Conceptual Test in Wave Optics

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Abstract: The presented article deals with the Conceptual Test in Wave Optics. It describes main steps of its development and structure and properties of the final version. Two sets of pilotage testing have been done so far. In the first part of the research 105 high school students were tested with a test reliability described by Cronbach’s alpha on the level 0.2. Due to this low value another testing was carried out, this time with university students. It has showed reliability on the level 0.72. This article deals with results from the analysis of these two data sets and shows examples of possible wave optics misconceptions detected by this testing. The test is attached.

1. Introduction

Students’ ideas in wave optics is not a very well researched area. [1] The number of articles devoted to this topic is low and also there was no standardized conceptual test, which is dedicated to wave optics topics on the high school level. For these reasons we took the opportunity to create the Conceptual Test in Wave Optics. The test should also contribute to the research of students’ misconceptions, which is our department’s systematic work. This article is devoted to its development. It describes a process of tasks selection as well as results of the pilotage, which was accomplished with two sets of students - 105 high school and 61 university students. We worked with high school students from two schools and four classes, where we knew the wave optics is taught. Most of the university students were freshmen and 52 of them studied educational programs. Those were students from three Universities (Charles University – 37 students, University of Hradec Králové – 16 students and University of West Bohemia – 8 students).

2. Development of the Conceptual Test

In the Czech Republic, the wave optics is traditionally taught on the high school level grammar school and at some vocational schools focused on engineering. Due to this fact the first part of the research was focused on high school students. We can think that it is a desirable circumstance – to teach wave optics already on high school level - with respect to increasing volume of modern technologies which our civilization uses. The knowledge of wave optics is the key to understand these technologies. It means that large number of high school students come into contact with this topic. On the other hand, the level of teaching and the width of knowledge which is discussed differ school to school. It is influenced by several factors. Wave optics is mostly taught in the third year (grade 12) of the high school and often in the end of the year when many school events usually take place. It means that some students do not concentrate to the subject matter properly and also the time devoted to this topic is limited. Moreover, the wave optics itself is demanding not only for students, but also for some of their teachers. For these reasons and from the informal interviews with teachers the doubts about the level of understanding of Czech high school students in wave optics arose.

To get the best picture of the students’ ideas we decided to contact experienced high school teachers, because teachers are the first and very important authority, who accompanies students on the way to
discover secrets and beauties of nature. We didn’t select the teachers randomly. We needed teachers, who are deeply interested in their work, who think about students’ ideas and who have broad experience with wave optics teaching. Based on these criteria, we asked teachers well known in the physics - teachers’ community. The teachers who contribute to physics-teaching conferences actively, and who publish articles. We recorded detailed interviews with four of them and the fifth completed it by correspondence. This was a keystone for the development of The Conceptual Test in Wave Optics. It brought a reservoir of tasks for the test, it helped to find possible students’ misconceptions, it created the overall picture of wave optics teaching and the structure of the curriculum which these teachers use, it presented which parts of wave optics are for students difficult and which are easier and in whole it showed the picture of students’ ideas, or at least as the teachers see it.

Fig.1. Schema of research [2]

The test was built on the basis of interviews with experienced teachers, tasks which they have suggested and with use of tasks from textbooks and another available literature. It was also discussed many times on doctoral seminars which were held on the Department of Physics Education to improve the tasks formulations, to remove redundant tasks and to find the best distractors. Also there were informal discussions with high school and university teachers and students witch helped to finalize the test. The final version of the Conceptual Test in Wave Optics and it’s properties are described in the same-named subsection The Conceptual Test in Wave Optics.

