15]. Interviews revealed student difficulties already with predicting and describing but especially with explaining the patterns. Regarding polarization, students were asked to design a simple experiment to discover with a known polarizer which of the other two slides, which looked alike, was also a polarizer, and then to explain what polarization of light means. Their answers not only revealed many difficulties with understanding of polarization of light but also with the underlying model of light [12].

The results have not only confirmed the presence of most of the previously known student difficulties but also revealed some new difficulties, especially those related to the recognizing and distinguishing of typical wave optics patterns and their explanations. The results were interpreted in the framework of knowledge-in-pieces [51] and resource-based model [52–57] and suggested that most of the student difficulties could be explained with student activation of p-prims and conceptual resources [15]. Most students did not seem to have formed any prior models of the wave optics phenomena but tried to form them on the spot, when they were asked to provide explanations of phenomena, activating various p-prims (elements of intuitive reasoning) or conceptual resources, such as those from geometrical optics or mechanical waves, in the process. An interesting result was students' extensive use of the p-prim "breaking," with which they often tried to explain or describe phenomena (e.g., observed patterns were described as a broken line of light and explained through the idea that the laser beam was broken by the slits or obstacles between them).

B. Selection of the participating physics teachers

A seminar was held early in 2019 for secondary school physics teachers from the Zagreb area, announcing the project and searching for volunteers. We accepted all teachers who were prepared to volunteer and participate in the teaching intervention (initially, nine teachers volunteered, but three of them dropped out over time for personal reasons), and all others who were willing to give us access to their students for testing and validating the new test on wave optics.

The teachers participating in the intervention were six physics teachers from six different secondary schools in Zagreb, Croatia. The schools of participating teachers represent well the major types of secondary schools in Croatia in which physics is a compulsory subject. In the Croatian school system, after eight years of compulsory elementary school, students can choose between secondary schools preparing for the continuation of education at the university level (called gymnasia) or different types of vocational schools. Gymnasia is further differentiated into general education type gymnasia, gymnasia focusing on classical or foreign languages, and those focusing on science and mathematics. Vocational schools have many types, but the most interesting for physics education are technical schools and natural science schools. Students from vocational schools can also enter universities if they pass state matriculation exams, which some do. In our sample, schools labeled A and B were general-type gymnasia, C was a foreign languages gymnasium, D was a science and mathematics gymnasium, E was a technical vocational school, and F was a natural science vocational school. In schools A, B, C, and F, physics was taught two periods per week for 4 years, and in schools D and E, three periods per week for 4 years (one period per week being dedicated to laboratory exercises, so basically all schools had two periods per week to introduce new content).

All participating teachers were qualified and experienced teachers, ranging in teaching experience from 10 to 30 years. They mostly practiced lecturing type of teaching with some demonstrations, although three younger teachers (A, B, and D) had been introduced to inquiry-based teaching in the physics education courses during their teacher study programs at the Faculty of Science, University of Zagreb. The participating schools are all urban public schools and are regarded as good schools.

C. Development and validation of the diagnostic instrument on wave optics

When we were starting the project, several diagnostic instruments already existed in the physics education community [8,10,11], however, none of them was well suited for our purposes. They were either intended for university, instead of secondary students, or did not cover the topics that we intended to cover in the teaching intervention (the topics prescribed by the Croatian curriculum). We, therefore, developed and validated a new diagnostic instrument for secondary school, the Conceptual Survey on Wave Optics (CSWO), to measure the level of student conceptual understanding of wave optics in the control and experimental group.

The process of test development included testing over 60 items on ca. 700 students in total, in several cycles of Rasch analysis, and finally retaining 26 items that showed the best functioning [14]. The construction of the test and its evaluation was guided by the Rasch analysis, which relies on the probabilistic modeling of the interaction of respondents with test items [58].

The construction followed the steps described by Liu [59], which include a definition of the construct (in our case, student understanding of wave optics), and its hierarchical organization, forming an item pool for different levels of the construct, administering items to a suitable sample of students, conducting Rasch analysis and removing items with poor characteristics, and repeating the process until a set of well-functioning items is obtained that function together as a valid and reliable instrument. Rasch analysis provides many tools for checking the quality of the instrument and its items, and its use in science education is constantly increasing [58]. The final version of the test, containing 26 multiple-choice items, was administered to 224 Croatian students after regular school instruction on wave optics and the test showed good targeting to the sample, appropriate width, good fit of items with the model, high item reliability (0.97), and good person reliability (0.78) for diagnostic purposes (related to the classical Cronbach's alpha of 0.77).

The construct of the test was organized around the cognitive complexity of items, and it was found that groups of items in the test, labeled Knowledge, Interference condition, Experiments, Patterns, and Explanations, showed statistically distinguishable levels of difficulty. The Knowledge group of questions investigates students' basic knowledge about wave phenomena and the wave model of light. Interference condition refers to a group of questions probing students' understanding and application in simple cases of the mathematical conditions for constructive and destructive interference. Experiments label a group of questions that probe students' reasoning about typical school experiments in wave optics. Group labeled Patterns refers to students' ability to distinguish and recognize typical patterns characteristic of basic wave optics phenomena covered in secondary school, such as double-slit interference patterns, single-slit diffraction patterns, and optical grating patterns. Group Explanations includes questions that refer to explanations of the formation of those patterns and the wave optics phenomena in general. These groups of questions showed, respectively, a statistically significant increase in difficulty, from Knowledge being the easiest group to Explanations being the most difficult, and corresponded well with the assumed increasing cognitive complexity of items in the groups [14].

D. Development and testing of the inquiry-based teaching sequence on wave optics

1. Selection of experimental equipment for wave optics school experiments

An important obstacle to the wider implementation of inquiry-based teaching in Croatia may be sometimes the lack of experimental equipment for school experiments. There are significant differences between schools in that respect. Some schools are very well equipped, others less so. All participating schools were well equipped, but since we were planning to conduct a teaching experiment, it was essential that all teachers worked with the same equipment. We therefore selected, tested, and purchased the same equipment for all participating schools as a part of our project. We formed sets for student experiments and sets for teacher demonstrations. Each school received six student sets and one teacher set. The sets were not readily available on the market: we assembled them from different elements, according to the needs of our teaching sequence. The sets were robust, inexpensive, and easy to use. The special problem was optical elements, such as single and double slits and optical gratings. Those that were commercially available for school experiments often produced poor patterns, especially in the case of the double-slit interference, where the interference pattern was merged with a strong diffraction pattern, which is not a favorable situation for the initial introduction of students to the interference pattern of equidistant and equal intensity maxima. We teamed up with another physicist and succeeded in producing good laser-printed slits, which gave interference patterns free of noticeable diffraction effects, with the use of the computer-to-film printing technique [60].

2. Development of the inquiry-based teaching sequence on wave optics

The new teaching sequence was designed as guided inquiry, promoting active learning through interactive engagement teaching methods, and grounded in research findings on students' conceptual difficulties with wave optics. The guided inquiry was chosen since it was shown in studies to be the most effective approach [31] and the one that fits best within the constraints of school physics teaching but still leaves enough autonomy to students in investigation. An investigation cycle that includes generating questions, designing experiments, collecting data, drawing conclusions from the data, and communicating findings was found to help students' learning of concepts [25] so this type of cycle was used in most lessons. The research questions were provided by the teacher, the design of the experiments was usually discussed by the whole class and then students either performed the experiments and reached conclusions in small groups (in four of eight lessons) or in some cases, the teacher performed the experiment, but students actively participated in the investigation process by providing their predictions, observations, and conclusions. Finally, the results of the experiments were gathered and discussed by the class, and the answer to the research question was reached. Interactive engagement methods were used as much as possible in all lessons. The effectiveness of interactive engagement methods in physics teaching was demonstrated in multiple studies [61,62] and the frequent use of these methods is the norm in reformed physics pedagogy. Systematic observation of new phenomena through interactive demonstrations, collaborative work, hands-on experiments paired with discussion, and conceptual questions in each lesson, aiming at problematic aspects of understanding wave optics concepts and phenomena, identified through research, was the backbone of the new teaching sequence. We will describe shortly how the most important interactive engagement methods are integrated into the new teaching sequence:

