Assessing Austrian high school students‘ understanding of basic wave optics phenomena using the Conceptual Survey on Wave Optics

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Abstract
The Conceptual Survey on Wave Optics (CSWO) is a new diagnostic instrument aimed at the assessment of high school students' understanding of some basic phenomena of wave optics. The CSWO consists of 26 multiple choice items that include questions about double-slit and optical grating interference, single-slit diffraction, and polarization of light. Both Croatian and Austrian students were tested in the process of the CSWO development and validation. The final version of the CSWO was administered to 167 students at several Viennese high schools, who took the test in an online form after finishing regular school instructions on wave optics. The survey was conducted during the summer term of school year 2020/21. The Rasch analysis of the results of Austrian students on this survey is presented and discussed, together with some implications for high school instruction on wave optics. The results suggest that wave optics is a rather difficult topic for high school students, and it seems that recognizing patterns and explaining the basic wave optics phenomena are especially difficult tasks for students.

1. Introduction

This study is part of the first authors' doctoral research, whose goal is to determine high school students' difficulties with wave optics and to create a measuring (diagnostic) instrument for determining prevalence of identified high school students' difficulties with wave optics. The research was mostly conducted in Croatia, within a research project granted by the Croatian Science Foundation, with Croatian high school students, who are introduced to wave optics for the first time in their final year of high school, when they are typically 18 years old. The diagnostic instrument, the **C**onceptual **S**urvey on **W**ave **O**ptics (CSWO) was developed and validated on Croatian (mostly) and Austrian students [1]. Then, the final version of CSWO was translated to German language[1] and administered to Austrian high school students, after their regular school instructions on wave optics. This paper will shortly present and discuss the results that Austrian high school students achieved on the CSWO.

2. Literature review

Previously conducted investigations of student understanding of wave optics included university level students [2-6], and high school students too [1, 7-10]. Their results were similar – wave optics is a rather difficult topic for many students at the university or high school level. Students are not sure when to apply geometrical optics and when to apply wave optics, so sometimes they mistakenly use geometrical optics for the case when light is passing through a very narrow slit, or they use wave optics for light passing through a very wide slit [2]. Geometrical optics phenomena, such as reflection and refraction of light, are sometimes used as the explanations of the process of polarization [9]. Some of the students even create hybrid models of optics with elements of both geometrical and wave optics. One example of a hybrid model is that students apply geometrical optics for light that is passing through the middle portion of the slit, and wave optics for the light passing near the edges of the slit [2]. Edges of the slit are also sometimes consid-

[1] The German version of CSWO is available upon request.

ered new sources of light, which shows students' tendency to simplify difficult parts of physics and their lack of understanding of the Huygens-Fresnel principle [6]. Slits are also sometimes considered to have polarizing characteristics [2, 9].

Application of the wave model of light is a source of some other difficulties, too. For example, students struggle with expressing distances in terms of wavelength [5], and some of them do not understand that the path length difference, not just the total path length, is a crucial condition for determining the type of interference that will occur [2]. Introducing modern physics concepts, such as photons and the quantum model of light in the following physics lessons, results sometimes in the common student (wrong) idea that photons move through space following sinusoidal paths [6].

Usually, students are not able to distinguish or predict basic wave optics patterns that are observed on the screen in typical school experiments [10-12], and they have difficulties with explaining basic wave optics phenomena [2-11].

3. The Rasch model

To quickly assess students' understanding of some topics, teachers and researchers often use multiple-choice diagnostic instruments (tests). Students' choices of answers on carefully designed items can give an important insight to their teacher, or researcher, about how well students understood the topic and what difficulty students are facing. Multiple-choice format enables easy administration to many students at once and easy grading. An ideal diagnostic instrument (test) should serve as a *ruler* that will enable us to estimate students' abilities regarding the investigated topic and to compare them. But, if the markings on this ruler are expressed in raw scores, there are some problems because not every raw point has the same weight. For example, in a math test, one can be asked to sum two one-digit numbers, to multiply two two-digit numbers, or to divide two multiple-digit numbers. If each correct response yields the same number of points, which is often the case on multiple-choice tests, we cannot conclude much from just raw scores, because it is obvious that answers for some items are much more complicated than the answers to the others [13-15].

