Exploring secondary school students’ understanding of basic phenomena relating to wave optics

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Abstract. Interference, diffraction, and polarisation of light are the basic phenomena of wave optics. According to the findings of previous studies on wave optics, these phenomena are the source of many students’ conceptual difficulties. The goal of the present study was to qualitatively investigate and compare Croatian and Austrian secondary school students’ understanding of the main concepts and phenomena of wave optics as a first step that will serve as a preparation for a large-scale study on secondary school students understanding of wave optics. Here we present the preliminary results of six semi-structured demonstration interviews conducted in Croatia and Austria with secondary school students (age 18-19), after regular school instruction on wave optics.

1. Introduction
Research on student understanding of wave optics, conducted mostly on university students, has shown that students have many difficulties with the wave model of light and wave optics. Students are often not sure when to apply geometrical or wave optics. For example, some of them may use laws of geometrical optics for light passing through a narrow slit and some may use wave optics for light passing through a wide slit. Sometimes students also form hybrid models of optics, where they combine elements both from physical and geometrical optics to explain some phenomenon. For example, students interpret the central maximum of a diffraction pattern in single slit diffraction experiment as the geometrical image of the slit but explain other maxima and minima of the same pattern using wave optics [1]. They may also consider the edges of the slit(s) as crucial for the creation of an interference or diffraction pattern [1,2]. Some students seem to think that the rays of light are reflected by the edges of a narrow slit. Also, they may treat the edges of the slit as new point sources of light and even think that single slit acts as a polariser [1].

The wave aspects of light also cause many student difficulties [1, 3]. For example, some students confuse the wavelength with the amplitude of the wave. They also do not understand the meaning of the path length difference and its importance for the interference. Some of them think, that the path length distance can be neglected, if the distances in the experiment are large enough [1]. Some students may treat waves as objects and expect their collisions instead of interference, whereas some other students think that interference is a reinforcement effect, both for the amplitude of the wave and its wavelength...
Studies also show that students prefer to use light rays, rather than the Huygens principle, when explaining wave phenomena of light [2].

The photon model of light is also a source of difficulty. Students may form a hybrid model of light, in which light consists of photons, but photons move in a sinusoidal path through space [1]. Some also think that a bunch of photons behaves like a wave [4].

The difficulties mentioned above all come from research on university students. Fewer studies have focused on secondary school students’ understanding of wave optics [4, 5]. It was reported in those studies that students develop and reject different models of light over the years of education, but also that they may create hybrid models [4]. Secondary school students may also have great difficulties when trying to predict how a change in the experimental setup (for example, a change of incoming light’s wavelength) affects the interference or diffraction pattern on the screen [5].

In order to explore secondary school students’ conceptual difficulties with wave optics in more detail, we conducted a qualitative study on Croatian and Austrian secondary school students, to investigate whether students from different countries have similar difficulties. Their understanding of wave optics was investigated through demonstration interviews conducted in Croatia and Austria. We will present and discuss here preliminary results of the six most informative interviews (due to the article length limitation). The answers of other students did not differ substantially from those discussed.

2. Demonstration interviews
The research was conducted in the form of semi-structured demonstration interviews [6]. Interviews included the topics of polarisation of light, interference of light from two sources, interference on optical grating and single slit diffraction. One demonstration experiment, as well as the accompanying interview questions, were prepared for each topic.

Nine final-year secondary school students in Zagreb, Croatia and six in Vienna, Austria, with different physics grades, were interviewed after their regular school instruction on wave optics. Students’ grades varied from good to excellent. Croatian students came from three different secondary schools of general education type (gymnasiums), where they study physics for four years with two 45–minute classes per week. Wave optics is covered in the 4th year of secondary school (age 18-19), typically for six to seven weeks. Austrian students learn about wave optics at the beginning of the 11th year of school (age 17-18). In many Austrian schools, wave optics is covered in four to six weeks with two to three 50-minutes classes per week.

During the interviews, students were shown the experimental set-up and told what would be done with it. Then they were asked for their predictions (in words and drawings) and explanations of the results of several demonstration experiments. If students had wrong predictions or explanations of the observed phenomena, they were not corrected during the interviews. Correct answers to the questions were discussed after the interview was completed if the student was interested in them. Students were encouraged to think aloud during the interviews and to express all their thoughts. All interviews were audio taped, transcribed, and analysed. The length of the interviews varied from 45 to 70 minutes. In chapter 3 of this article, some preliminary results of the study will be presented through the analysis of three interviews from Croatia and three from Austria.