1. Conducting class discussion: Every lesson starts with an opening problem that is followed by a class discussion, in which students are encouraged to give their ideas about the problem. In class discussion, it is important for the teacher to try to include as many students as possible, keeping a positive attitude to students' ideas, not being in search for "the correct answer" but allowing students to express their ideas and in this way also get an insight into their level of existing knowledge and possible preconceptions. Class discussion is also used after experimental investigation to discuss the findings with all students and construct mathematical descriptions of some phenomena, this time being led in a more converging manner.
2. Interactive demonstrations: All observational experiments, as well as a few investigative experiments, are performed by the teacher in front of the whole class, interactively. This means that students are asked to write down their predictions, where appropriate (in observational experiments usually not, since students do not have the knowledge on which to base their predictions if the phenomenon is completely new to them), sketch and describe the experiment on their own and state their observations, and to participate in class discussion about the possible explanations of the observed phenomenon and the conclusions drawn from the experiments. In this way, students are intellectually engaged with the experiment, even if they do not perform it themselves. The same principles are applied not only in the case of real experiments but also with occasional substitutes for real experiments, such as videos or simulations, which are presented to the whole class.
3. Collaborative work in small groups: Whenever possible, students work in small groups, either performing experiments or solving other tasks or problems. Groups usually have three to five members, depending on the size of the class. Working in small groups helps students to discuss problems more freely, express their difficulties and pose questions, learn from strategies and problem approaches of other students, and generally be more involved in the learning process. The teacher circulates among groups and monitors their work, helping when the group gets stuck or prompting their reasoning with questions, therefore providing support, and guiding their thinking, but usually not giving them direct answers and instructions.
4. Answering conceptual questions with ABCD cards (peer instruction): In each lesson, usually near the end of the class period, students' understanding of the new content and their reasoning about it is probed with several conceptual multiple-choice questions. Each question is projected, and students are given sets of ABCD cards in different colors to indicate their answers. The question is read aloud by the teacher and students are asked to discuss the question and the offered answers with students near them, after which they are asked to raise the card(s) indicating the answer(s) they consider correct. In this way, the teacher can obtain a quick insight into the state of the understanding of the physics content for the whole class. The teacher then initiates the discussion, asking for the reasons behind different answers and guiding students through the discussion to notice the possible reasoning mistakes and build correct reasoning for the problem. In this method, it is important to use well-formulated questions, which really probe student understanding of crucial aspects of the new phenomenon or concepts, along with their reasoning, and not just the factual knowledge. If some distractors include some common student mistakes, this provides an opportunity to probe and remedy those in the class, improving in that way student reasoning and understanding.

As much as it was possible in the given time, there was also an attempt to include some epistemic aspects of scientific knowledge through discussion of scientific models, historical aspects of some discoveries, and the testing of hypotheses.

It is important to stress that the new teaching sequence was founded on the research results on student difficulties with wave optics [12,14,15,18], aiming specifically at the identified problematic points in teaching and learning of wave optics.

The teaching sequence was developed for eight teaching periods, which is approximately the amount of teaching time that most secondary school physics teachers allocate to the introduction of this topic. Most teachers include an additional three to four periods for problem solving, reviewing, and regular testing (this was not included in our new sequence but was replaced with pre- and post-testing with diagnostic instruments, which were not graded). Eight school periods are not a lot of time, so we had to restrict the sequence to the fundamental topics: double-slit interference, optical grating interference, single-slit diffraction, and polarization of light. These topics are also prescribed for secondary schools by the Croatian physics curriculum and required for the state matriculation exam in physics. Polarization is listed as an elective topic in the curriculum, but we decided to include it because of its presence in everyday items, e.g., polarizing sunglasses. Table I presents a short overview of the content and goals of the teaching sequence. All lesson plans, as well as the methodological instructions for the unit, are available in Croatian on the website of the project [50].

Each lesson was structured in the following way: In the introductory part, an opening problem, related to the historical problem (e.g., Newton—Huygens debate on wave or particle model of light) or everyday items (e.g., how polarizing sunglasses work) is presented and shortly discussed with students, without resolving it immediately. Then some form of observational experiment [48] is performed (either a real experiment or in some cases a video or a simulation) with the intention of acquainting students with the new phenomenon that will be studied and letting them systematically observe it. After summarizing their observations, the new phenomenon is usually named and then investigated. The investigation begins with formulating one or more questions to which the answer can be obtained through an experiment. In four lessons, the investigations were experimental, where students carried out hands-on investigative experiments in small groups, and in the other three lessons, investigations were carried out either through teacher-led experiments with the participation of students in the experimental design, predicting and observing, or by students, working in small groups with auxiliary materials (e.g., transparencies with circular wave fronts). After investigation, the class would discuss the obtained answer(s) to the investigation question(s). Where necessary, the mathematical description of the phenomena would be derived interactively and discussed (the mathematical descriptions were developed for double-slit and optical grating interference and for Brewster’s law). The lesson would usually end with several conceptual questions, probing student understanding of the new phenomenon, to which students would answer by raising ABCD cards, followed by a discussion of their answers and explanations. In lesson 6 [systematization of phenomena and problem solving (Table I)], the structure was different. That whole lesson was dedicated to discussing conceptual questions for all phenomena studied up to that point (using ABCD cards) and later cooperatively solving and discussing a few numerical problems in small groups. Conceptual questions used in teaching differed from the questions in the CSWO.

In the traditional approach, the content would be presented through a lecture given by the teacher, outlining the main features of the phenomena and their mathematical descriptions, sometimes accompanied by a demonstration of the typical experiments or just the images of the key patterns (e.g., interference or diffraction pattern). That would be followed by numerical problems, solved in a traditional way (each student individually, or on the blackboard). There is typically far less interaction and experimental work in a traditional classroom and the content is not presented through inquiry but in the form of results and facts. The new teaching sequence covers the same basic content as the traditional sequences, but its novelty is in the collaborative organization of class work, the use of an inquiry-based approach through experiments, and much more interactive engagement of students than is typically the case in standard instruction, emphasis on conceptual understanding, and inclusion of some epistemic aspects (the nature of science).

3. Piloting of the new teaching sequence

The new teaching sequence was preliminary tested by our research team in one class of a secondary school in Zagreb (gymnasium of a general type) that was not included in the later teaching intervention. One of the researchers (K. J.) taught all eight periods. All lessons were videotaped and qualitatively analyzed by the research team. Students were tested with the CSWO. Five students of different physics grades from the class were interviewed for 15 min by the members of the research team. In the interviews, students generally expressed satisfaction with the new teaching, the experimental equipment, and the experiments. The interviews and observation of the classroom work helped us to pinpoint problematic areas in the new teaching sequence.

After the piloting, the teaching sequence was revised (mostly shortened and partly rearranged) based on the results and observations from implementation and interviews with the students. Some of the students from the trial class also participated in a follow-up eye-tracking study, which investigated the effect of the pilot intervention on students’ ability to recognize and distinguish wave optics patterns. The results showed improvement in wave pattern recognition in the intervention group compared to the nontreatment group [19].

E. Training of the participating teachers

Due to the outbreak of the COVID-19 epidemic and the epidemiological measures that followed, such as first switching to online teaching and later introducing social distancing in schools, the main teaching intervention,

TABLE I. Overview of the teaching sequence on wave optics.

