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Demonstration interviews with 27 high school students (18–19 years old) were conducted in Zagreb, Croatia, using several standard experiments on interference and diffraction of light. Students were asked for their predictions, observations, and explanations of the experiments. In this process, many student difficulties were identified, both regarding their understanding of interference and diffraction of light, but also regarding their skills of systematic observation and description of experimental patterns. The observed difficulties were analyzed in the resource-based model, suggesting the activation of some *p* prims, as well as other cognitive resources in the process of students' attempts to predict, describe, and explain the interference and diffraction patterns.

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I. INTRODUCTION

Wave optics is an important part of physics, taught in many countries both at high school and university level, in which students encounter phenomena of interference and diffraction of light. Wave optics and the wave model of light are introduced to students after they have covered geometrical optics, in which they were using the ray model of light, which may cause student difficulties with distinguishing and properly using the two models.

The main aspects of knowledge that high school students need to successfully explain interference and diffraction of light can be summarized in the following points:

(1) understanding the basic physical quantities that describe waves, such as wavelength, amplitude, frequency, and phase,
(2) understanding the idea of coherent light sources (with emphasis on constant phase difference),
(3) representing waves using circular wave fronts,
(4) expressing distances in terms of wavelengths,
(5) determining the path length and/or phase difference of waves traveling from the wave sources to the selected point in space,
(6) applying mathematical conditions for constructive and destructive interference,
(7) differentiating the double-slit, optical grating, and single-slit experimental patterns,
(8) analyzing and predicting the influence of the changes of the relevant physical quantities on the observed interference and diffraction patterns,
(9) applying the Huygens-Fresnel principle,
(10) describing mathematically interference of light on double-slit and optical grating.

In Croatia, some of the mentioned topics 1–7 are introduced already in the unit on mechanical waves, and others are introduced for the first time in the unit on wave optics, which is typically covered in a short period of time (in approximately ten school lessons).

We decided to investigate high school students' understanding of basic wave optics phenomena, such as interference and diffraction of light, after they had learned about them at school. To probe student understanding, we used several standard school experiments on interference and diffraction of light.

This research is a part of our larger study on wave optics, in which we have previously investigated and

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reported on high school students' difficulties with polarization of light [1] and difficulties with recognition of basic wave patterns [2,3], developed a new instrument for diagnosing student conceptual difficulties in wave optics [4], and compared Croatian and Austrian students' difficulties with wave optics [5]. In this paper, we aim to provide an insight into high school students' difficulties with interference and diffraction of light and to analyze them within the resource-based model framework.

II. LITERATURE REVIEW

High school and university level students' conceptual understanding of wave optics has been the subject of some physics education research (PER) studies [1–21], which showed that wave optics is a challenging topic for students of all levels. The previously identified student difficulties with wave optics can be summarized in the following groups:

(1) Difficulties distinguishing situations where geometrical or wave optics apply

In a short period of time students encounter principles and phenomena of geometrical and wave optics, which possibly creates confusion between the domains and areas of validity of geometrical and wave optics, resulting in students often trying to use geometrical optics to explain wave optics phenomena [6–11]. For example, some students tend to interpret the central diffraction maximum as a geometrical image of an illuminated narrow slit and some of them mistakenly predict that the narrowing of a single slit will result in a narrower central diffraction maximum [6].

(2) Creating hybrid models with elements of geometrical and wave optics

Some students combine both geometrical and wave optics when trying to explain some wave optics phenomena [5–9]. For example, when explaining the diffraction on a single slit, they apply geometrical optics principles for the light passing through the middle of the slit (light passes undisturbed) and wave optics principles for the light passing close to the edges of the slit (in their interpretation, only the edges become new sources of light, causing diffraction) [5,6].

(3) Difficulties with modeling of a single slit

One of the common students' tendencies is to treat every slit, regardless of its width, as a single point source of light [6,7]. This may be at least in part caused by the fact that in the analysis of the double slit and the optical grating interference at high school level slits are in fact conceptualized as point sources of light. Edges of the slit are often mistakenly considered by students as crucial for the diffraction of light, and some students consider them to be the only new sources of light or something that reflects, refracts, or bounces off the incident rays of light [6,7]. Some of the students also confuse slits with polarizers, thinking that the light passing through the slit becomes polarized [1,6,21].

(4) Difficulties with understanding waves, their properties, and interactions

Some students struggle with the basic properties of waves, such as their wavelength and amplitude, and sometimes confuse the two [12]. Waves are sometimes treated as objects, as some students think that two waves can bounce off each other if they meet [12,22]. Students often have difficulties adding waves point by point or understanding that the sum of waves can have smaller amplitude than the individual waves. Interference of light is perceived by some students as a phenomenon that always results in reinforcement of the waves and a greater amplitude of the resulting wave [12].

(5) Difficulties with expressing distances in terms of wavelength

Students often struggle with expressing distances in terms of wavelengths, which is one of the necessary steps in determining the path length difference as a criterion for constructive or destructive interference [13,14].

(6) Difficulties with understanding the role of path length difference

Many students fail to understand the crucial role of path length difference for determining the location of the interference minima and maxima of light waves. They have trouble realizing that the change in the initial phase difference between multiple coherent waves, traveling through the same medium, may occur only if there is a difference in their path lengths. Students may mistakenly think that the interference of waves at some point in space is determined by the total path length of waves, or by the relative direction of the waves' motion, concluding that the waves that move in the same direction always interfere constructively, and those moving in the opposite directions destructively [5–8,14].

(7) Difficulties with the relative size of the width of the slit and the wavelength or amplitude of light in diffraction

One of the conditions for the diffraction minima to appear on the screen is that the width of the slit is greater than the wavelength of the incoming light. Some students mistakenly conclude that, for the diffraction pattern to occur, the width of the slit must be equal to or less than the wavelength of light [6]. Students also tend to attribute spatial characteristics to the light wave oscillations, concluding that the light wave may or may not pass through the slit, depending on its size, or that only a fraction of its original amplitude will pass [6,8,12,13].

(8) Difficulties with modern physics concepts in the context of wave optics

After introduction of modern physics concepts, such as photons, some students try to combine wave and photon characteristics, which sometimes results in the mistaken conclusions that photons move like a sine wave, or that photons move in a straight line that bends near the edges of the slit [6,9].

(9) Difficulties with predicting and distinguishing patterns produced in wave optics phenomena

Eye tracking studies [2,3] report that students struggle with distinguishing patterns obtained in basic wave optics experiments. Although it may appear at first that this is a task of simple recognition, distinguishing wave optics patterns seems to be a complex cognitive task, since it requires knowing and looking for the distinct features of each pattern, as suggested by students' eye movements [2,3], as well as by their difficulties with the similar questions on the Conceptual Survey on Wave Optics [4].

In the context of the double slit experiment some students mistakenly believe that each illuminated slit in the double slit experiment produces one half of the interference pattern and predict that if one of them were covered with a nontransparent material, the resulting pattern would be one half of the initial pattern, expecting that either its left-hand side, right-hand side, or every other maximum would disappear [6]. Other students think that each slit produces the whole pattern and expect that covering one slit would result in the same pattern of diminished intensity [9].

(10) Simplifying complex phenomena

Even though interference and diffraction of light on a double and single slit are basic phenomena of wave optics, they are quite complex, and their explanations require multiple reasoning steps. Students sometimes tend to simplify complex concepts and phenomena by reducing them to simpler ones or omitting some steps in their reasoning, such as treating all slits (regardless of its width) as point sources [6,7] or replacing the path length difference with the total path length in the condition for constructive or destructive interference [6].

III. THEORETICAL BACKGROUND

To improve the learning process, it is important to understand how students use their prior knowledge in learning and reasoning, and what is the structure of their knowledge. Student knowledge can be analyzed from two different theoretical perspectives: knowledge as theory and knowledge in pieces [23]. Knowledge as theory assumes that students' naïve knowledge is theory-like, structured, and coherent, containing large and stable structures, such as relatively firm ideas and mental models. It implies that students' reasoning about a certain topic should be consistent and resistant to change, but to induce a change (for example, if student's existing knowledge is insufficient to solve some unknown problem), a method called cognitive conflict is often used [24,25]. However, there is significant evidence [26] that students' reasoning is often inconsistent, and strongly context dependent, which contradicts this theory. A different theoretical framework was therefore developed, known as knowledge in pieces or resource-based model [27–31], which assumes that students' knowledge consists of numerous smaller cognitive elements, called cognitive resources [23,29,30]. Resources are smaller or larger elements of students' prior knowledge, which can be activated in a specific situation (i.e., when solving a physics problem or producing an explanation) alone or in groups. Their activation in specific situations makes them highly context dependent. During the reasoning process students can easily abandon a previously activated resource and/or replace it with another resource. Activation of a single resource can cause a "snowball effect," meaning that it can trigger activation of other resources. But later activated resources can also sometimes override or contradict (some of the) previously activated resources.

Cognitive resources can be divided into three categories: phenomenological primitives [27,28], conceptual resources, and epistemological resources [29,31].

DiSessa first introduced small patterns of reasoning, that he called *phenomenological primitives*, or *p prims*, that are activated depending on the context [27,28]. *p* prims are phenomenological because they are abstracted from everyday phenomena, and they are primitive because one does not need to explain them any further in one's internal knowledge structure [27,28].

p prims are neither correct, nor incorrect *per se*. They place the reasoner on a specific intuitive reasoning trajectory that is quite evident to the person holding this *p* prim. However, the activation of an inappropriate *p* prim for the analyzed situation or problem may lead to wrong conclusions or create obstacles to physics learning [27]. Let us consider the *p* prim *closer is stronger*, which is a good example of *p* prim application that may lead to correct and incorrect conclusions. We have an intuitive feeling that the *effect* of something is greater when we are closer to its source (the *cause*) [30]. If we are closer to the fire, we will feel warmer. If students are, for example, presented with the problem of average temperatures on planets in the solar system, they might activate the *p* prim *closer is stronger* and conclude correctly that the average temperature is higher if the planet is closer to the Sun. But, if the students are asked why it is hotter in the northern hemisphere in summer than in winter, students might conclude, after activating the same *p* prim, that it is because the Earth is closer to the Sun in summer [30]. This time the activation of the same *p* prim led them to the wrong conclusion since the change in distance between the Earth and the Sun from summer to winter plays no role in seasons' exchange.

One of the common *p* prims is also the *Ohm's p* prim, that describes the effect of an agent that acts through a resistance. It allows a holder of this *p* prim to establish a link between the effort, the resistance and the result [28]—to overcome a larger resistance, more effort is needed. On the other hand, more effort, or the presence of several agents (increased cause) will result in increased effect (also known as the *p* prim *more is more*, which does not refer to resistance). For example, if two light bulbs are turned on, the resulting illumination will be larger than from just one of them. Another *p* prim (maybe a special reversed case of the *more is more p* prim) may be *one cause leads to one effect* (1 : 1), which results in one-to-one mapping of causes and effects. Even though this can lead to correct interpretations in some situations, such as that each laser dot on the screen is caused by a separate laser, when no other optical elements are present, it can lead to problems in interpretation of, e.g., interference effects, where each maximum is not caused by the light from one slit only.