3. Methodology

3.1. Used methodology

The methodology of test development was inspired by the article “Testing student interpretation of kinematics graphs.” [2] You can compare information about the test development from other sections with schema of research in figure 1. The need of the test is mentioned in introduction. Formulating of main objectives, the test should focus on, resulted from the interviews with experienced teachers. Check of content validity was performed by the expert-group at Department of Physics Education. Both processes are discussed in section Development of the Conceptual Test above. The reliability check was realized by the two sets of pilotage. Both reliabilities and the influence of their value on the development of the Conceptual Test in Wave Optics are described in section Selected results.
3.2. Conceptual Test in Wave Optics

The Conceptual Test in Wave Optics is composed of 17 multiple-choice tasks with closed answers, where just one answer is right. To each task the confidence indicator was added in the scale of four possibilities to examine how sure the students in their answers are. The graphical design of the scale can be seen in figure 2:

![Confidence Indicator](image)

The symbols mean:
- I know the solution, I am completely sure about it.
- I was able to exclude wrong answers, the correct answer was left.
- I’m not really sure about the right answer.
- I do not know the solution at all. I choose it randomly.

**Figure 2.** Confidence indicator in the Conceptual Test in Wave Optics [3]

We can divide the tasks into four areas according to the content. These are properties of light connected with its colour, polarization, interference and diffraction. These areas were identified by experienced teachers and it follows the traditional way in the Czech curriculum as it is often sorted similar in Czech textbooks.

The revised Bloom’s taxonomy of cognitive processes is used as the conceptual framework. [4] [5] The taxonomy is two-dimensional. There are six levels in dimension of cognitive processes and four general types of knowledge. All the tasks are set into a specification chart. You can see in the following table how the tasks cover different parts of the specification chart. (The numbers indicate the number of tasks assigned to each category.)

**Table 1:** Specification chart

| Knowledge          | Cognitive processes |
|--------------------|---------------------|
|                    | 1       | 2 | 3       | 4 | 5 | 6       |
| Remember           |         |   |         |   |   |         |
| Understand         |         |   |         |   |   |         |
| Apply              | A Factual knowledge | 1 |         |   |   |         |
| Analyse            | B Conceptual knowledge | 1 | 3 | 9 | 2 |         |
| Evaluate           | C Procedural knowledge | 1 |   |   |   |         |
| Create             | D Metacognitive knowledge | 1 |   |   |   |         |

4. Selected results

To inspect the properties of the test the pilotage was made in 2018 on the set of 105 high school students. The average score of this students was only 39% which indicates that the test is probably too demanding for high school students. It seems that students have plenty of misconceptions in wave optics and maybe even that the majority have no conception of wave optics phenomena at all. We have a good reason to think, that students answered as well as they were capable because to each task the confidence indicator
was added. The correlation coefficient of this indicator with correct answers was 0.75. This indicator should examine how sure the students are in their answers. The pretty high value of this coefficient also means, that students were able to judge very well, which tasks are difficult for them and which are easier. The result of the test of reliability represented by Cronbach`s alpha was on the very low level ($\alpha = 0.20$) which means that the test shouldn`t be used as an evaluation tool on this educational level. There was a question what is the reason of the low test reliability. We were considering two possibilities. It is something wrong with the test, or the group of respondents was not suitable. The low average score suggested that it could be the second option. Due to this we made a decision to test more advanced students who are more familiar with wave optics phenomena and who are more interested in physics in general.

We started to test university students in 2019. The average success rate of 61 tested students increased to 50 % and Cronbach`s alpha of the set of university students was 0.72. On this huge difference between high school and university level students is obvious, how important the choice of the sample of tested persons is. The results of the reliability showed, that the Conceptual Test in Wave Optics can be used also as an evaluation tool for the group of respondents familiar enough with wave optics phenomena.

As it was mentioned before the reliability of dataset obtained by high-school students was only 0.20 in comparison to data working with university students 0.72. In this section we present both of the researches in order to get wider view to students` difficulties in wave optics. The task distractors are heading to particular possible misconceptions. For example, in the task 13:

Light impacts from air perpendicular to an oil layer ($n_{oil} = 1.5$) on water ($n_{water} = 1.33$). What phenomena do we observe in the reflected light if the oil layer thickness is similar to the wavelength of the impacting light? (Do not consider multiple reflections.)

a) Decrease of intensity due to diffraction.

b) Increasing of intensity due to interference.

c) Increasing of intensity due to diffraction.

d) Decrease of intensity due to interference.