Lesson	Lesson goals	Activities
Lessons 1 and 2: Double-slit interference of light	Understand the role of models in physics and interference as a crucial phenomenon that distinguishes classical objects from waves	Discuss the Newton-Huygens dilemma of corpuscular vs wave model of light and how science models can be tested
	Recognize the double-slit pattern obtained with laser light as an interference pattern	Observe the double-slit pattern obtained with laser light
	Experimentally find out the relationship $s = \lambda a/d$	Investigate the pattern in groups using the mechanical waves analogy (transparencies with wave fronts) to find out if it is an interference pattern of light Investigate experimentally the dependence of adjacent maxima separation (s) on wavelength of light, distance of slits from the screen (a) and slit separation (d)
Lesson 3: Mathematical conditions for interference maxima and minima	Understand and apply the mathematical conditions for interference maxima and minima (known from mechanical waves) to light	Review and discuss the meaning of the mathematical conditions for interference maxima and minima.
		Apply the mathematical conditions to different examples by answering conceptual questions using ABCD cards and discussing answers with peers and teacher Apply the mathematical conditions to different examples by solving them cooperatively in small groups
Lesson 4: Optical grating	Extend the knowledge about interference of light to many slits (optical grating) Describe and understand qualitatively the difference between the double-slit and optical grating pattern Mathematically describe the optical grating pattern	Observe the optical grating pattern obtained with laser light and compare it to the double—slit pattern Investigate the pattern experimentally (qualitative dependence of maxima separation on optical grating constant and distance to the screen) Analyze the mathematical description of the pattern Predict, observe, and explain the white light pattern on optical grating
Lesson 5: Single-slit diffraction	Understand diffraction on a single slit as a phenomenon of light entering the area of geometrical shadowApply the Huygens-Fresnel principle and knowledge about the interference of light to explain qualitatively the single-slit pattern	Predict and observe the single-slit pattern
		Review and discuss the Huygens-Fresnel principle and its application to single slit Investigate experimentally how the width of the central maximum changes with the narrowing of the slit
Lessons 6: Systematization of the observed patterns and problem solving	Differentiate between different observed patterns Apply knowledge of double-slit and optical grating interference to conceptual and numerical problems	Analyze similarities and differences between all patterns observed so far Solve and discuss conceptual questions using ABCD cards
		Cooperatively solve numerical problems in small groups
Lessons 7 and 8: Polarization of light	Understand polarization of light as pointing to the model of light as an EM transverse wave Understand qualitatively the functioning of polarizing sunglasses and filters Form and test a hypothesis Analyze different ways of achieving polarization of light	Observe systematically changes in the intensity of light passing through one or two polarizing filters, or one filter and polarizing sunglasses, and the effect of their rotation Explain the observed phenomena using the mechanical waves analogy (wave on the rope and two fences with slits) Explain polarization of light as characteristic of a transverse EM wave Design and conduct experiments to test the hypothesis that light reflected off some surfaces is polarized, discuss findings for metallic and nonmetallic surfaces Derive Brewster's law and analyze it

which was initially planned for September 2020, had to be postponed until September 2022, when teaching in Croatian schools returned to the prepandemic mode. This also meant postponing the training of the included teachers.

In June of 2022, a 2-day education for the seven (at the time) participating physics teachers was held by the research team. Teachers were introduced for the first time to the new teaching sequence on wave optics. The teachers experienced all eight lessons in the role of students, with one of the researchers as the teacher (M. P.), and then discussed with the research team the sequence, the experiments, and the approach in general. They were provided with detailed written lesson plans, experimental equipment, and additional teaching materials. Each teacher was then given the task of preparing two lessons for the 3-day education workshop, which was held in August 2022. There they were in the role of teachers for other participating teachers (ca. 40) from all around Croatia, who came to be introduced to the inquiry-based teaching of wave optics. The participating teachers were divided into two groups of 20, and the seven teachers training for the teaching intervention (one of which could not continue with the project after the education because of personal reasons) taught the sequence to the other teachers (one lesson was taught additionally by one of the researchers). The program also included several short lectures, given by the members of the research team, on student difficulties with wave optics, the inquiry-based approach to physics teaching in general, and the results of the project available at the time, as well as plenary discussions of the parts of the teaching sequence, covered each day.

F. Implementation of the teaching sequence by the participating teachers

The six trained teachers implemented the new teaching sequence in their classes starting from September 2022 to January 2023, depending on their schedule. Their lessons were observed by the research team. All teachers but one completed the teaching sequence in the allocated eight periods, in about 4 weeks (teacher C completed it in 12 periods). The teachers managed to follow the lesson plans and to perform all the experiments that were planned. In schools where there were three physics lessons per week, only two were used for the teaching intervention, and the remaining period was used for laboratory exercises, unrelated to wave optics. Time was for most teachers the greatest struggle. The second struggle was the inquiry-based approach, which was relatively new for some of them. All teachers were not equally skilled in effectively guiding the students in reasoning and inquiry and that seemed to be the most problematic observed aspect of some teachers' performance. Students in all schools were mostly very cooperative and seemed to enjoy doing experiments and group work in general.

G. Evaluation of the teaching sequence

Students' scientific reasoning was evaluated with the well-known Lawson's classroom test of scientific reasoning (LCTSR) [63] and their understanding of wave optics with the Conceptual survey on wave optics (CSWO) [14]. The LCTSR is a very well-known test in the PER community, frequently used in research and classroom practice for the evaluation of student's scientific reasoning, including aspects such as control of variables, proportional reasoning, correlational and combinatorial reasoning, and hypotheses testing. The testing with the LCTSR (pretest and post-test), and with the CSWO (post-test) took three school periods. Students also filled out a questionnaire, constructed by the authors, in which they were asked about their attitudes toward and impressions of the new teaching sequence. The questionnaire consisted of statements about physics teaching and the teaching intervention with which students could agree or disagree on a four-point Likert scale, as well as some demographic and open questions. The results of the testing with the CSWO and the LCTSR were analyzed using the Rasch analysis, compared for the control and experimental group, and presented to the participating teachers in May 2023 together with the qualitative descriptive analysis of the experimental group questionnaire results. Their experiences and suggestions for the future implementation of the teaching sequence were discussed. Students' questionnaire results were also later analyzed with Rasch analysis to provide a more detailed insight into students' attitudes and impressions. With all these results, the impact of the new teaching sequence vs the traditional approach was estimated and will be presented in the Results section.

III. SAMPLE AND TESTING

A. Participants

The control and the experimental group both included six classes of students (one from each participating school). All classes were mixed regarding gender, with about 40% of the students being female in both the control and the experimental groups. Students were in the last year of their secondary schooling, aged 18–19 years, belonging to the urban population of middle socioeconomic status, and were predominantly Caucasians.

In the control group (in 2019/20), 140 students were pretested, 91 post-tested with the LCTSR, and 127 students were post-tested with the CSWO (the post-testing was performed after the traditional instruction on wave optics). The difference in the size of the LCTSR sample at pretest and post-test was due to the outbreak of the COVID-19 pandemic and the lockdown in the Spring 2020, because of which two classes (B and E) could not be post-tested with the LCTSR. Because of their incompleteness, the LCTSR post-test data will not be used in further analysis. The numbers of students who took the CSWO and the LCTSR

TABLE II. Overview of the participating schools and number of students who took the CSWO (post-test) and the LCTSR (pretest). The number of physics periods per week in each school is labeled N_{per}, control group is labeled CG, and the experimental group EG. Pre and post are abbreviations for pretest and post-test.

			CSWO		LCTSR	
School	Type	N_{per}	CG post	EG post	CG pre	EG pre
A	General type gymnasium	2	22	28	23	26
B	General type gymnasium	2	18	18	23	24
C	Foreign languages gymnasium	2	24	23	26	25
D	Science and math gymnasium	3	26	23	27	23
E	Technical vocational school	3	17	19	17	21
F	Natural science vocational school	2	20	19	24	19
Total			127	130	140	138

varied because not all students were at school when each testing was performed.

In the experimental group (in 2022/23), 138 students were pretested with the LCTSR, 132 students post-tested with the LCTSR, and 130 students post-tested with the CSWO. All students participating in the testing and teaching intervention were informed about the project and signed their consent for participation in the study. Their parents were informed by a written notice of the implementation of the project and the principals of the schools gave their consent. Students were generally excited to participate and for the most part collaborated actively in class activities. An overview of participating schools and students is provided in Table II.

B. Testing

The CSWO was used to evaluate student understanding of wave optics and was administered to students after they had completed the unit on wave optics and before any reviewing, additional problem solving or conventional testing was attempted by their teachers, usually 1 week after the completion of instruction. The testing was anonymous (students used a code name to receive their results) and students received no grades or other incentives for it.

Students' scientific reasoning was evaluated with the LCTSR before and after the teaching on wave optics, both in the control and experimental groups, with the intention to check for possible changes in the scientific reasoning due to instruction and also to compare the initial state of the control and the experimental group. The latter turned out to be important for this study because unexpectedly 2 years had passed between the control and the experiment, in which students were exposed to many personal stresses due to the COVID-19 pandemic and to new forms of teaching (e.g., online teaching), so it could not be readily assumed that both groups of students were initially comparable in their abilities. However, although it was planned to evaluate and compare student improvement in scientific reasoning in the control and experimental group, this turned out not to be feasible, due to the incomplete LCTSR data, so only the pretest LCTSR data were used to assess the comparability of the experimental and control group before the teaching on wave optics.