Blocking is a *p* prim activated for situations where an obstacle prevents the motion of an object or some other effects on the object (for example, the table is blocking the object resting on it from falling, a nontransparent obstacle is blocking the light from passing through it). The *p* prim *guiding* describes the motion of the object along the determined path [28], such as a ball moving though a hollow tube, and often accompanies *blocking* (the tube is *guiding* the ball through it and also *blocking* the ball from leaving it).

Breaking is a *p* prim activated for situations where a single object is split into parts after encountering an obstacle. An example can be the breaking of a glass object after hitting the floor. Closely related, but not the same, is the *p* prim *dividing*, which refers to dividing into parts without an obstacle, such as one flow dividing into two branches.

The *p* prim *canceling* describes the annulment of one influence with an equal and opposite influence [28]. The opposite *p* prim is *reinforcement*, which is used when several equal influences produce a larger effect than each one alone.

DiSessa described more than 20 *p* prims (and their activation mostly in the area of mechanics) [28], but Redish [32] argued that there may be many more and suggested that *p* prims can be at different levels of abstraction. The abstract *p* prims (which he also called reasoning primitives) can be mapped onto different specific situations, resulting in various domain-specific *p* prims, like those identified by diSessa in physics context. For example, the abstract *p* prim *agent causes effect* can be mapped onto situations involving forces and motions and result in a domain-specific *p* prim *force as a mover* (the body moves in the direction of the applied force), but also *force as a spinner* (the body spins if the force acts off center), so both can be regarded as facets of the same abstract *p* prim [33].

In addition to *p* prims, Hammer [29–31] differentiates *conceptual* and *epistemological* resources, as other two classes of cognitive resources. When learning or problem solving, students rely on and activate conceptual resources, cognitive structures typically larger in size than *p* prims and linked to a certain conceptual domain. Richards, Jones, and Etkina suggest that *p* prims usually represent students' initial intuitive knowledge, and conceptual resources are usually larger-grain structures, representing more advanced and content-specific knowledge [34].

Epistemological resources, on the other hand, describe students' attitudes about knowledge and learning, and can also be productive or hindering for learning, as other resources. Sometimes students have the attitude that knowledge should be exclusively passed from teacher (or textbooks) to students [29], which is known as the epistemological resource *knowledge comes from authority*. If students treat knowledge as something that can be discovered or constructed through investigation or reasoning, they are using the epistemological resource *knowledge is invented or created* [29]. Epistemological resources can greatly affect how students approach new problems and what they do when they cannot solve them, whether they wait for the answer from teacher or textbook (activation of this epistemological resource is usually less productive for learning), or if they try to approach the problem by themselves using the available resources and their own efforts (usually more productive for learning).

Hammer [31] also pointed out that student knowledge is often fragmented, and that the learned facts and principles remain disconnected, which is noticed by many physics teachers and faculty in their teaching practice. This may happen in part because many students do not even expect their knowledge to be coherent.

The resource-based model provides a good tool for understanding student use of prior knowledge in forming new explanations or predictions, since very often students use their cognitive resources to construct such explanations or predictions when prompted. The model can help researchers to analyze the cognitive resources that were used and get an insight into the structure and quality of students' knowledge. The resource-based model was already used and discussed in many PER studies, concerning various physics topics, such as photovoltaic cell [34,35], electromagnetism [36,37], momentum [38], circular motion [39], sound [40,41], and other.

IV. RESEARCH QUESTIONS

It became evident in the early stages of the current research, as well as during our previous research and analysis of student interviews, that students' answers to questions mostly did not seem to stem from prior well-formed and coherent models in wave optics but were rather formed on the spot, probably through activation of students' conceptual resources, such as their previous knowledge of optics (i.e., geometrical optics or mechanical waves) or of different *p* prims. We, therefore, concluded that the resource-based model would be the appropriate theoretical framework for interpreting our research results.

Two main research questions guided this study:

RQ1. What are the difficulties that high school students have with understanding interference and diffraction of light and with the related standard experiments?

RQ2. What *p* prims and cognitive resources are activated in the process of predicting, describing, and explaining the interference and diffraction patterns?

V. METHODOLOGY

A. Sample

The sample consisted of 27 high school students who participated in semistructured demonstration interviews. The interviewees (18–19 years old) were enrolled in the 4th (final) year of gymnasium. Gymnasium is a type of high school in Croatia that typically prepares students for the continuation of their education at the university level. By the end of gymnasium, students have been learning physics (as a compulsory subject) for six consecutive years: two years in middle school (with two 45-min physics lessons per week) and four years in high school (with two or three 45-min physics lessons per week, depending on the type of school). Prior to the interviews, all the participants learned about wave optics in their regular school instruction on physics, where they covered basic wave optics phenomena (interference, diffraction, and polarization of light). The teaching style in Croatian high schools is still of a predominantly traditional, lecture-based type, although there are efforts to transition to a more inquiry-based teaching. Teachers usually dedicate 10 to 12 lessons to wave optics.

All the students involved in the interviews volunteered to participate, after they had been informed about the interviews by their physics teachers. The number of female and male participants was balanced. During the process of participant selection, we made sure that the students with grades *good* (G), *very good* (VG), and *excellent* (E) were equally represented in the sample, as shown in Table I. In the text, students are represented by codes S1–S27, followed by the code of their physics grade (G, VG, or E). The sample did not include students with grades *sufficient* (D) and *insufficient* (F) because students with those grades are mostly not interested in voluntary taking part in such research.

The interviews were conducted by the first author of this paper at the Department of Physics, Faculty of Science in Zagreb, during 2018 and 2019. The average duration of the interviews was around 54 min, they were audio taped (via smart phone application for voice recording) and later transcribed. The part of the interviews concerning interference and diffraction of light lasted 45 min on average.

TABLE I. The gender and grade distribution of the interviewees.

		2018	2019
Female		3	10
Male		6	8
Grades	Good	3	6
	Very good	3	7
	Excellent	3	5

B. Methods

The experiments chosen for the interviews were the standard school experiments on interference and diffraction. The experimental setup consisted of a red-light laser, a slide holder, the screen, and the slides with a double slit or a single slit of a varying width or optical grating (80 and 300 lines/mm), as shown in Fig. 1. A source of white light and a converging lens were also used for the experiment with optical grating.

In total, students were shown three different groups of experiments:

(a) double-slit interference with laser light;
(b) optical grating interference with two different gratings (80 and 300 lines/mm), first with laser light and later also with white light;
(c) single-slit diffraction with laser light incident on a slit of adjustable width.

For each experiment, students were shown the experimental setup, and were told what would be done in the experiment, but not what would happen. Students were then asked to predict the pattern in words and drawing. The experiment was then performed, and students were asked to describe and sketch the observed pattern, explain it, and sometimes to predict how changes in the experimental setup would affect the pattern. Students were asked to include drawings as much as possible, because their drawings enabled a better understanding of their predictions and explanations of observed phenomena during the interview and in later analysis. Drawings were used only as an auxiliary element, which is sometimes used while conducting interviews with students [36,41], and were not in the focus of the study.

During the interviews, students were encouraged to express their thoughts out loud as much as possible [42]. Additional questions were asked to get a better insight into students' reasoning.

The patterns that were obtained in experiments are shown in Fig. 2.

All interviews were transcribed and analyzed using the framework for qualitative content analysis by Kuckartz [43]. As a starting point, deductive main categories were formed, based on known difficulties found in literature. Then, deductive main categories were refined by

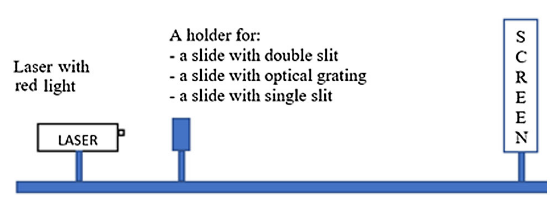


FIG. 1. Schematic representation of the experimental setup.

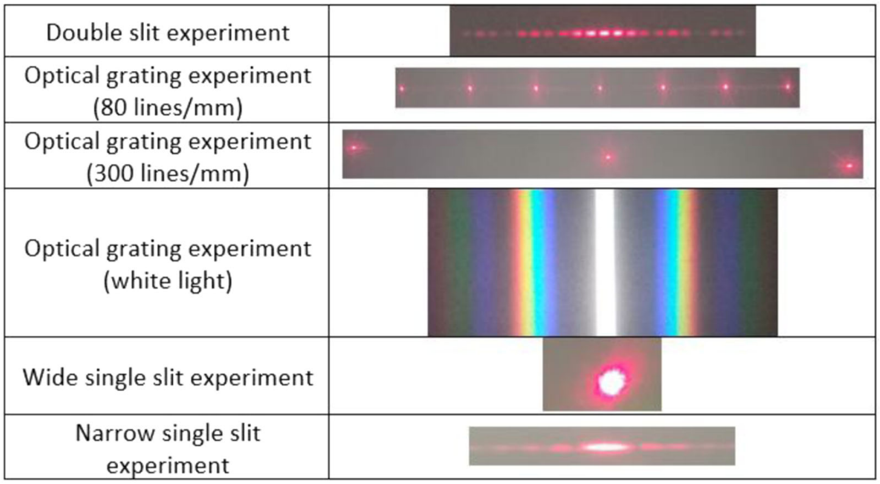


FIG. 2. Patterns obtained in experiments shown to the students.

creating inductive categories, where some of them were new *p* prims and resources. This process, described with examples in the following paragraph, had several iterations of qualitative content analysis, as instructed by Kuckartz [43]. The analysis was performed by two authors, K. M. C. and L. I., and discussed with the rest of the group. The steps of the identification and analysis of new *p* prims and resources are described in Richard, Jones, and Etkina [34]:

Step 1: Read the transcript and attempt to describe what is happening in the event with no mention or thought of resources. This is to make sure we recognize the context and can better understand the students' reasoning at a macro level.

Step 2: Identify key aspects of the reasoning event and determine whether or not they are being actively used in the event.

Step 3: Identify the specific words or phrases that serve as evidence that the particular knowledge aspect is being activated; it may be necessary to consult neighboring passages or utterances to ensure the proper context is understood.

Step 4: Classify this piece of knowledge based on previously identified resources from the literature, if possible.

Step 5: If the piece of knowledge does not seem to correspond to a previously identified resource, give it a tentative name, and classify it as a *p* prim, conceptual resource, or epistemological resource.

Step 6: Compile a running list of resources that have been identified in the investigation. We refer to this list in classifying future events to maintain consistency.