Table 1. List of the students, whose answers will be presented.

| Student  | Country | Gender | Interview duration | Physics school grade |
|----------|---------|--------|--------------------|----------------------|
| Student 1C | Croatia | Female | 70 min             | Excellent            |
| Student 2C | Croatia | Male   | 67 min             | Very good            |
| Student 3C | Croatia | Male   | 54 min             | Good                 |
| Student 1A | Austria | Male   | 85 min             | Excellent            |
| Student 2A | Austria | Male   | 57 min             | Good                 |
| Student 3A | Austria | Female | 67 min             | Very good            |
Three Croatian students will be labelled as Students 1C, 2C and 3C, while three Austrian students will be labelled as Students 1A, 2A and 3A (table 1).

3. Results

3.1. Polarisation of light

All interviews started with the polarisation of light. Students were given three slides. Two of the slides were polarisation filters and one was an ordinary transparent dark foil. One of the polarisation filters was marked, while the other slides were unmarked. Students were asked to design and perform the experiment which could help them determine which of the two unmarked slides was a polarising filter. Only two students (Students 3C and 1A) solved this task successfully.

When asked to explain the polarisation of light, students 2C and 1A gave similar explanations. They explained the polarisation as a weakening of light intensity. Two students, one from Croatia and one from Austria, briefly mentioned that polarisation may be related to poles. Student 2A mentioned that the change of the observed intensity of light passing through the polarising filter may be related to magnets. He then stated that he could not explain this effect. Student 1C said that the polarisation was the phenomenon of separating things into poles. When asked if that meant that light has poles, she said that light had crests and troughs instead of poles. However, she was not sure of her statement about crests and troughs. Both students could not explain their reasoning any further. Student 2A also remembered that 3D glasses in the cinema worked on the principle of polarisation of light but could not give any further explanation. Student 3C talked about the oscillations of a light wave and said that polarising filters are preventing light to oscillate in some directions. He was the only one, in this sample, who showed some understanding of polarisation.

3.2. Double slit interference of light

The second part of the interview was about the interference of light from two slits. Students were shown the slide with two very narrow and parallel slits and asked what they expected to see on the screen if red laser light was passed through these two narrow slits.

Student 1C expected to see maxima and minima on the screen but thought that they would be placed vertically on the screen. Student 2C also expected to see maxima and minima on the screen but thought they would look like concentric circles. Student 3C expected the maxima in the middle of the pattern to be closer to each other than maxima on the outer edge of the pattern.

After observing the patterns on the screen, Student 1C said that two slits are the two sources of light and that they somehow interact to create the pattern on the screen. She recalled the interference phenomenon and explained it through overlapping of crests and troughs of the waves. Student 2C proposed that the light had somehow been “broken” by the obstacle between the two slits, but he could not explain why the pattern was spread across the screen. Student 3C said that this spreading was due to the diffraction of the light around the obstacle between the two slits, but that maxima were a result of the interference of light.

Austrian students 1A and 3A expected to see horizontally placed maxima and minima, where the intensity of the maxima decreases with the distance from the central maxima, while Student 2A expected to see only one point on the screen.

Student 1A explained that the light was coming to the side of the screen (where it was not before) because of the quantum mechanical effects. But, when he was asked about the origin of the interference maximum, he tried to explain it with waves. He claimed that maxima were created at the points of intersections of light waves. Student 2A said that this pattern had something to do with particle-wave duality but could not explain it any further. Student 3A thought that minima and maxima on the screen appear because light from one slit traverse a longer distance and because one of the paths is steeper than the other one.

Croatian students in this sample treated light as a wave. All of them described constructive and destructive interference of light using crests and troughs of waves. None of them knew how to
mathematically express the condition for constructive or destructive interference. Student 3C was the only one who mentioned the path length difference as a relevant criterion for interference to occur. Two out of three Austrian students had expressed hybrid models of light but treated light as a wave when explaining interference. Based on the preliminary results we could conclude that students are familiar only with the term interference, but none of them managed to explain the phenomenon of interference.

3.3. Diffraction of light on a single slit
In the third part of the interview, students were first asked what they expected to see on the screen when laser light was passed through a wide slit (figure 1).

Students 1C and 3C expected to see only one point on the screen, because the slit was wide enough for the laser beam to pass and there were no obstacles. Student 2C expected to see one horizontal line on the screen because now there was no obstacle inside the slit on the slide (like there was between the two slits in the previous experiment).

Student 1A used the particle model of light and expected that particles of light would somehow be scattered while passing through the slit. He expected that most of the particles would be found around the centre of the screen. Student 2A expected only one point on the screen. Student 3A expected to see an interference pattern, because this slit was bigger than the slits in the previous experiment with two slits. After the observation, student 3A was very surprised that there were no maxima and minima on the screen. She then concluded that the other maxima were lost.

In the next step, the slit was narrowed. Students were asked what they expect to see on a screen when laser light was incident on a very narrow slit. Student 1C now expected to see maxima and minima. Student 2C once again expected to see a long horizontal line across the screen. Student 3C said that the slit was narrow enough and that interference of light would happen, but the pattern would be slightly larger than interference pattern obtained with two slits.