Each test was administered in a pencil-and-paper form with an allocated time of 45 min, but most students finished before that. The testing was always performed by the members of the research team and the participating teachers were not given a copy or the name of either test. No answers to any questions were given to students after the testing.

1. Control group testing

The control group was formed of six classes of students of participating teachers (one class per teacher) taught by them in their usual way of teaching, which was predominantly of the lecturing type (with some demonstrations) and did not include inquiry-based teaching. In schools B–F, the teachers in the control and experimental groups were the same. In school A, the teacher who initially volunteered to participate, and whose students were tested in the control group, later decided not to participate in the teaching intervention, for personal reasons, and was replaced by another teacher from the same school, who underwent training and performed the intervention. Even though the teachers in the control and experimental group in school A were different, we would not expect a large difference between the control group results of these two teachers, due to the homogeneity of the student population at school A and the similar teaching methods that were typically used before intervention.

The pretesting with the LCTSR was done at the beginning of the school semester and the post-testing with the LCTSR and the CSWO after the regular standard teaching on wave optics had been completed and before the students had their school test on wave optics. The duration of the teaching intervention differed, depending on the school, and may have included some reviewing and problem solving.

2. Experimental group testing

The pretesting of the experimental group with the LCTSR was performed at the beginning of the school semester and the post-testing with the LCTSR and the CSWO after the students had completed the new teaching sequence on wave optics and before any reviewing or additional problem solving or conventional testing was attempted, on average one week after the completion of instruction. Students also filled out a questionnaire at the end of the teaching intervention containing questions about their impressions of the teaching sequence on wave optics.

IV. DATA ANALYSIS

The data were analyzed with the Rasch model, using Winsteps software [64]. The post-test results on the CSWO, as well as the pretest LCTSR results, were compared between the control and experimental groups. The Shapiro-Wilk test showed a significant departure of the CSWO (post-test) and the LCTSR (pretest) scores of the control and experimental group from the normal distribution [CSWO: $W(127) = 0.94$, $p < 0.0001$; $W(130) = 0.91$, $p < 0.0001$; LCTSR: $W(140) = 0.97$, $p = 0.01$; $W(138) = 0.97$, $p = 0.005$, respectively]. The Mann-Whitney U test was used to assess the difference between groups (using Rasch measures), and its statistical significance and effect size ($r = z/\sqrt{N}$) were calculated. The corresponding Cohen's d was also computed [65] to facilitate comparisons with the results of previous studies. Partial credit Rasch analysis was conducted to compare the difficulties of groups of the CSWO items labeled Knowledge, Interference condition, Experiments, Patterns, and Explanations for the control and experimental group. These groups of questions in the CSWO allow for a more detailed analysis of aspects in which students may or may not have improved during the teaching intervention. The questionnaire on student attitudes was analyzed using the rating scale Rasch model.

V. RESULTS AND DISCUSSION

A. The CSWO results

The results obtained with the CSWO are shown in Figs. 1 and 2, presenting comparisons of raw scores and Rasch scores for control and experimental groups of students The data on which these figures are based (number of students, mean scores, and standard deviations for control and experimental group) are presented in Table III.

The Mann-Whitney U test for the CSWO Rasch scores showed that the differences between the results of the control and experimental group on the CSWO test are statistically very significant ($U = 4536.5$, $p < 0.0001$). The effect size r was found to be 0.39, and the corresponding Cohen's d was 0.85.

On the other hand, the analysis of the pretest LCTSR data showed that the difference between the control and the experimental group is not statistically significant ($U = 8905.5$, $p = 0.26$; $r = 0.068$, corresponding to Cohen's $d = 0.14$), so the two groups may be considered as being of similar ability before the teaching on wave optics. The difference in their CSWO results can therefore be attributed to different types of instruction in the groups.

Rasch measures were used for calculations since there may be issues with calculating with raw scores, because of their nonlinearity in the variable that they represent. It is therefore recommended to transform raw scores into Rasch linear measures expressed in logit and then express gains or perform calculations with them [66–68]. Since raw scores, such as fractions of correct answers, are expressed on a limited scale of 0 to 1, they cannot accurately map students' ability that is on a continuous scale (ability being conceptualized in the case of this study as student level of conceptual understanding of wave optics, not as some form of general ability, such as intelligence), and this mapping may become distorted, especially near extremes [58]. This problem is solved by transforming the raw scores into Rasch measures of ability, which are expressed on a continuous logit scale. By comparing graphs in Figs. 1 and 2, it can be noticed that the difference in mean ability appears much larger on the logit scale than for raw scores. The difference in raw scores of about 15%, which does not seem like much, translates into a 0.83 logit difference, which is a large difference, implying that students from the experimental group have on average 2.3 times higher odds of success on items of the mean (zero logit) difficulty in the CSWO than the students from the control group.

TABLE III. Number of students N, mean scores from the descriptive and Rasch analysis (fraction of correct answers and Rasch measures in logit), and standard errors SE (standard deviations or Rasch standard errors) for the control and experimental group.

	Control group			Experimental group		
Test	N	Mean	SE	N	Mean	SE
CSWO post-test (descriptive)	127	0.43	0.19	130	0.58	0.19
CSWO post-test (Rasch measures/logit)		−0.30	1.06		0.53	1.19
LCTSR pretest (descriptive)	140	0.59	0.21	138	0.62	0.19
LCTSR pretest (Rasch measures/logit)		0.58	1.31		0.73	1.15

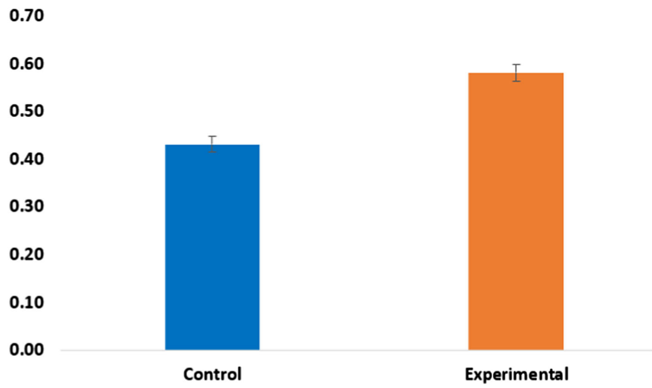

FIG. 1. Comparison of the average fractions of correct answers on the CSWO for the control and the experimental group. Error bars represent the standard error of the mean.

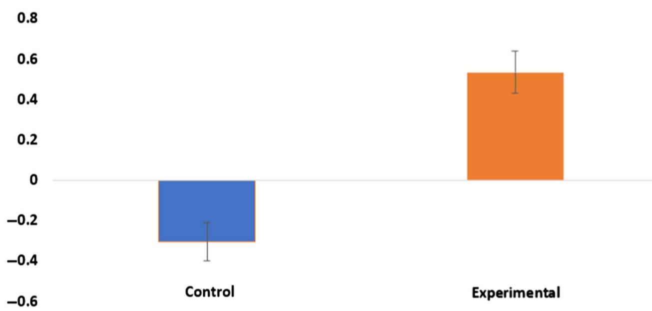

FIG. 2. Comparison of the mean Rasch CSWO person ability scores for the control and the experimental group, expressed in logit. Error bars represent the standard error of the mean.

Additionally, Rasch measures come with their standard errors, enabling better and more realistic comparisons of ability and difficulty calibrations than in the case of raw scores. The zero-logit level is determined as the mean item difficulty in the test, and person abilities and item difficulties are expressed on the same logit scale, allowing for their comparison. The negative value of the Rasch mean ability score for the control group can be interpreted as this group of students having on average less ability than the mean difficulty of the test, or in other words, that the test was difficult for them. The positive value of experimental group mean ability means that this group of students is on average more able than the test is difficult, or that the test was far easier for them than for the control group. To find out which conceptual areas of the test were easier for them, a partial credit Rasch analysis [58] was performed. Groups of items were treated as super items, in that for each student, the scores from all the items in the group were added up, so the group could have different maximum scores, depending on the number of items that were in a particular group. The distribution of questions in groups is described in the publication on the construction and development of the CSWO [14]. The Rasch-Andrich partial credit model was then used for analysis [58,66], in which super items were not dichotomous but were treated as being awarded credit for partial answers (credit for answering some of the items in the group). The results are presented in Fig. 3. Both control and experimental groups were analyzed together so that their item calibrations could be expressed on the same scale. Table IV. brings data from the partial credit analysis, which enabled us to obtain more precisely the difficulties of groups of items and their uncertainties. The CSWO raw data comparison for item groups can be found in Supplemental Material [69].