As a starting point, the transcripts were first thoroughly read so the analyzers could familiarize themselves with the content. Then for each interviewed student, the parts of the transcripts that corresponded to their predictions were extracted to separate tables, where each row contained a student code, quotes (together with interviewers' quotes), and students' drawings. After the tables with students' and interviewers' quotes and drawings were created, the analyzers scanned separately through the tables and, as a starting point in analysis, looked for correct, partially correct, and incorrect answers, which were then compared and discussed with the rest of the team. A fraction of students' answers was then independently categorized for student difficulties and resources by K. M. C. and L. I. as in steps 3–6. The assigned categories and their names were discussed first by both analyzers and later checked and discussed with the rest of the team. Through team discussions, the whole process of categorization was refined and sometimes took a different course than was initially intended by the categorizers. After the consensus of the team was achieved, the rest of the answers were separately categorized by K. M. C. and L. I. and later again checked and discussed with the rest of the team. The identification of activation of resources is not an easy or straightforward task, as other researchers have also suggested [34], since it requires a lot of subjective estimation, and often student answers and reasoning are not presented in a clear and orderly fashion. The process of categorization, therefore, required a lot of consultations and discussions between the two categorizers and the rest of the team. It was therefore not possible to achieve a completely independent categorization and to calculate the interrater reliability, but it could be estimated that the two categorizers initially agreed on 70%–80% of their classifications.

Here is an example of categorization: if a student stated that *the beam of light could only partially pass through the narrow slit because the diameter of the light beam was bigger than the width of the slit*, and the accompanying drawing also indicated that the part of the incoming light was blocked, it was concluded that this student probably activated the *p* prim *blocking*.

We were also aware that students often used conceptual resources from other domains of physics besides wave optics (such as mechanical waves or geometrical optics), so their answers were also scanned for activation of possible conceptual resources. An example of conceptual resource activation is some students' idea that the edges of the slit are new sources of light because two sources are needed for interference. This is obviously a (wrong) application of a content-specific idea (at least two sources of waves are needed for interference to occur). With no understanding or idea of Huygens-Fresnel principle application, students applied a fact learned at school, that resulted with idea that edges of the slit are the only new sources of light that contribute to the formation of a diffraction pattern.

VI. RESULTS AND DISCUSSION

In this chapter we report and discuss students' answers to the tasks that were described in the previous section, grouped as predictions, observations, and explanations.

A. Predictions

1. Double-slit experiment

In this experiment, students were asked to predict what they would see on the screen when laser light illuminated two close narrow slits. The summary of students' answers is given in Fig. 3. From our experience, the double-slit interference pattern, that is usually presented in textbooks with equidistant maxima of the same intensity (which was also our expectation for the correct answer), is quite different than the interference patterns that could be produced with the standard experimental equipment available to teachers. Most of the available double slits produce a combination of diffraction and interference patterns: inside every diffraction pattern there is an interference pattern (Fig. 2). Experts (i.e., teachers) usually focus only on the interference pattern inside the central diffraction maximum, but students still observe multiple diffraction maxima, which can be confusing.

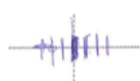
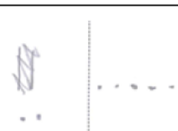
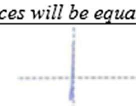
	Examples of students' sketches	Examples of students' comments
Correct prediction $N = 7$		Student S19_E: *"If there is a diffraction, then this one [the central maximum] is the biggest and, and the others will be smaller as we are moving away from the central [maximum]. … This is Young's experiment, interference [of light happens]. The laser is like one source and then, when [the light] comes to the slit[s], we have two very close coherent light sources. […] The interference of light is happening and because of that we have dark and light areas."*
Partially correct prediction – multiple maxima $N = 5$		Student *S05_G:* *"The dots are denser in the middle, and they will be less dense the further away we move from the center."*
Incorrect prediction – two bright spots $N = 9$		Student *S13_E:* *"The plastic in the middle might break the light in half, that will be seen. But it is quite small to be seen. "* *"This [separation in the middle of the drawn dot] is this plastic between two slits."*
Incorrect prediction – vertical pattern on the screen $N = 2$		Student S01_E: *"I expect… There will be some dark and white fringes on the screen. … Dark and light fringes."* *"I never understood whether they would be horizontal like this or [vertical] like this."*
Incorrect prediction – circles $N = 1$		Student S02_VG: *"I remember from one class that there was talk about maxima and minima of broken light. That is what I remember. It won't be correct, but that's ok. There will be one little dot in the middle and around it there will be light and dark shadows of light."*
Double prediction – what student thought would happen and what he was taught would happen $N = 1$		Student S06_E: *"Should I draw what I think or what I was taught at school?"* *"I think that there will be only two dots. There are two slits and there is a continuous light that should be split in two parts."* *"If I have not confused it, there should be multiple dots. … And I think the distances will be equal."*
Other $N = 2$	 only parts of the *laser dot* are visible because of the slits	 the "shadow" of the obstacle

FIG. 3. Frequencies of students' predictions for double-slit experiment, with some examples of students' sketches and comments.

Fifteen students expected multiple maxima, but only seven students out of 27 offered a prediction that could be considered correct (expecting multiple equidistant maxima, either of decreasing or constant intensity).

Students were taught at school that the intensity of the maxima is the same in the ideal double-slit experiment, but in the actual experiments they could have noticed some decrease in intensity, so for that reason, both predictions were treated as correct. Some of the students expected the central maximum to be slightly larger than the rest of the maxima, but that could be due to the equipment used in school for the demonstration of Young's experiment, where the central maximum sometimes could appear slightly larger than the rest of the maxima. Some of the students recognized this experiment as Young's experiment (e.g., student S19_E in Fig. 3).

Predictions given by five students, that were considered partially correct, included multiple maxima. But their answer was often unclear, because some of them gave no additional information about the pattern or expected either nonequidistant maxima (e.g., student S05_G, Fig. 3) or stripes instead of dots.

The most common incorrect prediction was that of only two bright spots on the screen. The obstacle between the two slits was suggested by many students as the reason for that. Student S24_VG argued his prediction of two bright spots: "*It's probably because this one line divides this laser [beam] into two parts*." Student S16_VG simply stated: "*…., I think it will break and then we will have two [spots]*."

Some students expected fringes instead of dots. Student S22_E, for example, predicted vertically elongated fringes because of the shape of the slits: "*…since the slits are straight [vertical], they (the maxima) will be stripes*."

Two students predicted multiple maxima but expected them to be vertically distributed on the screen, because they thought light could only pass through slits in that direction.

Student S06_E offered two predictions—one was based on his intuitive thinking, where he expected two bright spots on the screen, but the other was based on what he was taught at school, where he remembered equidistant multiple dots.

Two students gave predictions that could not be categorized because their drawings and explanations were vague.

2. *Optical grating experiment*

The experimental setup for this experiment consisted of an optical grating with 80 lines/mm, and later with 300 lines/mm, illuminated with laser light.

In the experiment with the optical grating of 80 lines/mm almost all students expected multiple maxima on the screen, as shown in Fig. 4. Identifying correct and incorrect predictions, however, was not an easy task. Only seven students gave predictions (in combination of words and drawings) that were considered correct, like the prediction of student S21_G (Fig. 4). She expected multiple equidistant maxima of equal intensity, and she expected them to be separated more than in the double-slit experiment.

Most of the students who gave wrong predictions ($N = 10$) expected a denser distribution of maxima on the screen. Some of them, like student S16_G, expected many maxima on the screen because there were many more slits on the optical grating than in the previous experiment with the double slit. After the observation of the pattern, she was asked why she expected maxima to be closer, and she replied: "*Since there are so many slits, I thought there would be more of them [maxima]*." Student S12_E expected that there would be 80 bright and 80 dark lines on the screen because there were 80 lines on the optical grating.

Two students expected maxima aligned vertically across the screen (these are different students than those who expected the same in the experiment with the double slit). Six other students gave predictions that could not be grouped with any other predictions. For example, they confused the patterns of various wave optics phenomena, thus expecting a prominent central maximum, maxima that are not equidistant, a pattern with no central maximum, or maxima scattered around the screen. Two students gave no prediction at all.

When the grating with 80 lines/mm was replaced with an optical grating with 300 lines/mm, 17 students gave a correct prediction (Fig. 5). Some of them based their expectations on the observations from the previous two experiments. Student S09_VG stated: "*We noticed that when we had 80 [lines per millimeter] the dots were more separated than when we had only two of them. Now, when we have 300 [lines per millimeter] they will be more separated than [in the experiment with grating] with 80 [lines per millimeter]*." Some of the students had similar reasoning, but they simply stated that the distance between maxima would be greater than before, because now there were more lines per millimeter of the grating.

All students who gave incorrect predictions expected a very dense distribution of maxima on the screen (Fig. 5). Student S22_E reasoned, for example, that there would be more maxima on the screen because there were "*many more sources that interfere*," student S24_VG expected more maxima because there were now more slits per millimeter on the grating, and student S12_E once again predicted the same number of maxima on the screen as there were lines on the grating, 300.

The experiment with the white light incident on an optical grating (80 lines/mm) was difficult for students, because now they had to consider polychromatic light (white light). The additional elements were added to the experimental setup consisting of a white light source and the grating, like a wide entrance slit (to narrow the beam of light from the source) and a convex lens (to focus the image of the slit on the screen). Only four students offered the correct prediction in case of white light.

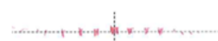
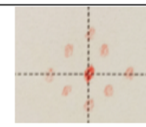
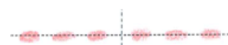
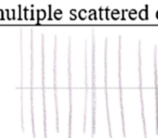
<table>
<tr><th></th><th>Examples of students' sketches</th><th colspan="2">Examples of students' comments</th></tr>
<tr><td>Correct prediction
$N = 7$</td><td></td><td colspan="2">S21_G:
"There will be dots again, but I think this time they will be the same. There will be no, as we saw before that they disappear, but they will be of the same strength."
The interviewer: "What separation do you expect between them?"
S21_G: "Equal."
The interviewer: "Comparing to the experiment before?"
S21_G: "Bigger."</td></tr>
<tr><td>Incorrect prediction – very dense maxima
$N = 10$</td><td></td><td colspan="2">S06_E:
"I expect denser and many more dots."</td></tr>
<tr><td>Incorrect prediction – maxima aligned vertically
$N = 2$</td><td></td><td colspan="2">The interviewer: "So, you drew them vertically on the screen?"
S15_G: "Yes, I think it could be that way…"</td></tr>
<tr><td rowspan="2">Incorrect prediction – other</td><td>
a prominent central maximum</td><td>
maxima are not equidistant</td><td>
multiple scattered dots</td></tr>
<tr><td>
a vague prediction</td><td>
central maximum is missing</td><td>
elongated maxima</td></tr>
<tr><td>No prediction at all
$N = 2$</td><td colspan="3">Student S24_VG: "I really have no idea what could happen. I really don't know."</td></tr>
</table>

FIG. 4. Frequency of students' predictions for optical grating (80 lines/mm), with some examples of students' sketches and comments.