In order to avoid the problem with raw scores, many researchers use the Rasch model, one of the most used statistical models that helps (and guides) researchers in the process of test construction and evaluation. This statistical model is capable of evaluating each item in the test, and also to evaluate the test as a whole [16].

The basic role of the Rasch model is to transform non-linear raw scores (number of points on the test that students achieved) into linear measures of student ability and item difficulty expressed in the mathematical unit defined by the model, called *logit* [17].

Some of the assumptions of the Rasch model used to construct the CSWO were unidimensionality, meaning that the test should investigate only one variable or construct (here: understanding of basic phenomena of wave optics) and local independence of items, meaning that the answer to one item should not influence the answer to some other item [18].

4. Methodology

4.1. CSWO development and validation

The new instruments' (CSWO) development and validation were conducted in a period of slightly over a year. More than 700 high school students from Croatia and Austria took part in five cycles of testing, where more than 60 items were probed. After the final cycle of testing, we obtained 26 coherent and well-functioning items, that are distributed across five following learning outcomes (LO) [1]:

LO1. Demonstrate knowledge of basic wave concepts and the wave model of light

LO2. Apply mathematical conditions for the interference of light from two sources

LO3. Reason about school experiments in wave optics (interference of light on two slits, interference on an optical grating, diffraction of light on a single slit, and polarization of light with polarizers or by reflection on different media)

LO4. Differentiate patterns of basic interference and diffraction phenomena introduced in high school physics

LO5. Explain wave optics phenomena and apply them to real-life situations.

The items in LO1 are expected to be the easiest group of items for students, while items in LO5 are expected to be the most difficult group of items for the students. Each learning outcome (from LO1 to LO5) is expected to be more and more complex for students.

The CSWO is focused only on basic wave optics phenomena: interference of light on two slits and on optical grating, diffraction of light on a single slit and polarization of light. In high schools, the CSWO should be used only as a posttest.

4.2. Sampling

The testing of Austrian high school students was conducted in the school year 2020/21. Considering that most of the schools were having online teaching at that time, the CSWO could not be administered to students in paper form, so an online questionnaire was created on the UNIPark platform [19]. At the beginning of the 2021, the invitation for participation in the study was sent via an e-mail to several Austrian high school (gymnasium) teachers. Interested teachers, who responded to our invitation received a link to the online questionnaire containing all CSWO items in the multiple-choice format. After finishing lectures on wave optics, teachers forwarded the link to their students and students mostly solved the CSWO during Physics lessons. The online questionnaire was open until the end of June 2021, and there were 167 respondents from nine Viennese gymnasiums. At the beginning of the questionnaire, students were assured that their participation in this study was purely voluntary and that they were allowed to stop responding to the survey at any time, without penalty.

5. Results

The maximum score that the students could achieve on the CSWO was 26, and the average score that Austrian students achieved was 10 points (38%). Cronbach alpha (the measure of internal consistency of the test) of this test was 0.5.

The Cronbach alpha coefficient corresponds to Rasch model parameter person reliability *prel* = 0.56 (where *prel* = 1 is the maximum value). The person reliability index indicates the replicability of person ordering if this sample was given another set of items that is measuring the same construct (here understanding the basic wave optics phenomena) [13]. Item reliability index here is very high, *irel* = 0.93 (where *irel* = 1 is the maximum value). This index indicates the replicability of the order of items according to their difficulty, had these items been given to another same sized sample, that behaved in the same way [13]. Item reliability is usually higher than the person reliability index because we know more about items (each item was solved by 167 persons) than we know about persons (each person was probed by 26 items).

The item-person map (shown in Fig. 1, sometimes also called the Wright map) is the standard output of Winsteps [20], the software that was used in this study for analyzing data with the Rasch model. It offers a comparison of the distribution of persons (on the left-hand side of the map) and the distribution of items (on the right-hand side of the map). In the middle of the item-person map, there is a vertical line that represents the underlying variable of the test, the measured construct (here students' understanding of wave optics). On the right-hand side of the item-person map, there is the distribution of the items, where the easiest items are at the bottom of the map, and the most difficult items are at the top of the map. The item of average difficulty has measure of 0.0 logits. Easier items have negative estimated measures, and harder items have positive estimated measures [13, 14]. On the left-hand side of the map, there is the distribution of students according to their estimated ability in wave optics (which should not be confused with any general ability indicators, such as e.g. intelligence), from the least able students at the bottom (with negative values of the estimated measures of ability) to the most able students at the top of the map (with positive values of the estimated measure of ability).