Two possible misconceptions were suggested by experienced teachers. The first misconception is that the students do not distinguish between diffraction and interference at all. The second misconception is that they do not consider the change of phase during the reflexion on the environment with higher index of refraction. Distractors a) and c) correspond to the first misconception, distractor b) to the second one. As you can see in figure 3, the misconception dealing with change of phase is present in the whole range of scores and in all three groups of students (grouped by the total score) when answer b) is the most frequent. On the other hand, first misconception is present intensively by students with lower total score.

![Distractor plot for item 13](image)

![Multinomial plot for item 13](image)

**Figure 3.** Distractor and multinomial plot for the item 8 (university students) [6]
Figure 4. Difficulty (red) of items is estimated as a percent of the respondents who answered correctly to that item. Discrimination (blue) is described by the difference of the percent correct in the upper and lower third of respondents. (Upper-Lower Index, ULI). By a rule of thumb, it should not be lower than 0.2 (borderline in the plot), except of very easy or very difficult items. [6] (university students)

As another example, we can choose question number 8, which distinguishes between university students very well as you can see in figure 4. The text of the task was:

The magnetic induction of an electromagnetic wave is given by relations
\[ B_x = B_m \sin(ky + \omega t), \ B_y = B_z = 0. \]
Specify the direction of propagation of the wave. [7]

a) In the direction of axis \( x \).

b) In the direction of axis \( y \).

c) In the direction of axis \( z \).

d) It is alternating between axes \( y \) and \( z \).

This task was one of the most difficult not only by the results but also by the used mathematic formalism and it is the most demanding task according the Bloom’s taxonomy of cognitive processes (Table 1 – task was classified as C4). We can see in the multinomial plot (figure 5) that the most attractive distractor was answer a). We can explain it by the idea that in the most pictures illustrating similar problems is wave propagating in the \( x \) axis and students are just used to it. Another explanation could be put together with situation that just the \( x \) – component of vector of magnetic induction is nonzero, which can evoke that the wave is spreading that way.
We can compare these results with data from high schools. Task number 8 didn’t distinguish between high school students at all, as we can see in figure 6, and the correct answer was chosen just randomly. The reason is probably that the students have not come into the contact with formalism of the task 8 before. The multinomial plot (figure 7) shows that the most attractive distractor was as by the group of university students answer a). This time it was chosen by students with all values of total score equally.

![Figure 6](image6.png)

**Figure 6.** Difficulty and Discrimination of test items (high school students) [6]

![Figure 7](image7.png)

**Figure 7.** Distractor and multinomial plot for the item 8 (high school students) [6]

5. Conclusion

On the basis of interviews with experienced teachers, textbooks and available articles the Conceptual Test in Wave Optics was created. It was improved with expert groups in the Department of Physics Education, Faculty of Mathematics and Physics, Charles University, Prague and the pilotage was done on two sets of students – 105 high school students and 61 university students. The results from the pilotage showed which of considered misconceptions are present. Next steps in the research will head to make it available to teachers and researchers. They could use it as an evaluation tool (Cronbach’s alpha of the set of university students was 0.72), use it to uncover some student’s misconceptions or as a reservoir of interesting tasks. For this purpose, the English translation of the test is attached in appendix.

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6. Appendix

You can use the Conceptual Test in Wave Optics for teaching and research purposes freely. The recommended time for the test is 30 minutes. Students can use calculators if it is necessary. For the calculations use the approximate value of speed of light in vacuum and in the air as $3 \cdot 10^8 \text{ m/s}$.

Conceptual Test in Wave Optics

A glass table (refractive index 1.5) is illuminated by a red laser light with wavelength of 600 nm.

1. Specify the wavelength of the light during its propagation in the glass.
   a) 900 nm
   b) 600 nm
   c) 550 nm
   d) 400 nm

2. How does the original frequency of light change during the light propagation in the glass?
   a) Increases 1.5 times.
   b) It stays the same.
   c) Diminishes 1.5 times.
   d) Diminishes 3 times.

3. What colour is the light during its propagation in the glass?
   a) Green.
   b) Red.
   c) Violet.
   d) It is not visible.