Student S07_E gave the correct prediction of the pattern, as shown in Fig. 6. He correctly predicted a white central maximum, and continuous white light spectra in higher maxima, with the correct ordering of the colors. He also included a wrong explanation for the spectra, stating that the colors occur due to the refraction of light.

Wrong predictions were quite diverse (Fig. 6). Students were given optical grating for examination before any of the experiments with grating was performed, so many of them looked through the grating to the ceiling light and observed spectra. Therefore, some of them knew that the pattern in this experiment should be colorful, so they

	Examples of students' sketches	Examples of students' comments
Correct prediction $N = 17$		S15_VG: *"In comparison to these two experiments, the separation [between maxima] was bigger because you said they have more [slits], 80 or how many there were. Here we have 300 of them, so I presume the separation will be even bigger now. "*
Incorrect prediction – denser maxima on the screen $N = 10$		S11_G: *"It seems that there are more lines, so there will be more dots."* *"[In comparison to the previous observation] it will be denser."*

FIG. 5. Frequencies of students' predictions for optical grating (300 lines/mm), with some examples of students' sketches and comments.

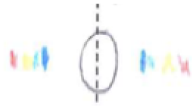
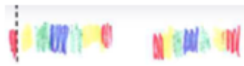
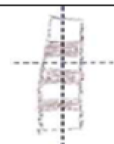
	Examples of students' sketches	Examples of students' comments
Correct prediction $N = 4$		S07_E: *"In the middle will be white… spot. Because the light… Like, light of different wavelengths refracts differently, but everything will meet in the middle so there will be white. And, on the side it will look like a rainbow, it will go from the purple in the inside to the red."*
Incorrect continuous spectra $N = 8$		S04_VG: *"I will draw multiple spectra because, when I looked [through the grating] to the light, I saw more of these lines. Little spectra."* *"Blue one is in the middle, then green from both sides [of the blue], then yellow, then red…"*
Incorrect prediction – discrete spectra $N = 3$	 (*C* stands for *red*, *LJ* for *purple*, *B* for white color)	S09_VG: *"I think there will be some stripes for sure but… I think that the middle stripe will be white (B) and others… The closest one is, I don't know, either red (C) or purple (LJ), one of that. And the rest between the red and the purple should be other colors…"* *"[The closest one] should be purple. I'm not sure, but I think it's purple. Then go other colors. I really don't know how the colors of the rainbow go."*
Incorrect prediction – white and black fringes, vertically aligned $N = 3$		S11_G: *"I suppose there will be broken light with dark and white parts."*
Incorrect prediction – white and black fringes, horizontally aligned $N = 9$		S16_G: *"I think the light will be broken to the smaller lines."* The interviewer: *"The lines will be of what color?"* S16_G: *"The same as the light."* The interviewer: *"In this case…?"* S16_G: *"White."*

FIG. 6. Frequencies of students' predictions for optical grating (80 lines/mm) illuminated with white light, with some examples of students' sketches and comments.

predicted various colorful spectra, like discrete spectra ($N = 3$) and continuous spectra (or spectrum) at different positions ($N = 8$). Students who expected continuous spectra (or spectrum), expected no central maximum at all, or expected it to contain a spectrum, too.

The rest of the students predicted a pattern consisting of multiple white and dark fringes, even though many of them looked through the grating to the ceiling light. Three of them predicted maxima aligned vertically on the screen, and all of them mentioned breaking of the light while describing their prediction, like student S11_G (Fig. 6). Nine students, like student S16_G (Fig. 6), expected multiple alternating white and dark lines, but distributed horizontally on the screen.

3. Single slit experiment

The experiment with a wide single slit was the easiest for the students, and almost all of them ($N = 25$) gave the correct prediction of only one dot on the screen (Fig. 7). For their prediction, many of them compared the width of the slit to the diameter of the laser beam. Since the slit was wider than the diameter of the laser beam, they concluded there would be no pattern on the screen. Two students expected something different than one dot on the screen. Student S02_VG, for example, expected to see only one long horizontal line on the screen. In this prediction, he continued to use his idea of the breaking of the light. He noticed that there were no obstacles in a wide slit (like the plastic separating the two slits before), so he expected to see a long uninterrupted line. Student S08_G expected multiple maxima and minima aligned vertically on the screen but did not offer any explanation for his prediction.

Unlike the experiment with a wide slit, the experiment with a narrow slit was the hardest experiment of all for the students (Fig. 8). Only one student gave the correct prediction (S20_VG), who tried to remember what experiments she saw at school, so she assumed she saw this one too: "*I'll trust myself and say this time there is the bigger one [central maximum], and then the smaller ones [other maxima].*" Nine students gave a prediction that had at least some correct elements (e.g., multiple maxima, but with little to no distinction from the double-slit pattern).

Other students expected to see on the screen either one smaller dot than before ($N = 9$), one narrow vertical line ($N = 6$), or one horizontal line ($N = 2$). Students who expected one smaller dot than before mostly explained that only a fraction of the beam will pass through, since the slit

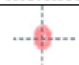
	Examples of students' sketches	Examples of students' comments
Correct prediction $N = 25$		S22_E: *"Considering this width [of the slit], I expect to see one dot… where all of the light is concentrated."*
Incorrect prediction – vertical pattern $N = 1$		S08_G: *"They may be separated again, but this time not horizontally, but vertically [aligned]."*
Incorrect prediction – long horizontal line $N = 1$		S02_VG: *"… considering there is no obstacle, it might be only one straight line with no minima and maxima. … I think this will be a straight line."*

FIG. 7. Frequencies of students' predictions for a single wide slit, with some examples of students' sketches and comments.

width is smaller than the laser beam diameter. Student S15_VG expected to see a little line because "*the gap is narrower, and light cannot pass through that gap*." Some of the students who expected the line to be vertical, argued their prediction based on the slit orientation.

B. Observations

After the students gave their predictions of the pattern on the screen, each experiment was performed. Students were then asked to sketch and describe their observations. Students were expected to describe all the features of the pattern, e.g., distribution of maxima and minima, the separation between the maxima, intensity of the maxima and, in some cases, give comparison with the observations from the previous experiments. Patterns from the experiments shown to students are given in Fig. 2. The main finding from this task is that students' observations were often incomplete and imprecise. Table A in the

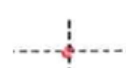
	Examples of students' sketches	Examples of students' comments
Correct prediction $N = 1$		S20_VG: *"Hm, I don't know. I'll trust myself and say that this time there is the bigger one [central maximum], and then the smaller ones [other maxima]."* *"I remember we did this [experiment], and it was… one of them certainly was like this. I believe it's the one with a single slit."*
Partially correct – expecting multiple maxima $N = 9$		S06_E (while drawing): *"I think we will get stripes of light and darkness."* The interviewer: *"Is it similar to something we have already seen?"* S06_E: *"Yes."*
Incorrect prediction – smaller dot $N = 9$		S14_G: *"First, I think only one small part will pass through, and second, it will pass undisturbed. I can't decide."* *"I will draw a smaller dot."* The interviewer: *"So, smaller dot [now] than it was when the slit was wide. Why do you think that?"* S14_G: *"Well, it is a really small gap, that slit…"*
Incorrect prediction – one vertical line $N = 6$		S16_G: *"I think it will spread like this."* The interviewer: *"Vertically?"* S16_G: *"Yes."* The interviewer: *"Why vertically?"* S16_G: *"Because the slit is vertical."*
Incorrect prediction – one horizontal line $N = 2$		S09_VG: *"Now, I think, there should be a line on the screen because there will be diffraction. Then, I think, it should be a line."*

FIG. 8. Frequencies of students' predictions for the single narrow slit experiment, with some examples of students' sketches and comments.

Supplemental Material [44] shows the number of students who mentioned a certain feature of the observed pattern. Students most often commented on the intensity of maxima, whereas separation between maxima was noticed or commented less often, except in the case of optical grating experiment, where the separation seemed surprisingly large to them.

We noticed that students generally seemed to lack the skill of systematic observation of experiments, which is not very surprising for high school students. When starting to describe the pattern, students usually referred to the differences between their prediction and the observation, and to the most prominent features of the pattern. For the double-slit experiment, the most prominent features were multiple maxima and the intensity of the maxima. Since many students predicted only two bright spots on the screen, some of them, like student S06_E, who gave double prediction, simply stated that he "*sees more than two dots*." In addition to the two students who predicted a vertical pattern, many other students (mostly those who expected only two bright spots on the screen) noticed also that the pattern was horizontal, which they seemed to find surprising. Student S14_G noticed: "*You placed this [the slits] vertically, and it [the pattern] turned out to be horizontal*." Many students were able to correct themselves while observing, like Student S05_G who expected multiple, but not equidistant maxima (Fig. 3), but corrected himself while observing: "*I see what I predicted. They are more visible in the middle, but not because they are denser, but because they are more visible. The dots are thicker, wider, and the dots away from the middle are smaller, thinner, and less visible. They are not separated more*."

In addition to not noticing every feature of the patterns, some students struggled with the basic physics terminology. They referred to the maxima as "*dots*" or "*line*," and one student even named them "*the wavelengths*." Even though some students used the word intensity in their descriptions, many of them were saying that "*the brightness decreases*."

An important new finding was that the pattern of alternating maxima and minima was often described as "*the broken line on the screen*" or "*the horizontal red line divided into multiple parts*."

Student S02_VG described the double-slit pattern in the following way: "*…the most important thing is that [the light] was broken and we can see the holes. … So, this line of light, that is more intensive in the middle, is broken in equal intervals*." His observation also convinced him that his idea of breaking the light makes sense, he just had to make some adjustments to what the *broken* light looked like.

Most of the mentioned difficulties with observations in the double-slit experiment were repeated when students were giving observations of other patterns. For the optical grating experiment, the separation between the maxima, compared to previous experiments, was also the prominent feature, alongside the intensity. Many students referred to the separation of maxima.

The most prominent feature of the single-slit experiment was the bright and wide central maximum and the very rapid decrease in the intensity of the maxima, as student S13_E noticed: "*So, the central dot, let's say, is much brighter than the others. Light is spreading horizontally. The further it goes [to the side], the less intensity, just like on the first one [the double slit experiment]. So, it is alternating bright, dark, bright, dark*." Here, students also used the idea of breaking the light in their observations: "*I see, as before, a horizontal line with cracks*."

When asked for the observation, some students named the phenomenon instead, e.g. interference, diffraction or started to explain it, with or without a description.

The experiment with white light incident on an optical grating was slightly different than the rest of the experiments shown to the students, because polychromatic light was used (white light) instead of the monochromatic light (red laser light). The most prominent observed feature were colorful spectra (maxima of higher order), mentioned by all students. The second most mentioned feature was the white central maximum.

C. Explanations

1. Double-slit experiment

The double-slit (Young's) experiment is the basis of wave optics, whose explanation requires several steps. Two slits should be very narrow, so that we can treat them as point sources of light. If the waves from the two slits meet in phase at some point on the screen (so that their path length difference is a natural multiple of light's wavelength), they interfere constructively, resulting in a maximum (a bright spot on the screen). If the waves meet by 180° out of phase (so that their path length difference is an odd multiple of half wavelength) they interfere destructively, thus creating a minimum on the screen (a dark area between the two maxima).