After observing the diffraction pattern on the screen, Student 1C recognised the pattern and said that now the two edges of the slit acted as two sources of light. Student 2C was very surprised there were maxima and minima on the screen. He said that the narrowing of the slit was somehow breaking the light apart. He said that some of the central maximum intensity was divided among other maxima.

Student 1A expected a continuous pattern, similarly to his previous expectation. Student 2A expected to see a diffraction pattern on the screen with a large central maximum. Student 3A expected to see a narrower point than previously on a wide slit.
After the observation, Student 1A thought this pattern was due to some quantum mechanical effect, unknown to him. He said that this reminded him of the probability (function) of the wave but could not explain this pattern. Student 2A gave no explanation of the pattern but said that diffraction of the light is when light is bent sideways. Student 3A said this pattern occurred because the slit was too narrow, so the light had to shrink while passing. After passing through the slit, light spread across the screen.

As presented in these preliminary results, most of the students knew that there would be a difference in the pattern obtained on a wide and narrow single slit, but none of them could correctly explain the single slit diffraction.

3.4. Interference of white light on a diffraction grating
The final part of the interview included an experiment with white light and a diffraction grating, as seen in figure 2. The experimental setup included a wide slit, that narrowed the beam of the white light. A convergent lens was used to obtain a sharp image of the slit.

![Figure 2. The experimental setup for the experiment with white light incident on a diffraction grating.](image)

Students 1C and 3C expected to see multiple white and dark fringes across the screen. Student 2C expected to see one rainbow, but he was not sure about the order of the colours.

Student 2C recalled that white light consisted of all colours and suggested that the spectrum appeared due to the refraction of the light on the grating. Student 3C also recalled that (visible) white light consists of all colours. He thought that the colours appeared because the convergent lens in the apparatus separated white light into its components.

Student 1A expected one spectrum on the screen that has blue colour in the middle, and red colour on both sides of it. Students 2A and 3A expected to see white and dark fringes across the screen.

After observing the experiment, Student 1A tried to explain the existence of colours on the screen with the refraction of light on the optical grating. Student 2A compared the observed maxima to the rainbow and also attributed the colours to the refraction of light. Student 3A at first referred to the grating as a filter, but later said that this grating separates white light into colours.

Based on the preliminary results, half of the students expected that pattern on the screen would contain colours, but they didn’t expect that central maximum would be white. Others expected black and white pattern on the screen. Some of the students in both countries suggested that colours appeared due to the refraction of light.

4. Conclusion
Some of the difficulties found in this preliminary study agree with the previously reported students’ difficulties. For example, Student 1C suggested that the edges of the slit were acting as sources of the light. Student 3A used geometrical optics to explain passing of the light through a narrow slit and wave optics to explain light passing through a wide slit. Student 1A formed a hybrid model of optics,
combining quantum mechanical effects with the wave model. None of the students showed a sufficient understanding of the interference criterion, or diffraction of the light.

To our knowledge, student difficulties regarding polarisation of light are scarcely represented in the literature. We encountered a possibly new student difficulty concerning polarisation in the interviews: associating polarisation with light having poles (e.g. like magnetic poles).

Some interesting differences arose between the Austrian and Croatian students. The most notable difference was in the approach to explaining wave optics phenomena. The preliminary results suggested that Croatian students tried to explain wave optics phenomena using the wave model of light, whereas Austrian students 1A and 2A tried to explain wave optics phenomena using the hybrid quantum mechanical approach, because the topic of quantum mechanics was most recently covered in their physics lessons in Austria, whereas interviewed Croatian students had not yet learned about quantum mechanics at the time of the interviews. The differences may have arisen from the fact that that the curriculum of physics in Croatia is prescribed by law, and in Austria it is not.

It is hard to distinguish an interference and a diffraction pattern without seeing one, because these phenomena are not encountered on the daily basis, so experiments in this area of physics are crucial. On the other hand, polarisation of light is maybe a slightly more familiar effect, because many of the students at least heard of polarisation sunglasses. However, their understanding of polarisation is equally poor. In general, students’ understanding of wave optics after regular school instruction can be described as insufficient.

Previous studies, as well as the present study, show that students have numerous interesting, but wrong models about wave optics phenomena. When teaching wave optics, it would be important to ask students about their explanations of observed patterns. Their ideas could be tested via students’ investigative experiments. More experiments and conceptual questions should be included in the teaching to help students develop, evaluate, and strengthen their models of wave optics phenomena.

5. Acknowledgements
This work has been supported in part by Croatian Science Foundations’ funding of the project IP-2018-01-9085.

6. References
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