Figure 3 and Table IV show the better success of the experimental group (lower item difficulty) on all groups of questions except Knowledge, in comparison to the control group. Rasch measures are considered statistically significantly different when the difference between them exceeds 3 SE [70], and this is the case for groups Interference condition, Experiments, Patterns, and Explanations. Again,

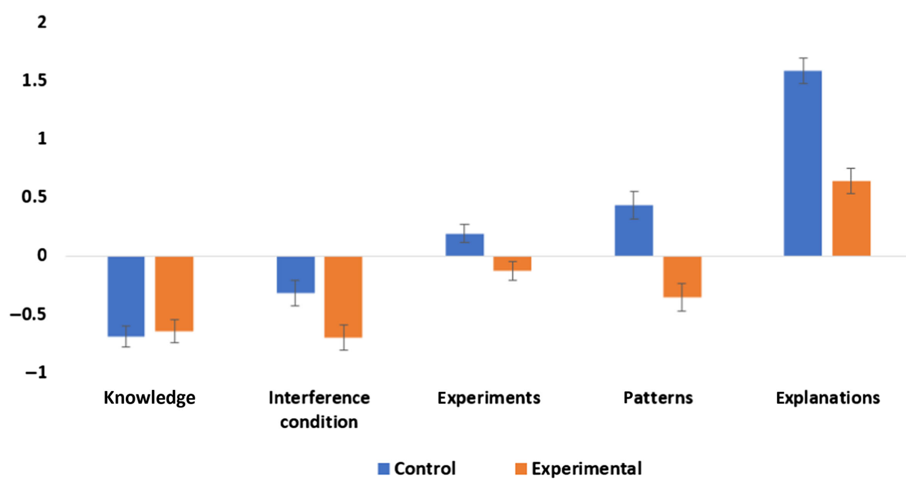

FIG. 3. Comparison of difficulties of groups of questions in the CSWO for the control and the experimental group, expressed in logit. The zero-logit difficulty corresponds to the average difficulty of all items in the test. Groups below zero are less difficult than the average. Error bars represent one Rasch standard error.

TABLE IV. Results of the partial credit analysis (Rasch ability measure with their standard errors, all expressed in logit) for the control ($N = 127$) and the experimental ($N = 130$) group.

	Control group		Experimental group	
Conceptual area	Measure	SE	Measure	SE
Knowledge	−0.69	0.09	−0.65	0.10
Interference condition	−0.32	0.11	−0.70	0.11
Experiments	0.19	0.08	−0.13	0.08
Patterns	0.43	0.12	−0.36	0.12
Explanations	1.58	0.11	0.64	0.11

the zero-logit level corresponds to the average difficulty of items in the CSWO, and item difficulties in the negative range indicate groups of items that were easier for students than the average, and those in the positive range indicate groups of items more difficult than the average. So, the easiest item group is knowledge about the wave model of light, then comes the application of interference condition (for the experimental group, this is equally easy as knowledge), and then reasoning about typical experiments in wave optics (it is of average difficulty for both groups of students). The difficult areas for the control group are recognizing and differentiating typical wave optics patterns and explaining phenomena, whereas for the experimental group, the patterns have become easier than the average, leaving explanations as the most difficult aspect of wave optics for them, although much easier than for the control group.

B. Students' attitudes

One important aspect of the new teaching sequence is how it was perceived by the students and how willing they were to engage in inquiry-based learning and activities. We have observed students' reactions and engagement during the teaching intervention and noticed that they were generally cooperative and willing to engage in the work in all schools. To probe their attitudes further, we administered a written questionnaire after the teaching sequence.

The questionnaire originally included, among some other questions, 12 statements probing students' impressions of the teaching intervention. After preliminary Rasch analysis of the questionnaire, nine well-functioning statements probing students' impressions of the teaching intervention on wave optics were retained, which will be further analyzed. The statements were rated by the students on a four-point Likert scale: 1—completely disagree, 2—disagree more than agree, 3—agree more than disagree, and 4—completely agree. Students expressed a high degree of agreement with the statements, with an average raw score of 3.2 ± 0.2. Students were also invited to give their comments and suggestions in open form.

The rating scale Rasch analysis [58] was conducted on the questionnaire data related to the teaching intervention to

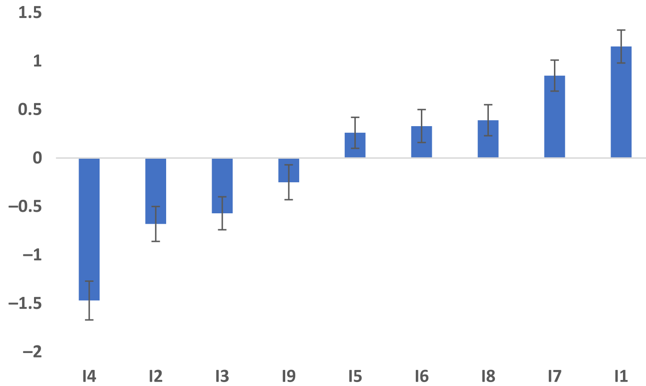

FIG. 4. The Rasch item measures (difficulties) for all statements, sorted from the easiest to endorse (on the left) to the most difficult to endorse (on the right). The error bars represent Rasch standard errors.

analyze its functioning and obtain linear measures of students' attitudes toward the intervention. The Rasch measures for nine statements on the teaching intervention are presented in Fig. 4. The statements are listed in Table V with their Rasch measures and standard errors.

Statements with lower Rasch measures (lower item difficulty) are those more easily endorsed by students, meaning that students expressed higher values of agreement with such statements on the Likert scale. The value of zero logit in Fig. 4 represents the average item difficulty (endorsability of statements), corresponding to the raw score value of 3.2, meaning that students on average agreed with the statements more than they disagreed.

The findings from the questionnaire were consistent with our observations during the intervention, that

TABLE V. Statements from the questionnaire with their Rasch measures and standard errors.

Statements related to the teaching intervention (in ascending difficulty of endorsement)	Rasch measure/logit	SE/logit
I4. I felt good in group work.	−1.47	0.2
I2. Teacher's demonstrations were interesting.	−0.68	0.18
I3. Experiments that we performed in groups were interesting.	−0.57	0.17
I9. Computer simulations were helpful.	−0.25	0.18
I5. It was clear to me what we investigated in group experiments.	0.26	0.16
I6. The conclusions of experiments were clear to me.	0.33	0.17
I8. Worksheets for investigation were helpful.	0.39	0.16
I7. Conceptual questions with ABCD cards were helpful.	0.85	0.16
I1. Instruction on wave optics was generally understandable.	1.15	0.17

students liked it and were willing to engage in inquiry-based activities and learning.

It was found that these nine items defined a sufficiently unidimensional construct—item misfit was within the allowed range of 0.5–1.5 for items to be productive for measurement and person and item reliabilities were satisfactory (person reliability index was 0.81, and item reliability 0.95). The classical reliability index Cronbach's alpha was 0.86.

Students did not give many additional comments, but those who did praised group work, experiments, and questions in class, as well as the relaxed atmosphere. A few students criticized the lack of numerical problems or the pace as being too slow (quite the opposite from their teachers, who mostly struggled with time, but the pace also varied among teachers). Here are some examples of students' comments:

> "I liked this type of teaching very much. Because of many experiments and group work, I felt more relaxed and so I better understood the content as well."

> "I usually don't like physics, because I will not be needing it in life, so I rarely work and follow the teaching in class, but during the project I followed much more, although not completely, and I think I learned in class more than usual. Also, the experiments performed by the teacher and by us were more interesting than the rest of the lesson, and I learned from them quite a bit."

> "Great compliments for organization and design of teaching. I liked reviewing with (ABCD) cards very much."