Analysis of students' answers showed that only five students offered the correct explanation for the observed phenomenon, and another five students offered an explanation that was only partially correct (Fig. 9). Student S09_VG, who gave a correct explanation, recognized the interference pattern. She said that each slit was acting as a source that emits light. Light is emitted in every direction and, if waves from the two slits meet in phase, there will be red maxima on the screen. Student S27_E gave a similar explanation but used the circular wavefront representation of the light (Fig. 9).

Student S21_G said that "*they [the teachers] told them*" that light is passing through two slits, and that light is "*full of crests and throughs, which then overlap and come to the screen, where they are gathered in one place, and that's how those dots are created*."

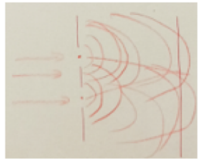
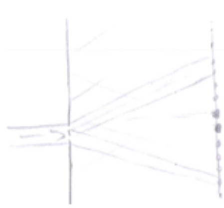
	Examples of students' sketches	Examples of students' comments
Correct explanation $N = 5$		S27_E: *"In red are the bright areas, and between them are the dark areas because… This is the Young's experiment, and the interference of light happens. So, the laser is, like, one source and then, when it comes to the slit, we have two coherent sources that are very close. I presume that the separation between them is approximately of the size of the red light wavelength. Then the interference of those two waves occurs and that's why we have dark and bright areas. "*
Partially correct explanation $N = 5$		S25_G: *"[The interference is] when… So, we can consider these two slits as two sources when light comes to them and then… Then the waves interfere, I mean… That means that they, like, create the light together. Their… these are the areas which [waves] influence together and then they [the waves] merge."*
Incorrect explanation – breaking of the light $N = 5$		S20_VG: *"[The interference is] when, I mean, the light passes through the narrow slit and breaks. It somehow… passes."* The interviewer: *"Here we have two narrow slits. Light passes through each [of the slits]?"* S20_VG: *"Hm, it breaks… because there is this middle line between [the slits]. Like, it divides [the light] in two parts…"*
Incorrect explanation – overlapping of the light beams $N = 4$		S05_G: *"[We see the dots] because the light diffracts through the narrow slits... The diffraction is, in layman's terms, bending of the light around some obstacle, in this case this black mask…"* Then he illustrated his idea in a drawing: *"The light comes like this [from the left-hand side of the image]. It will go like this [draws the arrow]. And then, because here is the densest interference [in the middle of the pattern], I mean, the interference of all… Ok, now we have two beams of light that come from the same source and that's why they have the same wavelength. In the middle is the biggest interference, and that's why there are the densest dots. And as we go away from the center, where there is only one beam of the light, where the other one doesn't come, here are thinner and smaller dots, and then there are no more of them [dots]."*
Incorrect explanation – mixture of different fragments of knowledge $N = 5$	S24_VG: *"Why do we see [this pattern]? Well, there is one source of light that is divided later… there is an obstacle later where we have two slits, which break the light, and we see [the light] on the screen as a line. An interference line."* … The interviewer: *"How did the light come to the dot at the far right [side of the pattern]?"* S24_VG: *"I'd say by reflecting off something… Probably from another wave, but I'm not sure."* The interviewer: *"You explained the maximum, how is the minimum created?"* S24_VG: *"… There is an area [on the screen] where no wave reflects to. "*	
No explanation given $N = 3$		

FIG. 9. Frequencies of students' explanations of double-slit experiment with some examples of students' sketches and comments.

The rest of the students offered incorrect explanations (Fig. 9). Five of them, like the student S02_VG, tried to explain the pattern in a double-slit experiment, using the idea of breaking of the light. He did not know the name of the observed phenomena, nor did he react when he was told that it was the interference of light. He said: "*It seems that the light is broken, but… I cannot explain why it spreads [across the screen]. I understand why it was broken because there is that obstacle [between the slits]*." Student S13_E also noticed the "*plastic*" between the slits, so he stated that the plastic "*disperses*" light and causes "*wavelengths to merge or to cancel each other out*." Student S16_G also stated that the light was broken by the slits, and she drew an image to support it. In Croatian language the same word can mean breaking or refraction, but the context of students' answers suggested that they did not mean refraction. *p* prim *breaking* involves splitting into several fragments due to some obstacle. Students often referred to some obstacle as the reason for the breaking of the light, and the result of the breaking was several fragments (several maxima). In refraction, on the other hand, one monochromatic beam of light remains one, only changes the direction of propagation.

Student S05_G mentioned interference and diffraction of light a lot in his explanation, but when he drew the image to support his explanation, it became evident that he used interference of light as a synonym for the overlapping of the light beams (Fig. 9). He expected that each slit is a source of a light beam. He explained that maxima are denser in the middle because there are two light beams overlapping, and that they become more separated as we move further away from the center of the screen because only light from one source arrives to that area. At the beginning of this experiment, he predicted that maxima created in this experiment would be denser in the middle, and separated more as they were further from the center. While observing the pattern, he corrected himself, stating that the maxima were equidistant. In his explanation, he once again returned to his initial idea, that maxima are denser in the middle.

Five other students offered an explanation in which they mixed several fragments of knowledge from various parts of physics, like student S24_VG. Even though he mentioned interference of light, he mentioned that "*the obstacle*" is breaking the light, and it seems that he treated waves as objects. He guessed that waves reflected (bounced) off each other and maxima appeared where wave was reflected (bounced) to, while minima were places where no waves were reflected (bounced) to.

Three students gave no or very vague explanations.

2. Optical grating experiment

In this experiment, students were expected to recognize that the optical grating consists of a very large number of slits, which act as new sources of light, that are much closer to each other than the sources in the double-slit experiment. Principal maxima are formed in the same way as in the case of a double slit, through constructive interference. Additionally, students may have explained the reasons for the difference between the optical grating and the double-slit pattern: since there are so many sources, the maxima are more intense, and since the sources are so close to each other, the distance between the adjacent maxima is larger for optical grating than for a double slit. The overview of students' answers is given in Fig. 10.

There were six students whose answers could be considered correct. All of them recognized that an illuminated optical grating acts as a source of many light waves that can interfere constructively and destructively. They did not try to explain the intensity of the observed maxima, but some of them did try to explain a large separation between maxima.

Four other students had the idea that the pattern is somehow created by the interference of light, but they were unsure of exactly how. Student S19_E was confused with the same intensity maxima. She noticed that the pattern was much wider than the grating, which was one of her criteria for recognizing diffraction. But her other criterion was the decrease of intensity, which she did not observe here. She tried to explain that light travels in different directions and drew rays emerging from the grating in multiple directions. Still, she attributed the maxima to overlapping parts of the waves (i.e., crest and crest). Student S21_G explained that "*the light of the same wavelength passes through more gratings, and they [parts of the waves] overlap in some places*." She added that maxima are created by the overlapping of the same parts of the waves (i.e., crests), and minima by the overlapping of the opposite parts of the waves (i.e., crest and through). She could not explain the larger separation between maxima, saying that it did not seem logical.

Four students expressed variations of the idea that each maximum is created by the light coming from its respective slit. Student S08_G explained that the grating separated light because it consists of "*holes and walls*." When light comes to "*the hole*" (the slit) it passes through, and if the light comes to "*the wall*" it does not pass. He represented light with arrows (Fig. 10) and explained that when light was passing through the slits it produced "*the dot*" on the screen. He then drew dots representing maxima for each slit. Student S12_E combined many fragments in his explanation, but the underlying motive was very similar to the previous example. He drew semicircular wave fronts emerging from the slits and explained that "*the top parts of the semicircles are actually the dots [on the screen] that we observe*." He seemed to not understand the idea of constructive interference, but he explained minima using the destructive interference idea. According to him, minima are "*area(s) where [the waves] overlap*," where crests and throughs of different waves arrive.

Some students expressed the idea that light was broken by optical grating. They noticed that maxima looked almost identical to the laser beam trace on the screen, but some of them noticed a slight change in intensity. Student S11_G imagined that the grating consisted of broken glass that breaks the light that is passing through it (Fig. 10). Student S16_G repeated the drawing she made for the double-slit experiment, where incoming ray of light was divided to multiple rays on the grating. She concluded that one ray was reflected by the grating to multiple rays. With each new experiment, student S02_VG was more and more convinced that his idea about breaking of the light was correct. After observing the pattern on the screen, he noticed: "*The first dot that was here disappeared. It lost its precedence and was broken to many others that… do not go in the direction that was before*." He suggested that the edge of the slit bounced (broken) light off in other directions.

Three students expressed the idea that maxima are created where beams of light overlap (Fig. 10). Student S05_G referred to his previous explanation and drawing for the double slit experiment (Fig. 9) and explained that now there were multiple sources, which led to the interference of the light, thus making maxima more intense and more separated. Even though he mentioned interference of light,

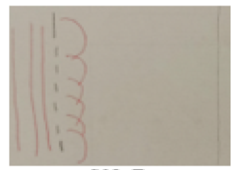
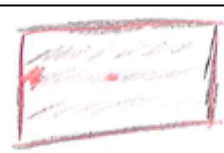
Correct explanation $N = 6$	S22_E: *"Since there are more slits now, there are more of these unique [separate?] sources. New sources that are created from this one [the laser]. And that's why the light can spread more [across the screen]. A lot more minima and maxima."* The interviewer: *"How come that in the maxima we again have light? What arrives to that point that we see a bright spot?"* S22_E: *"The constructive interference occurs. Two waves that are in phase and have a condition for constructive interference."* The interviewer: *"The separation between two maxima is bigger than before. How do you explain it?"* S22_E: *"Because there are more waves that interfere. Not only two, because there are not only two sources, but more. … 80 lines/mm, this [points to the grating] is something like 50 mm… 450, 500 [waves] perhaps."*	
Partially correct – using fragments of knowledge $N = 4$		S10_VG: *„[I explain what happens on] one slit, but there are more slits."* *„Here again the diffraction happens and then here too [shows the place on the screen]. They overlap together [she draws wavefronts] and then… they [maxima]are equidistant."*
Incorrect explanation – 1:1 (each maximum is linked with a specific slit on the grating) $N = 4$	 S08_G: *"When [the light] came to the grating, the grating separated the light."* *"[Before the grating, the light] goes in one straight line. When it comes to the grating, there are holes and walls. When it comes to the hole, it passes through. When it comes to the wall, it doesn't. And like that for each hole. "*	 S12_E: *"So, again I have a wave like this (parallel lines on the left-hand side of the image) and then it again the diffraction occurs. Like, one, two, three, four, five, six (he's drawing semi-circles). Then, the tops of the semi-circles are actually the dots[on the screen]…"*
Incorrect explanation - breaking of the light $N = 4$		S11_G: *"It seem to me that through that grating… that [the grating] is somehow broken on the inside … and when the light passes through, then through that broken glass [the light] somehow breaks across the line."*
Incorrect explanation - overlapping beams of light $N = 3$		S13_E: *"If we have a slit and here is a source of light [draws a point on the left-hand side of the image], the light will pass. It spreads."* *"When the light comes to those slits, it goes from each [slit] like each [slit] is a separate source. … Each slit actually emits a new part of the light and they merge at some instant and where they merge, that can be seen on the screen as those… bright, dark, bright, dark."*
Incorrect explanation – fragments of geometrical optics $N = 1$	The interviewer: *"How did light come to this side? … How come we see bright spots in multiple places?"* S03_G: *"Reflection of light."* The interviewer: *"How exactly does the light reflect?"* S03_G: *"These… slits, they reflect [the light]. So, here they are the cause of this reflection of light."*	
Vague or no explanation $N = 5$		

FIG. 10. Frequencies of students' explanations of the optical grating experiment with some examples of students' sketches and comments.

he once again stressed the overlapping beams of light coming out of the slits.