We observe a candle through two polarizers. Let’s assume polarizers behave ideally and the intensity of light observed without polarizers is 100%.

4. Specify observed intensity of light with the use of one polarizer.
   a) 100 %
   b) 75 %
   c) 50 %
   d) 0 %

5. Specify observed intensity of light with the use of two polarizers. Polarization planes are rotated relatively to each other by the angle of 90°.
   a) 50 %
   b) 25 %
   c) 12.5 %
   d) 0 %

6. Specify observed intensity of light with the use of two polarizers. Polarization planes are rotated relatively to each other by the angle of 45°.
   a) 75 %
   b) 50 %
   c) 25 %
   d) 0 %
7. Consider the arrangement from task 5 with the only one difference. The third polarizer is inserted in between the two above mentioned polarizers. Its polarization plane is to both polarizers rotated by the angle of 45°.
   a) 50 %
   b) 25 %
   c) 12.5 %
   d) 0 %

8. The magnetic induction of an electromagnetic wave is given by relations
   \( B_x = B_m \sin(ky + \omega t), B_y = B_z = 0 \). Specify the direction of propagation of the wave.
   e) In the direction of axis \( x \).
   f) In the direction of axis \( y \).
   g) In the direction of axis \( z \).
   h) It is alternating between axes \( y \) and \( z \).

Linearly polarized electromagnetic wave is described by vectors of electric intensity \( \vec{E} \) and magnetic induction \( \vec{B} \) (as in figure on the right side). Vectors \( \vec{E} \) and \( \vec{B} \) have the maximum magnitude at that time.

9. Choose the diagram which corresponds to the situation after time \( T/2 \) at the same place, where \( T \) is a period.
   a)
   b)
   c)
   d) zero vectors

10. Choose the diagram which corresponds to the situation after time \( T/4 \) at the same place, where \( T \) is a period.
   a)
   b)
   c)
   d) zero vectors
Two electromagnetic waves arising from two slits S1 and S2 interfere. (Young experiment. The arrangement can be seen in figure.)

11. Specify the light intensity in the middle of the screen. (The point on the screen where the horizontal axis passing through the middle of the slits intersects the target.)
   a) Maximum.
   b) Minimum
   c) Average.
   d) None of the previous answers, it depends on the wavelength of the light.

12. Define the phase difference between the waves which make the 3rd interference minimum in the Young’s experiment.
   a) $0 \text{ rad}$
   b) $\frac{3}{2} \pi \text{ rad}$
   c) $3\pi \text{ rad}$
   d) $5\pi \text{ rad}$

13. Light impacts from air perpendicular to an oil layer ($n_{oil} = 1.5$) on water ($n_{water} = 1.33$). What phenomena do we observe in the reflected light if the oil layer thickness is similar to the wavelength of the impacting light? (Do not consider multiple reflections.)
   e) Decrease of intensity due to diffraction.
   f) Increasing of intensity due to interference.
   g) Increasing of intensity due to diffraction.
   h) Decrease of intensity due to interference.

Laser light with wavelength $\lambda$ goes through a slit.

14. Specify what happens with distribution of maxima of diffraction pattern if we narrow the slit.
   a) The maxima will be more spread-out.
   b) The maxima will be closer.
   c) It will not change.
   d) It is not possible to decide.

15. Specify what happens with the distribution of maxima of the diffraction pattern if we cover half of the slit.
   a) The maxima will be more spread-out.
   b) The maxima will be closer.
   c) It will not change.
   d) It is not possible to decide.
16. The light from source Z impacts a slit. Specify the wavelength needed to measure non-negligible intensity in the point A.
   a) Significantly lower than the width of the slit.
   b) Approximately the same as the width of slit.
   c) Significantly higher than the width of the slit.
   d) Arbitrary, it is not dependent on the wavelength of the light.

17. The light from source Z with frequency $5 \cdot 10^{14} \text{Hz}$ impacts on the slit. Non-negligible intensity of light was measured at the point A. Choose the possible width of the slit.
   a) 50 pm
   b) 5 nm
   c) 600 nm
   d) 20 µm

7. References
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