> "I didn't particularly like the pace of the teaching. I think it could have been done more efficaciously, since it was kind of slow. Otherwise, I liked interaction with experiments and group work. I consider this type of work helpful."

> "Things were sometimes too slow, it took long to come to some, for me trivial conclusion, so I would drift off and be bored, and then miss some important part. I liked that it was conceptually very well explained, but I missed mathematics…"

> "With experiments, it is easier to understand that our predictions are wrong, and the group work makes it easier to come to conclusions that made me understand the content easier. Work at home is still needed, at least some review, but questions in class are a good way to check knowledge and understanding."

C. Discussion

The teaching sequence on wave optics was designed according to the theoretical principles of IBL, described in Sec. I. B. It engaged students with scientific questions, observation, and description of phenomena, encouraged them to design and conduct investigations, formulate explanations from evidence (building on scientific knowledge), and communicate and justify those explanations. All three Duschl's [32,33] categories of inquiry were present: (i) conceptual structures were built through teaching, and scientific reasoning was promoted and developed, (ii) epistemic aspects of scientific knowledge were included in teaching as much as possible through discussion of scientific models and need for their change, and (iii) social interactions by communication and representation of knowledge were very strongly promoted through group work and class discussions. The collaborative aspect was strongly emphasized throughout the intervention, as well as the interaction between students and their peers and students and the teacher.

Some of the interactive engagement methods that were often used in the teaching sequence included the previously described class discussion, interactive demonstrations, collaborative work in small groups, and answering conceptual questions with ABCD cards (peer instruction). These strategies were observed to be beneficial for students, and students also expressed their satisfaction with many of them (e.g., group work, questions with ABCD cards, performing and observing experiments). It seems that the new teaching sequence on wave optics achieved in its design and implementation a sufficient level of inquiry and students' intellectual engagement to be called an inquiry-based teaching sequence. The overall results of the testing seem to suggest its benefits for students' conceptual understanding of wave optics.

Regarding our first research question RQ1, we can say that the new inquiry-based teaching sequence outperformed the traditional lecture-based teaching in developing a conceptual understanding of wave optics. Students showed overall significantly better conceptual understanding, as measured by the CSWO. Compared to the reported effect sizes for the inquiry-based teaching interventions in literature [27,31], the effect size of 0.85 (equivalent to Cohen's d value, typically regarded as large) seems to be a good result for such a short intervention. We attribute the effectiveness of the new teaching sequence to the higher level of intellectual engagement of students (achieved through the extensive use of different interactive engagement teaching methods) than is typically present in lecture-based teaching, as well as to the structure of the lessons. In each lesson, the new phenomenon was first introduced and demonstrated, giving students the opportunity to systematically observe it, and then further investigated by the students, providing at the end also the opportunity to apply the new knowledge and test their understanding. Such a structure may have helped students to follow and engage more in the lesson and gain familiarity with wave optics patterns. Students showed improvement in differentiating the essential features of different wave optics patterns, which seems to be a cognitively complex skill [14,19], which requires attention and intellectual engagement of students, and is unlikely to be acquired in a predominantly passive learning environment. Other improved areas, such as explaining the phenomena and applying them to everyday life situations, are also cognitively complex tasks that require a solid underlying understanding of basic concepts and connections between those concepts. We have noticed in earlier interviews with students, conducted after the standard lecture-based school instruction on wave optics [12,15], that students' knowledge was typically very fragmented and lacked structure. The new teaching sequence with its higher level of interactive engagement, emphasis on direct experience of phenomena through experiments, and building of conceptual knowledge may have promoted the formation of better structured and more integrated student knowledge networks related to wave optics than was typically the case in lecture-based instruction. Improved student knowledge networks were also suggested as a cause of the effectiveness of teaching interventions in some other studies [71,72]. Well-integrated conceptual networks may help students to better interpret novel situations and form explanations using that knowledge.

Regarding our second research question RQ2, we showed that all groups of items in the CSWO, except Knowledge (referring to the basic factual knowledge), were significantly improved with the inquiry-based teaching sequence. To find improvement in the experimental reasoning and pattern differentiation may not be surprising, since inquiry-based teaching focuses much more on experiments, as well as on observing and differentiating experimental patterns, than the lecture-based teaching. However, it is surprising that students showed improvement in the application of interference conditions, which was tackled quite shortly, compared to the traditional teaching, where it is much more stressed and practiced in numerical problems. Possibly, this improvement can be attributed to the more conceptual approach, aimed at developing understanding, students' investigation of interference patterns with circular wavefronts, and conceptual questions that were used in the new teaching sequence. Even though less time was spent on the application of interference conditions, compared to traditional teaching, more emphasis on the meaning of those conditions and more active engagement in discussing and applying them may have contributed to better results. The improvement in explanations is also striking and suggests that the experimental group students have formed a better understanding of typical wave optics phenomena than the control group students. The same level of success on knowledge questions in both groups is not surprising since both groups acquired the same basic information on wave optics phenomena and wave model of light during teaching, and no special emphasis was put in the new sequence on that aspect.

Regarding our third research question RQ3, from the results of the questionnaire related to the teaching intervention, we concluded that students were generally satisfied with the new type of teaching, the experimental and collaborative work, and the interactive engagement methods. Students seem to have found the teaching intervention on wave optics generally understandable and teacher demonstrations and student experiments interesting. It seems that students liked the collaborative aspect (working in groups) the most. Investigations, as well as their conclusions, seemed overall clear to them. They rated conceptual questions with ABCD cards, worksheets, and computer simulations as helpful. This is consistent with what was generally observed during the intervention, where students mostly cooperated and actively engaged in experimental work and inquiry-based learning.

D. Limitations of the study

Even though the study produced positive results, we are aware of some of its limitations. It was conducted only on the urban population in the capital of Croatia and in quite good schools. The schools in the sample did represent the major types of secondary schools in Croatia that have physics as a compulsory subject, but they did not represent all types of student populations that can be found in Croatia—such as rural or small-town populations in different regions of Croatia or students from more average schools. The teachers were volunteers, who were obviously motivated to engage in such a project that cannot be automatically generalized to all physics teachers in the country. They were willing to put a lot of effort into the preparation of lessons, learning the new approach, studying the teaching materials, participating in training, and were willing to be observed during teaching by the researchers. It may be questioned whether other teachers would be willing to do all that. However, the large turnout of physics teachers to our 3-day professional development program dealing with implementing inquiry-based teaching to wave optics is a sign that there are more teachers who would like to know more about this type of teaching and try it out for themselves. A large setback for the study was the pandemic of COVID-19, and the epidemiological measures that followed, due to which there was an unplanned 2-year gap in the project activities at schools, resulting in some teachers not being able to continue with the project.

The short duration of the teaching intervention and the relatively small breadth of the covered topics are additional limiting factors that suggest the need for more extensive research to support the study findings.

VI. CONCLUSIONS

The presented results suggest that the new inquiry-based teaching sequence on wave optics was more effective than the traditional lecture-based type of teaching in developing secondary school students' conceptual understanding of wave optics. There are several findings that can be stressed.

A. The experimental group outperformed the control group on the whole test and in almost all aspects of understanding probed by the CSWO

This suggests that inquiry-based teaching may be a good way to improve outcomes of secondary school physics instruction and students' overall understanding of physics topics. The challenge remains how to fit it into the constraints of the quite extensive physics curriculum and limited time available (usually two periods of physics instruction per week), as well as how to solve the equipment problems in some schools.

B. Even a short teaching intervention can produce positive measurable results

Our teaching intervention was quite short, lasting in most cases only 4 weeks, but it still produced a significant effect on students' conceptual understanding of wave optics. We can only imagine what effects on the overall student understanding of physics the implementation of inquiry-based teaching could have if it were applied systematically and consistently throughout secondary school. However, the student population in the study was not average, and the teachers seemed to be very motivated, so this leaves open the question of how the intervention would function in less favorable circumstances.

C. Students seem to be willing to engage in inquiry-based learning and have positive attitudes toward it

Physics teachers often doubt that students would be willing to engage in experimental investigation and reasoning required in inquiry-based teaching, but our experiences were very positive in this respect. Students' attitudes and impressions seemed to be mostly positive, as observed in their work and conduct during the intervention, and as expressed in the questionnaire. However, a question remains for further study on how students in other types of schools or other social environments would respond to this or similar teaching interventions.