Student S03_G explained that light reflects off the grating, thus resulting in multiple maxima all over the screen, even though his explanation for the double-slit experiment included the interference of light. The answers of the remaining five students were too scarce or vague for proper analysis.

In the case of white light incident on an optical grating (80 lines/mm), even though many students ($N = 15$) expected to see colors, no one managed to explain correctly why and how exactly the colors appeared. Most students ($N = 21$) explicitly or implicitly expressed the idea that white light is polychromatic, but the concept of how the grating created spectra of colors seemed to be too difficult for students. The students' explanations were very scarce.

Six students reasoned based on geometrical optics and/or combined it with wave optics in their explanation. Student S07_E used the mathematical expression for maxima created by the optical grating and said that "*red has the biggest wavelength, so it will have the biggest angle of refraction*." In the continuation of the conversation about this topic, he mentioned diffraction on the slit and interference fringes. Student S19_E also seemed to confuse the refraction and diffraction of light: "*The white light of certain wavelength is not a point source and when it comes to diffraction, under some angle, we observe different colors*." Student S23_G, when asked for his observation said: "*Refraction of the light, different colors. Rainbow colors*." He explained that observing the colors indicated that refraction of light happened here.

Student S13_E remembered the experiment with a glass prism, and he described how the white light was refracted there. He could not explain why the colors appeared with the grating.

Student S05_G explained that the convex lens and the optical grating separated the white light in its components (multiple colors). In the white central maximum, he recognized "*the perfect interference*" where the path length difference was zero. Further away from the central maximum, the path length difference was increasing and there the light was separated its components. Since he used the similar explanation for the double-slit experiment, where he talked about interference and diffraction of light, but stated that maxima are created where two beams of light overlap, his explanation was considered as hybrid between geometrical and wave optics.

Four students used the idea of breaking of the light, like student S11_G who said that "*light separated in a spectrum of colors*." Student S16_G explained the creation of the colors: "*When [the light] passed through the grating, then that light was broken into multiple colors*." She added that the colors were in the optical grating all along and that we observed colors only when the white light was incident on the grating, because the white light's intensity was less than the intensity of the red laser light. In the context of the white light, it was less clear whether students activated the breaking *p* prim or the geometrical optics resource of refraction, in an analogy with a glass prism.

Four students expressed the idea that white light has a single wavelength. Student S08_G tried to explain the pattern and the order of colors using this idea: "*Hm, let's say that the white color is 0 [nm]. Then, 400 [nm for blue color] is closer to the 0 than 650 [nm for red color]*." He knew that the angle under which we see certain color must relate to the wavelength of the light, so he probably created his idea on the spot. Student S17_VG expressed a similar idea and he said that "*white light might have a specific wavelength that enables creation of colors*."

Seven students did not know how to explain this phenomenon, even though some of them tried, and three students did not offer any explanation.

3. Single-slit experiment

Explanation of the single-slit experiment is very complex and includes many steps that are difficult for students. However, the single-slit diffraction is a part of the compulsory physics curriculum in Croatia, meaning that the teachers had to cover it. Even though this is a challenging topic, since students learned about it, we wanted to investigate their understanding of it. The single slit cannot be modeled as a point source of light to understand diffraction, like each slit was modeled (at least in theory) in the double-slit and the optical grating experiments. Instead, the Huygens-Fresnel principle must be used to model the wave front passing through the slit as consisting of infinitely many point sources, each emitting new wavelets which interfere. Student S07_E made a remark that "*one slit is slightly more complicated*" than the situation with the two slits. Although student S07_E observed the "*fringes of interference*" with "*one very bright (fringe) in the middle*," he was the only one who knew that there were countless new sources in the slit ("*If there is only one slit, there we have a lot of new sources*."). He explained the lower intensity of higher order maxima with the textbook derivation (Fig. 11), where the light coming out of the slit to form the first maximum, was divided into three equal parts, and rays from the first two parts canceled out, leaving only one-third of the light to form the first maximum. Bright spots, as he argued, are "*not the real constructive interference, but simply not all the rays canceled out*."

Many students, after seeing the single slit pattern, expressed the idea that for the interference to occur there should be two waves or two sources. Four of them attempted to solve this problem by stating that the edges of the slit are now new sources of light, effectively turning the single-slit situation into the double-slit situation. Student S09_VG stated that the multiple fringes are here because of the interference, and that meant that "*there must be two waves that can interfere together*" so "*both edges of the slit are separate sources*" (Fig. 11). When asked whether the light passes through the middle of the slit, she estimated that "*the space between the edges is very small, so the whole wave cannot pass, only a fraction of it can*." Student S26_VG also considered the edges of the slit to be the new sources of light, but she argued that the rays that go through the middle of the slit pass undisturbed, expressing a hybrid model of geometrical and wave optics.

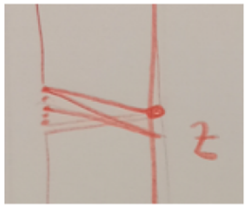
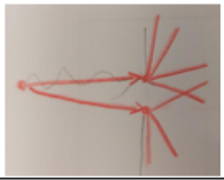
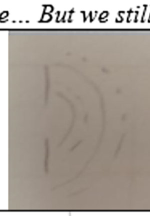
	Examples of students' sketches	Examples of students' comments
Correct explanation $N = 1$	 "Z" is for screen	S07_E: *"Usually when we have two slits, then those points are… all the rays interfere constructively, and bright spot is created. But here when we have one slit… If there is only one slit, there is a lot of new sources. … I mean, in the middle will always be [maximum] because… they are equally separated and there will always be bright spot. But, if we go on the side, for example, this one [ray] and this one in the middle will destructively interfere and then, I don't know, there will be one source that will not cancel with other [ray] and that's why such dim light spot is created."*
Two sources of light are needed for interference – edges of the slit as new sources $N = 4$		S09_VG: *"The diffraction is still happening because there are slits. But there is an interference too. Which means there must be two waves that can interfere together. Then each… each edge of the slit should be a separate source."*
Two sources of light are needed for interference – a single slit is a single source of light $N = 4$	S22_E: *"Here, in this case, after the light passes through the slit the diffraction happens. But why is there an interference… So, here should be some two waves that interfere. How they are created, I have no idea. A similar thing happens as in the case of optical grating [situation], but here is only one slit. This is some characteristic if waves, considering there is a diffraction, but I'm not sure."* *"[Huygens' principle] is used to explain any experiment with light and slits. When light passes through the narrow slit then… a new source is created in the slit… Here should be one source… But we still see interference pattern."*	
Example of a solution of "a single slit is a single source of light" problem $N = 4$		S21_G: *"I think that, when light passes through the slit, as we drew before for double slits, it spreads like crests and throughs."* *"Why are the dots created? Probably in the places where crest touches [the screen]. Maybe there will be a bright [spot]. And where not, there probably the through [touches the screen]. Probably, I don't really understand this part."*
Breaking of the light $N = 4$		S16_G: *"The slit broke it, so [the light] spreads."* *"[The light] broke. I mean, the slit broke one ray when the ray tried to pass through this one slit."*
Reflection of the waves $N = 1$	The interviewer: *"How did the light come to the place where it wasn't before?"* S24_VG: *"The same [as before], by reflection of the waves."* The interviewer: *"… But how was the central maximum created?"* S24_VG: *"Maybe plenty of waves were reflected to the same place. I'd say so."*	
Vague, no idea, or no answer $N = 9$		

FIG. 11. Frequencies of students' explanations of the single narrow slit experiment with some examples of students' sketches and comments.

The other four students treated the single slit as a single source, and they could not understand why maxima on the screen were there. Student S23_E mentioned Huygens-Fresnel principle but was unable to apply it to a single slit: "*Huygens principle*[1] *is used for explaining experiments with light and slits. When light passes through the narrow slit, it seems that the new source is created in the slit*." She was very confused with the observed pattern: "*Here should be one source. But we observe an interference pattern*." Student S15_VG said that the observed pattern would be logical if there were two slits "*where refracted light could intersect*."

Four other students also treated the slit as a single source, but they tried to explain the single-slit pattern using the idea of circular wavefronts. Student S21_G drew circular wavefronts and pointed to the crests and troughs. She guessed

[1]In Croatian textbooks, the Huygens-Fresnel principle is usually referred to as the Huygens principle only.

maxima on the screen are located "*where crest touches the screen*" and minima where the through touch the screen. At the end of her explanation, she stressed that she really did not understand this part.

Four students expressed the idea that breaking of the light was responsible for the obtained pattern. Student S16_G drew the same representation she drew for the previous experiments (Fig. 11). She supported her drawing: "*The slit broke one beam when it tried to pass through that one slit*." Student S02_VG was very surprised to see maxima and minima in this experiment, because now there was no obstacle to break the light, as he explained for the previous experiment(s). He observed that the "*(laser) dot was spread across the screen*," so he modified his model of breaking the light once again and concluded that in this case "*narrowing of the slit breaks the light*."

Student S24_VG noticed the prominent central maximum and decided that it was so prominent because the slit was not very narrow. Narrowing the slit, he thought, would narrow the central maximum too. He repeated his idea of wave reflection: light came to the area of geometrical shadow because waves bounce off each other. The remaining eleven students offered very scarce answers, or no answers at all.

D. Summary of the observed student difficulties

We will now try to summarize our findings from the interviews and provide a response to our first research question: What are the difficulties that high school students have with understanding interference and diffraction of light with the related standard experiments?

Students expressed various difficulties in all three studied aspects: predictions, observations, and explanations of standard wave optics experiments. General difficulties that students showed regarding experiments were their inability in most cases to predict standard wave optics patterns, their lack of systematic observation skills, unfamiliarity with the patterns, and poor understanding of the phenomena involved. Generally, students seemed to lack previously formed models of the phenomena and they seemed to have formed some provisory models when they were asked to provide explanations of the observed patterns.