In addition, it seems from our observations during the project that to help teachers transition from traditional lecture-based teaching to inquiry-based teaching, substantial support may be needed. Traditional lecturing may be appealing to teachers as a teaching method in which they have more control and with which they are familiar, while the inquiry-based teaching may initially appear to them as complex, less controlled by the teacher, and with the potential to go in unplanned directions. Inquiry-based teaching has many aspects that could be initially difficult for teachers, from structuring the lesson and guiding students' investigations in a way to promote inquiry, to using many interactive-engagement teaching methods. The last aspect appeared to us to be one of the greatest difficulties for teachers in our study, who were not all equally skilled in using such methods.

In conclusion, we believe that teachers should be provided with a lot of support from educational authorities, educational experts, as well as PER researchers, to find the optimal path of transitioning to inquiry-based teaching. The use of research-based, inquiry-based teaching materials can help a lot in that process. In this study, we provided teachers with detailed lesson plans, experimental equipment, and education on inquiry-based teaching in general and on the specific physics content, including related student difficulties. We also modeled the teaching, as well as provided opportunities for teachers to practice the teaching of the new sequence with their colleagues. Although the quality of the actual performance of the inquiry-based teaching by the participating teachers still varied from teacher to teacher, it is worth stressing that, despite all the limitations in the process, all teachers in this study achieved with the inquiry-based approach an improvement in students' learning over their own previous lecture-based teaching, and we feel that this is a very valuable message coming from our project.

ACKNOWLEDGMENTS

This work has been fully supported by the Croatian Science Foundation's funding of Project No. IP-2018-01-9085. We sincerely thank all participating teachers (especially Mirjana Dabac, Jelka Delić, Ivana Fundurulić, Marko Movre, Emil Šatalić, and Boris Štimac), and students, who made this study possible. We also thank Antun Lovro Brkić, who helped us with the development and production of printed optical elements (slits and gratings).

[1] B. S. Ambrose, P. S. Shaffer, R. N. Steinberg, and L. C. McDermott, An investigation of student understanding of single-slit diffraction, and double-slit interference, Am. J. Phys. **67**, 146 (1999).

[2] K. Wosilait, P. R. L. Heron, P. S. Shaffer, and L. C. McDermott, Addressing student difficulties in applying a wave model to the interference and diffraction of light, Am. J. Phys. **67**, S5 (1999).

[3] P. Colin and L. Viennot, Using two models in optics: Students' difficulties and suggestions for teaching, Am. J. Phys. **69**, S36 (2001).
[4] P. Hubber, Year 12 students' mental models of the nature of light, Res. Sci. Educ. **36**, 419 (2006).
[5] L. Maurines, Geometrical reasoning in wave situations: The case of light diffraction and coherent illumination optical imaging, Int. J. Sci. Educ. **32**, 1895 (2010).
[6] S. K. Şengören, How do Turkish high school graduates use the wave theory of light to explain optics phenomena?, Phys. Educ. **45**, 253 (2010).
[7] A. Coetzee and S. N. Imenda, Alternative conceptions held by first year physics students at a South African university of technology concerning interference and diffraction of waves, Res. Higher Educ. J. **16**, 13 (2012).
[8] V. Mešić, E. Hajder, K. Neumann, and N. Erceg, Comparing different approaches to visualizing light waves: An experimental study on teaching wave optics, Phys. Rev. Phys. Educ. Res. **12**, 010135 (2016).
[9] B. S. Ambrose, P. R. L. Heron, S. Vokos, and L. C. McDermott, Student understanding of light as an electromagnetic wave: Relating the formalism to physical phenomena, Am. J. Phys. **67**, 891 (1999).
[10] V. Mešić, K. Neumann, I. Aviani, E. Hasović, W. J. Boone, N. Erceg, V. Grubelnik, A. Sušac, D. Salibašić Glamočić, M. Karuza, A. Vidak, A. Alihodžić, and R. Repnik, Measuring students' conceptual understanding of wave optics: A Rasch modeling approach, Phys. Rev. Phys. Educ. Res. **15**, 010115 (2019).
[11] R. Dai, J. C. Fritchman, Q. Liu, Y. Xiao, H. Yu, and L. Bao, Assessment of student understanding on light interference, Phys. Rev. Phys. Educ. Res. **15**, 020134 (2019).
[12] K. Matejak Cvenic, L. Ivanjek, M. Planinic, K. Jelicic, A. Susac, and M. Hopf, Analyzing high school students' reasoning about polarization of light, Phys. Rev. Phys. Educ. Res. **17**, 010136 (2021).
[13] D. Salibašić Glamočić, V. Mešić, K. Neumann, A. Sušac, W. J. Boone, I. Aviani, E. Hasović, N. Erceg, R. Repnik, and V. Grubelnik, Maintaining item banks with the Rasch model: An example from wave optics, Phys. Rev. Phys. Educ. Res. **17**, 010105 (2021).
[14] K. Matejak Cvenic, M. Planinic, A. Susac, L. Ivanjek, K. Jelicic, and M. Hopf, Development and validation of the Conceptual Survey on Wave Optics, Phys. Rev. Phys. Educ. Res. **18**, 010103 (2022).
[15] K. Matejak Cvenic, L. Ivanjek, M. Planinic, K. Jelicic, A. Susac, M. Hopf, and M. Cindric Brkic, Probing high school students' understanding of interference and diffraction of light using standard wave optics experiments, Phys. Rev. Phys. Educ. Res. **19**, 020118 (2023).
[16] M. C. Wittmann, The object coordination class applied to wave pulses: Analysing student reasoning in wave physics, Int. J. Sci. Educ. **24**, 97 (2002).
[17] M. Kryjevskaia, M. R. Stetzer, and P. R. L. Heron, Student difficulties measuring distances in terms of wavelength: Lack of basic skills or failure to transfer?, Phys. Rev. ST Phys. Educ. Res. **9**, 010106 (2013).
[18] A. Susac, M. Planinic, A. Bubic, L. Ivanjek, and M. Palmovic, Student recognition of interference and diffraction patterns: An eye-tracking study, Phys. Rev. Phys. Educ. Res. **16**, 020133 (2020).
[19] A. Susac, M. Planinic, A. Bubic, K. Jelicic, L. Ivanjek, K. Matejak Cvenic, and M. Palmovic, Effect of students' investigative experiments on students' recognition of interference and diffraction patterns: An eye-tracking study, Phys. Rev. Phys. Educ. Res. **17**, 010110 (2021).
[20] M. Pedaste, M. Mäeots, L. A Siiman, T. de Jong, S. A. N. van Riesen, E. T. Kamp, C. C. Manoli, Z. C. Zacharia, and E. Tsourlidaki, Phases of inquiry-based learning: Definitions and the inquiry cycle, Educ. Res. Rev. **14**, 47 (2015).
[21] D. C. Ernst, A. Hodge, and S. Yoshinobu, What is inquiry-based learning?, Notices AMS **64**, 570 (2017).
[22] C. Attard, N. Berger, and E. Mackenzie, The positive influence of inquiry-based learning teacher professional learning and industry partnerships on student engagement with STEM, Front. Educ. **6**, 693221 (2021).
[23] M. Cakir, Constructivist approaches to learning in science and their implications for science pedagogy: A literature review, Int. J. Environ. Sci. Educ. **3**, 193 (2008).
[24] National Research Council, *Inquiry, and the National Science Education Standards: A Guide for Teaching, and Learning* (The National Academies Press, Washington, DC, 2000), 10.17226/9596.
[25] D. D. Minner, A. J. Levy, and J. Century, Inquiry-based science instruction—what is it and does it matter? Results from a research synthesis years 1984 to 2002, J. Res. Sci. Teach. **47**, 474 (2010).
[26] L. C. McDermott, The physics education group at the University of Washington, *Physics by Inquiry (Volumes I & II)* (John Wiley, New York, 1996).
[27] C. M. Schroeder, T. P. Scott, H. Tolson, T. Y. Huang, and Y. H. Lee, A meta-analysis of national research: Effects of teaching strategies on student achievement in science in the United States, J. Res. Sci. Teach. **44**, 1436 (2007).
[28] E. Anton Lawson, The nature of advanced reasoning and science instruction, Int. J. Res. Sci. Teach. **19**, 743 (1982).
[29] A. E. Lawson, The development and validation of a classroom test of formal reasoning, J. Res. Sci. Teach. **15**, 11 (1978).
[30] A. Cheung, R. E. Slavin, E. Kim, and C. Lake, Effective secondary science programs: A best-evidence synthesis, J. Res. Sci. Teach. **54**, 58 (2017).
[31] E. M. Furtak, T. Seidel, H. Iverson, and D. C. Briggs, Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis, Rev. Educ. Res. **82**, 300 (2012).
[32] R. A. Duschl, Assessment of inquiry, in *Everyday Assessment in the Science Classroom*, edited by J. M. Atkin and J. Coffey (NSTA Press, Arlington, VA, 2003), pp. 41–59.
[33] R. A. Duschl, Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals, Rev. Res. Educ. **32**, 268 (2008).
[34] Croatian Ministry of Science, and Education, National Physics Curriculum (2019), https://narodne-novine.nn.hr/clanci/sluzbeni/2019_01_10_210.html.
[35] National Research Council, *Inquiry and the National Science Education Standards: A Guide for Teaching, and*

Learning. (The National Academies Press, Washington, DC, 2000), 10.17226/9596.