Some difficulties that were identified in students' predictions are the following:

(1) The dominant incorrect prediction in double-slit experiment were two bright dots and some students interestingly predicted a vertical interference pattern.
(2) The dominant incorrect prediction for the optical grating experiment with monochromatic light was a pattern of very densely spaced maxima, and for the optical grating with white light, the pattern of black and white fringes, either horizontally or vertically aligned.
(3) For the single-slit experiment, the most common predictions were one small dot or one vertical line of light.

Students' observations were often incomplete and imprecise. They tended to focus usually on one aspect of the pattern, most often the intensity or the number of maxima, whereas the spacing of maxima was rarely mentioned.

In explanations students showed the following difficulties:

(1) Invoking "breaking of the light," occurring either at the slits or at the obstacle between the slits, to explain the appearance of maxima and minima in the double-slit, optical grating, and single-slit experiment; the resulting pattern in the double-slit experiment is also often described as a broken line of light.
(2) Explaining maxima as being produced at the places of overlapping of light beams (represented as geometrical light cones) from the slits.
(3) Associating each maximum in the interference pattern with one slit only.
(4) Using geometrical optics to explain wave optics phenomena (e.g., maxima are created by the reflection off the edges of the slits, refraction of white light on optical grating causes appearance of colors, etc.)
(5) Conceptualizing the single slit always as a point source of light and concluding that for the interference to occur on a single slit two waves or two sources are needed (usually identifying edges of the slit as these sources).

Difficulties concerning explanations (4), (5) were identified in previous PER studies on university students' understanding of wave optics [6,8,12], but difficulties (1) and (2) were, to our knowledge, not previously reported and difficulty (3) was reported in the context of the double-slit experiment [6,8,14], but not in the context of the optical grating.

E. Student answers within the resource-based model

The overview of the results suggests that students have numerous difficulties when it comes to interference and diffraction of light. Students struggled to predict, describe, and explain the interference and diffraction patterns. It was noticeable that many interviewed students had not formed a coherent model of wave optics during standard instruction at school. Many students seemed to have created their predictions or explanations on the spot, expressing in that process different ideas about how patterns were formed. Students' predictions of the patterns in each experiment were probably given as a combination of remembering (if they remembered seeing or learning about the specific experiment in the school) and reasoning about the situation. Among those answers and ideas many of the already known students' difficulties with wave optics could be recognized. Students often confused the domains of geometrical and wave optics (for example, when predicting a smaller dot on

TABLE II. The frequency of students' use of specific *p* prims and resources on different experiments. Labels *P*, *O*, *E* stand for prediction, observation, and explanation, respectively. The second column contains data for three experiments: optical gratings of 80 or 300 lines/mm with laser light and optical grating of 80 lines/mm with white light (labeled as 80, 300, and white, respectively, in the table).

	Double slit			Optical grating			Single slit		
	P	*O*	*E*	*P*	*O*	*E*	*P*	*O*	*E*
P prim or resource				80/300/white	80/300/white	80/300/white			
Breaking	8	5	4	1/0/3	1/0/2	4/0/3	0	3	4
Blocking	2	0	1	0/0/0	0/0/0	3/0/0	12	0	1
More is more	0	0	0	11/17/0	0/0/0	0/7/0	0	0	0
One cause, one effect	4	0	0	1/1/0	0/0/0	6/1/0	0	0	6
Guiding	1	0	0	0/0/0	0/0/0	0/0/0	6	0	0
Mechanical waves resources	0	0	10	0/0/0	0/0/0	3/2/0	0	0	1
Geometrical optics resources	0	0	5	0/0/3	0/0/1	3/2/4	0	0	0
Two sources are needed for IF (resource)	0	0	0	0/0/0	0/0/0	0/0/0	1	0	6
Prior experiments (resource)	0	0	0	0/5/6	0/0/0	0/3/0	0	0	0

the screen when the single slit was narrowed and/or predicting a diffraction pattern when the slit was wide or when attempting to explain maxima by reflection or refraction of light) [6,10], treated slits as point sources [6,7], considered the edges of the slit as the only new sources of light [6,7] in the single slit diffraction or simplified complex concepts [6,7] (for example, reduced the interference of light to the overlapping of the beams of light). The drawings made by student S16_G as explanation for maxima in every experiment (Fig. 11), showing incoming ray of light divided to multiple rays after the obstacle [slit(s) or grating] was something that Maurines [7] called the "*division diagram*," and drawings showing illuminated slits as sources of the light cones (Fig. 9 and Fig. 10) could be interpreted as the "*Deviation diagrams*," that show bending and spreading of the beam on the slit [7]. Depicting the edges of the slit as the new sources of light (Fig. 11) and drawing rays emerging from the edges only, are "$D + d$ *diagrams*," a combination of "*the Deviation and the division diagrams*" [7]. Results also showed that students used terms with defined meaning in physics (such as "*refraction*," "*reflection*," "*scattering*") wrongly, using them as an indication of change in the direction of the incoming ray(s) of light. The described discrepancy between true meaning of a physical term and its (incorrect) usage was found in other studies too [7,41], and some authors refer to this phenomenon as *language degeneracy* [41].

Students also focused on the dominant dimension of the illuminated slit(s) and expected all the maxima to look like the slit(s) [16] or expected maxima to be aligned on the screen in the direction of the dominant dimension of the slit. Some of the wrong predictions given for the experiment with white light incident on an optical grating, such as white and black pattern or discrete spectra, were also found in the previously conducted study of students understanding of atomic spectra [45,46].

In the following analysis we will try to answer our second research question: What *p* prims and cognitive resources are activated in the process of predicting, describing, and explaining the interference and diffraction patterns? When looking at the student answers within the resource-based model, one might see that many of their predictions, observations and explanations can be explained by the activation of certain *p* prims or the use of other resources, such as, e.g., concepts from geometrical optics.

We were able to identify the use of several *p* prims and resources in student answers. The frequency of their occurrence on different experiments is presented in Table II. There were probably more instances of students' use of *p* prims, which were implicit in some answers, but we have counted only those cases in which their use was explicit and corroborated by students' drawings.

1. Observed p prims

Breaking.—*p* prim *breaking* can be activated when students need to explain how one thing separates into many by way of encountering some obstacle. There were a few students who quite eagerly expressed their idea that the light was somehow broken by different mechanisms, to explain the appearance of multiple maxima from one original light beam. They used this idea when giving their first prediction, for the experiment with a double slit, where they expected that light would be broken into two parts, which would result in two bright spots on the screen. Student S13_E was one of the students who thought that light would be broken by the obstacle between the two slits: "*The plastic between the slits might break the light to two parts. But it is very small, so it might not be visible with the naked eye*." He drew the red circle that was separated into two parts by a very thin line (Fig. 3).

Student S02_VG used the idea of breaking whenever possible. He expressed this idea for the experiment with a double slit when he expected that light would be “*broken in two parts*.” Observing the pattern strengthened his reasoning, because he proudly exclaimed that “*the most important thing is that it [the light] is broken, and we see obvious holes [minima]*.” He then continued to use the idea of breaking of the light for the double slit and optical grating because there were obvious “*obstacles*” between the slits. He explicitly stated that he was “*almost 100% sure that, if there was no obstacle, it would only be one straight line [on the screen]*.” After observing the diffraction pattern, he adapted his idea once more: narrowing the slit breaks the light too. He also described the pattern in the double-slit experiment as “*a line that is broken in equal intervals*,” which is something that several other students have done too. Various patterns were described as a “*broken line*,” which suggests that this *p* prim was activated already during the observations.

Students S16_G also used the idea of breaking of the light to explain every observed pattern. She drew the same image of breaking of the light for every experiment (as shown in Fig. 11), only changed the obstacle.

One of the problems in recognizing this *p* prim is the language, because Croatian words for refraction of light and breaking are the same, which may also indicate language degeneracy [41], because students attributed different meaning to a well-defined physics term [41]. To identify what student really meant by some expression, we had to analyze the entire part of the interview where “breaking” was mentioned. The condition for recognition of breaking was that students talked about the slits or obstacles between them as acting on the light in some mechanical way. There is also one crucial difference: the refraction of light means that ray of light passes through different media and deflects from its original direction. But there is only one ray after refraction of light. In *breaking*, one ray was “divided” to many rays, as indicated by a drawing in Fig. 11.

To our knowledge, this *p* prim and its mechanism have not yet been reported. However, Watts, in his paper from 1985 [20], described a student who talked about breaking-up of the light or splitting of the light, while light was passing through a prism, or a rain drop. This student imagined the light as consisting of “threads” which were separated out of the beam while passing through the glass or the water, thus creating different colors [20]. This student used similar words to describe his idea [20] as the students in this sample: break-up, separate, split.

Blocking.—This *p* prim was most often activated in predictions for the experiment with a single narrow slit (Table II). Most students expected that only a part of the laser beam could pass through the slit, since the mask was blocking the rest. The *p* prim *blocking* might go together with students’ incorrect belief that light oscillations have spatial dimensions and therefore light may or may not fit through a slit. Student S15_VG expected to see “*a little line of light, because the gap is narrower [than the laser beam] and the light cannot pass through*.” Student S19_E expected to see a smaller dot than before because “*the slit is much narrower than the source*.”

Some students used the principle of blocking when explaining the pattern obtained by the optical grating. They stated that light passes through “*the holes*” (the slits on optical grating) and that, logically, it does not pass through “*the walls*” (separation between the slits).

Some students were quite surprised that the patterns were horizontal, while slit(s) were oriented vertically. That might also indicate the activation of the *p* prim *blocking* since they expected that light could only spread in the direction where it is was not blocked.

DiSessa introduces *blocking* as something that describes the phenomenon visually and geometrically [28]. An everyday example for *blocking* is something that prevents the motion of the body in a certain direction (if there was no table beneath the book, the book would fall to the ground, meaning the table is blocking the book from the fall). One of the internal justifications for blocking is that it would be absurd to observe that, for example, the ball penetrates the wall [28]. Some students probably expected only a fraction of laser beam to appear on the screen if laser beam was incident on a very narrow slit, because it would be equally absurd if the entire laser beam passed through the slit if the slit was narrower than the beam.

Guiding.—*p* prim guiding is introduced when something forces an object to follow a certain path [28]. In our interviews, *guiding* sometimes appeared in combination with *blocking*, which might explain why some students expected vertically aligned maxima on the screen (the mask beyond the edges of the slit *blocked* the light from spreading horizontally, in their view, and the light was *guided* to spread vertically on the screen). Some students were therefore quite surprised to see the horizontal pattern appear.

Increase in cause leads to increase in effect (more is more).—While predicting the pattern obtained by the optical grating, many students simply expected more dots than before on the screen. Student S08_G argued his expectation for the experiment with 80 lines/mm grating: “*Before there were two slits, and now we have* 80 lines/mm … *we will see more slits now [student confuses maxima with slits]*.” His expectation was partially based on the observation of the previous experiment with a double slit (two slits lead to many *dots*), so he expected to see even more dots with the grating (more slits lead to even more *dots*).