[36] A. Lehtinen, S. Lehesvuori, and J. Viiri, The connection between forms of guidance for inquiry-based learning and the communicative approaches applied—a case study in the context of pre-service teachers, Res. Sci. Educ. **49**, 1547 (2019).

[37] D. M. Ferreira, F. C. Sentanin, K. N. Parra, V. M. Negrao Bonini, M. de Castro, and A. C. Kasseboehmer, Implementation of inquiry-based science in the classroom and its repercussion on the motivation to learn chemistry, J. Chem. Educ. **99**, 578 (2021).

[38] Z. Berie, D. Damtie, and Y. N. Bogale, Inquiry-based learning in science education: A content analysis of research papers in Ethiopia (2010–2021), Educ. Res. Int., 6329643 (2022), 10.1155/2022/6329643.

[39] University of Manchester, Centre for Excellence in Enquiry-Based Learning What is Enquiry-Based Learning (EBL)? (2010), http://www.ceebl.manchester.ac.uk/ebl/.

[40] R. E. Yager and H. Akcay, The advantages of an inquiry approach for science instruction in middle grades, School Sci. Math. **110**, 5 (2010).

[41] H. Aktamiş, E. Hiğde, and B. Özden, Effects of the inquiry-based learning method on students' achievement, science process skills and attitudes towards science: A meta-analysis science, J. Turkish Sci. Educ. **13**, 248 (2016), https://asosindex.com.tr/index.jsp?modul=articles-page&journal-id=1795&article-id=300823.

[42] H. L. Tuan and C. C. Chin, Promoting junior high school students' motivation toward physical science learning (III), Report for Taiwan National Research Council Report No. NSC 89-2511-S018-030, 2000.

[43] P. Mupira and U. Ramnarain, The effect of inquiry-based learning on the achievement goal-orientation of grade 10 physical sciences learners at township schools in South Africa, J. Res. Sci. Teach. **55**, 810 (2018).

[44] M. Kogan and S. L. Laursen, Assessing long-term effects of inquiry-based learning: A case study from college mathematics, Innovative Higher Educ. **39**, 183 (2014).

[45] R. Geier, P. C. Blumenfeld, R. W. Marx, J. S. Krajcik, B. Fishman, E. Soloway, and J. Clay-Chambers, Standardized test outcomes for students engaged in inquiry-based science curricula in the context of urban reform, J. Res. Sci. Teach. **45**, 922 (2008).

[46] L. McDermott and P. Shaffer, *Tutorials in Introductory Physics* (Prentice Hall Inc., Upper Saddle River, NJ, 2002).

[47] ISLE website https://www.islephysics.net/.

[48] E. Etkina and A. van Heuvelen, Investigative science learning environment: Using the processes of science and cognitive strategies to learn physics, in *Proceedings of the 2001 Physics Education Research Conference*, edited by S. Franklin, J. Marx, and K. Cummings (American Institute of Physics, Melville, NY, 2001), pp. 17–21.

[49] Eugenia Etkina and J. Michael Gentile, Alan van Heuvelen, *College Physics, A la carte edition* (Pearson Education, San Francisco, 2014).

[50] INVESTIGATE research project, 2018–2023, Website of the project in English: https://www.pmf.unizg.hr/phy/en/zavodi/zef/physics_education. Website of the project in Croatian: (https://www.pmf.unizg.hr/phy/physedu).

[51] A. A. diSessa, Knowledge in pieces, in *Constructivism in the Computer Age*, edited by G. Forman and P. Pufall (Lawrence Erlbaum, Hillsdale, NJ, 1988), pp. 49–70.

[52] D. Hammer and A. Elby, Tapping epistemological resources for learning physics, J. Learn. Sci. **12**, 53 (2003).

[53] D. Hammer, Epistemological beliefs in introductory physics, Cognit. Instr. **12**, 151 (1994).

[54] D. Hammer, Student resources for learning introductory physics, Am. J. Phys. **68**, S52 (2000).

[55] A. A. diSessa, Toward an epistemology of physics, Cognit. Instr. **10**, 105 (1993).

[56] E. F. Redish, A theoretical framework for physics education research: Modeling student thinking, arXiv:physics/0411149.

[57] J. Tuminaro and E. F. Redish, Elements of a cognitive model of physics problem solving: Epistemic games, Phys. Rev. ST Phys. Educ. Res. **3**, 020101 (2007).

[58] T. G. Bond and C. M. Fox, *Applying the Rasch Model: Fundamental Measurement in the Human Sciences*, 2nd ed. (Lawrence Erlbaum Associates, Mahwah, NJ, 2007).

[59] X. Liu, *Using and Developing Measurement Instruments in Science Education, A Rasch Modeling Approach*, edited by Xiufeng Liu (Information Age Pub, Charlotte, NC, 2010).

[60] V. Cviljušac, A. L. Brkić, B. Sviličić, and M. Čačić, Computer-generated hologram manipulation and fast production with a focus on security application, Appl. Opt. **61**, B43 (2022).

[61] R. R. Hake, Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses, Am. J. Phys. **66**, 64 (1998).

[62] C. H. Crouch and E. Mazur, Peer instruction: Ten years of experience and results, Am. J. Phys. **69**, 970 (2001).

[63] A. E. Lawson, Lawson's classroom test of scientific reasoning. Retrieved from http://www.public.asu.edu/~anton1/AssessArticles/Assessments/Mathematics%20Assessments/Scientific%20Reasoning%20Test.pdf (2000).

[64] J. M. Linacre, WINSTEPS Rasch measurement computer program, Winsteps.com, Chicago, 2006.

[65] C. O. Fritz, P. E. Morris, and J. J. Richler, Effect size estimates: Current use, calculations, and interpretation, J. Exp. Psychol. **141**, 2 (2012).

[66] M. Planinic, W. J. Boone, A. Susac, and L. Ivanjek, Rasch analysis in physics education research: Why measurement matters, Phys. Rev. Phys. Educ. Res. **15**, 020111 (2019).

[67] E. Ene and B. J. Ackerson, Assessing learning in small sized physics courses, Phys. Rev. Phys. Educ. Res. **14**, 010102 (2018).

[68] C. S. Wallace and J. M. Bailey, Do concept inventories actually measure anything?, Astron. Educ. Rev. **9**, 010116 (2010).

[69] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevPhysEducRes.20.010156 for the CSWO raw data comparison for item groups.

[70] J. M. Linacre, A user's guide to Winsteps Ministep Rasch-model computer programs, Standard errors: model, and real. https://www.winsteps.com/winman/standarderrors.htm (2018).

[71] K. Fiedler, M. Kubsch, K. Neumann, and J. Nordine, Fields in Middle School Energy Instruction to Support Continued Learning of Energy, Phys. Rev. Phys. Educ. Res. **19**, 010122 (2023).

[72] D. Fortus, M. Kubsch, T. Bielik, J. Krajcik, Y. Lehavi, K. Neumann, J. Nordine, S. Opitz, and I. Touitou, Systems, transfer, and fields: Evaluating a new approach to energy instruction, J. Res. Sci. Teach. **56**, 1341 (2019).