Student S23_G also stated: “*[The maxima will be denser] because now there are more slits*.” This mechanism could be summarized as: more slits on the grating (increased *cause*) lead to more maxima on the screen (increased *effect*).

Student S16_G also expected to see multiple dots with the grating with 80 lines/mm. When asked why there would be many dots, she simply stated that it was because on the grating "*there are more slits*." After observing that pattern, this student adapted her reasoning: the cause is the same (more slits), but the effect has changed (more separation). So, she expected only three dots on the screen, but more separated, because "*there are more of these lines now*."

The activation of this *p* prim was described by Richards, Jones, and Etkina [34], who called this *p* prim "*more cause means more effect*." Richards [35], describes its' application to photovoltaic cells—if more light (*cause*) hits the metal, more electrons (*effect*) are ejected. DiSessa also mentioned similar reasoning as an internal mechanism where "*more of x yields more of y*" [28].

One cause leads to one effect (1∶1).—This *p* prim was probably activated in ten students who expected two bright spots on the screen when two slits were illuminated, since two slits (two causes), produce two spots (two effects). Student S11_G expressed such an idea: "*Probably the light from the laser will pass through the two slits so the two slits will be seen*."

The same idea was used by student S12_E, who predicted that there would be 80 (or 300) bright spots on the screen in the experiments with optical gratings with 80 lines/mm and 300 lines/mm. He explicitly stated: "Well, *there are 80 slits, so probably there should be 80 [lines]*." For the next experiment with 300 lines/mm, when asked, he again expected 300 maxima.

During the interviews students also tended to state that each slit was one point source of light, which is something that was probably learned, but it might also be that students accepted that idea because it agrees with their internal *1:1* mechanism. *1:1 p* prim could probably be understood as a special case of the *more is more p* prim.

2. Observed conceptual and epistemological resources

Resources from mechanical waves.—During the interviews, some students explained constructive and destructive interference using the analogies and images of mechanical waves. If the crests (or throughs) of two waves overlap, this will result in an even bigger crest (or through), in the process called constructive interference. Destructive interference was explained by the overlapping of the crest (of the first wave) and the through (of the second wave), which then cancel each other out. It seems that many students internalized this visualization of the interference process, and it helped them to understand it. On the other hand, some students used mechanical analogy to create wrong explanations. One student who treated the single slit as a single point source (1∶1 *p* prim) used in addition mechanical analogy of crests and throughs to explain how maxima and minima in a diffraction pattern are created by only one source (an example is in Fig. 11, where this student described maxima as the places where the crest of the wave touches the screen, and the minima as the places where the through touches the screen: "*Why are the dots created? Probably in the places where crest touches [the screen]. Maybe there will be a bright [spot]. And where not, there probably the through [touches the screen]. Probably, I don't really understand this part*.").

Resources from geometrical optics.—Resources from geometrical optics were also sometimes activated and used by students during the interviews. Students sometimes mentioned in their explanations that light refracts or reflects from the slit(s). It is also possible that students sometimes used those words to indicate the change in the direction of the spreading of the light. If someone is not familiar with wave optics principles, explaining maxima of the higher order in interference or diffraction pattern using reflection or refraction of light might seem logical (to explain how the light reached some distant spot on the screen). Some students used the idea that a conical light beam comes out of each illuminated slit. This mechanism was used to explain the pattern of maxima and minima on the screen: overlapping of light beams produced maxima, and minima appeared in places where no light had arrived (Fig. 9).

The geometrical optics resources were also activated when students tried to explain the experiment with white light incident on an optical grating. A few students mentioned a similar experiment of white light being refracted by a glass prism, and for one student (S23_G) colors in the screen were an indication that the refraction of light had happened.

Two or more sources are needed for interference.—Many students have learned that for interference to occur at least two waves (from two sources) are needed. This resource worked well when it was activated to explain interference on a double slit or on an optical grating. In the context of single-slit diffraction, although it is in itself appropriate, the same resource led many students to confusion, because of another difficulty (the idea that each slit is a single point source of light). Some of them, like student S22_E, were very confused when multiple maxima appeared on the screen. She repeated a few times that even though the slit is one source of light, interference is obviously happening, and she could not understand why (i.e., she could not identify the second source). Some students tried to solve this problem by stating that the edges of the slit function as the only new sources of light since two sources are needed for interference to occur (Fig. 11, Table II).

Prior experiments in the interview.—It was evident that some students were able to learn during the interview from the observed experiments. This was especially evident when students were predicting the pattern on the screen for optical grating with 300 lines per millimeter, illuminated with laser light. Some of them based their (correct) prediction on the outcomes of the previous two experiments: double-slit and optical grating with 80 lines per millimeter. They noticed the trend of increasing separation between maxima with increasing number of illuminated slits and stated that they are making a prediction based on the prior observations. This was an example of successful learning during the interview.

Another example of the same resource activation may be when students predicted that white maxima would appear on the screen as the outcome of the experiment where optical grating was illuminated with white light. Students' prediction was probably based on previous observations in the interview: when optical grating was illuminated with red laser light, red maxima appeared on the screen. Here, students applied what they have learned during the interviews, but less successfully. They did not expect that white light would produce colors, maybe because they did not know that fact or they did not understand how polychromatic light behaves on an optical grating. Although incorrect, the prediction of white maxima was more in line with interference phenomenon, than, for example, the prediction of only one spectrum of visible light on the screen, given by some other students.

Knowledge comes from authority and knowledge is invented or created (epistemological resources).—During the interviews, many students referred to something they saw, heard, or learned at school. One interesting example was student S06_E who, when asked for his prediction of the double-slit experiment, asked what prediction he should share—what he *thinks* would happen, or what he was *taught* at school. Student S21_G said multiple times during the interviews that she was told something, that she remembered how teacher, or her friends explained something to her, so she reported how she understood their explanations. Generally, most students were able and willing to engage in thinking and answering even if they did not have ready answers to offer. They constructed models on the spot, and although these models were often wrong from the physics point of view, they showed that students relied on the *knowledge is invented or created* epistemological resource, which opens them to future learning and investigation. The minority of students possibly relied on *knowledge comes only from authority* resource and would not engage in creative thinking or attempt to answer on their own if they could not remember the answer from school. Even though there is sporadic evidence for epistemological resources activation, students expressions in this respect were very vague, thus making it impossible in most cases to identify with certainty students' use of epistemological resources.

As a final general remark, we can say that data in Table II suggest that most p prims and resources are context dependent, and more likely to be activated in some situations rather than others. Students usually used them when a cue of some sort was present (e.g., switching from two slits to 80 slits per mm was very likely to trigger the *more is more* p prim). It is important to stress that p prims and resources can be very helpful in some contexts but can be a hindrance in others. So, teachers can sometimes build on them, in situations where this is productive (as was suggested in other studies, i.e., Refs. [34,36,38,41,47], but generally teachers should help students move away from simplified reasoning and build more complex reasoning as well.

VIII. CONCLUSION

The goal of our study was to investigate high school students' difficulties with basic wave optics phenomena, after students had learned about it during their regular instruction at school, mostly lecture-based with some demonstrations. The investigation was conducted in the form of semistructured demonstration interviews, where students were shown several standard wave optics experiments (double-slit or optical grating interference and single-slit diffraction). Students were asked for their prediction of each experimental pattern, their observation and explanation. The results suggest that, even though students had learned about wave optics in school and passed the school test, they still have many difficulties in all the investigated aspects—predictions, observations, and explanations. Predictions were mostly incorrect, but surprisingly the observations of the patterns were also not an easy task for students. Students would mostly point out only the most prominent features of the pattern, and/or the difference between their prediction and observation. Subtle features of the pattern, such as equal separation of maxima in the double-slit pattern, were often not noticed. Monochromatic interference and diffraction patterns may look very similar to students, so skills of systematic observations should be developed more in physics teaching. The results also suggest that many students benefited by observing the experiments and the resulting patterns. Some showed that they could learn already from the mere observation of the experiments. Patterns obtained in the experiments with the double slit and optical grating with 80 lines/mm were unexpected by most of the students, but after that, students were quite successful in predicting the pattern for the experiment with 300 lines/mm.

Explanations were the biggest problem for the students. It was evident that many of them remembered some wave optics facts they had learned at school, but they had mostly failed to form adequate models of interference and diffraction. It seems that students therefore created explanations of the observed phenomena on the spot during the interviews. For example, students' explained that light was broken by the double slit, optical grating, or a single slit, or that interference maxima occurred in places on the screen where two light beams overlapped, or where wave crest touched the screen. They seemed to activate various conceptual resources and p prims in the process. They expressed most of the difficulties that were known from earlier PER studies on interference and diffraction. Some of those difficulties may stem from the inappropriate application of *p* prims and other resources.

We believe that students might benefit from the inclusion of more hands-on investigative experiments in the teaching process. Allowing students to install the experiment setup by themselves, obtain the pattern on the screen, observe it, and investigate how changes in the experimental setup affect the pattern might increase the quality and robustness of their knowledge. Giving a prediction of the pattern before the experiment might increase students' intrinsic motivation for the topic and expose their reasoning, allowing them to correct it, if necessary, in the process of a later student and/or teacher led discussion and construction of explanation.

Even though this study was limited to high school students, the conceptual knowledge required for forming the basic understanding of interference and diffraction can be considered roughly the same for beginning university students to. Some findings may be applicable to university students as well, although they differ from high school students in the number of the studied wave optics phenomena, and the math complexity used to describe them.

Students' difficulties with wave optics are numerous and, most definitely, not explored entirely yet. If teaching is focused on numerical exercises only, student conceptual and experimental difficulties may remain hidden and thus impossible to be tackled.

The more detailed information on how the interviewed students were taught the topic of wave optics could maybe give an additional insight in the possible formation of certain difficulties that students expressed during the interviews. It is also important to note that this is a qualitative study whose findings should be further tested on larger samples of students. However, the finding that many of the 27 participants showed common difficulties, often similar to those of the students from other countries, points to the possible common origin of those difficulties in similar underlying reasoning patterns, which can be important to recognize to improve the teaching and learning of wave optics. One benefit of knowing that the typical students' wrong explanations are formed through activation of resources is that this suggests that they are only provisory models and not firm alternative ideas, and that—unlike firm ideas—they can be modified relatively easily. Also, since they originate from reasoning elements common to most people, they will be found in many students and many situations. If students are prompted often during instruction to provide their explanations of phenomena, the incorrect explanations and their origins can be discussed, and students can be directed to more complex and more appropriate reasoning paths about physics phenomena. This can also help the development of students' metacognitive knowledge. We can work as well on the development of learning activities which will help students to activate appropriate resources on which a better understanding of physics can be built [48].

The resource-based model, we believe, explains well the findings of this study and the obtained student answers. We hope to have demonstrated by our analysis that most of the student answers were likely to originate from the activation of cognitive resources, rather than from previously held firm ideas about wave optics, since students did not seem to have possessed any firm prior models at all, but instead seemed to form provisory models when they were prompted to answer the interview questions.

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