It is noticeable that there is a gap between the means of the two distributions, which indicates that this test was too difficult for this sample. There are some gaps between the difficulties of the items on the right-hand side of the map, meaning that adding some easier items would be beneficial. There are many students

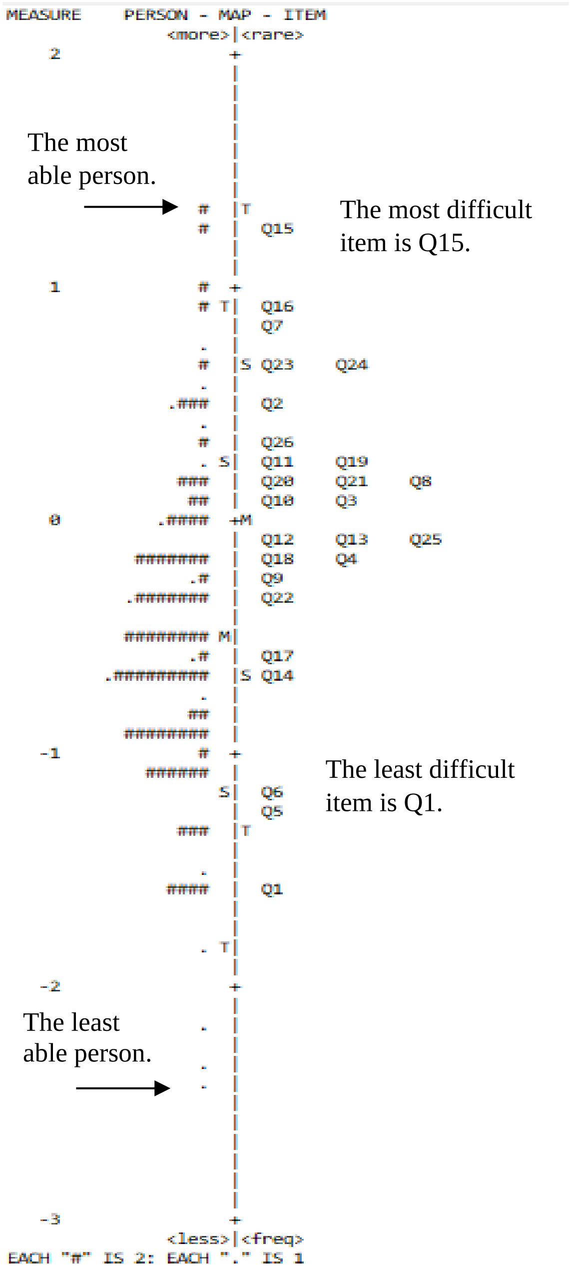


Fig.1: Item-person map.

with the estimated ability of around -1 logit, but there are no items whose difficulty corresponds to students' estimated ability. Nevertheless, most of the students have items that are in the range ± 1 logit of their estimated ability, which is the range that allows good measurement [21].

5.1. Students' achievements on LO1-LO5

At the beginning of the process, we expected on the basis of our previous results with Croatian students [1] that LO1 would be the group of items that is the easiest for the students, and that the LO5 would be the most difficult for the students. In order to validate our predictions (the theoretical construct), we conducted the partial credit analysis of the data [1, 22]. For each student that solved the test, we added up their raw scores (points that students achieved) for each of the groups of items and each group was then analyzed as a new item. There were five groups of items (LO), so now each LO was represented as a single item, that had different maximum score (corresponding to the number of items in the group). For example, in LO4 there were 3 items, so the maximum score that a student could achieve on the *item_group* LO4 was 3.

	LO1	LO2	LO3	LO4	LO5
measure	-0.56	-0.11	-0.03	0.37	0.33
error (3SE)	0.24	0.27	0.18	0.3	0.27

Tab.1: Data from the partial credit analysis that were used to create Fig. 2. Data are expressed in logits.

Empirical validation of the theoretical construct is shown in Fig. 2. The group of items belonging to the LO1 is, as expected, the easiest group of items for the students in this sample. The difference in the difficulty of groups of items LO2 and LO3 seems to be statistically insignificant, and the same is true for groups of items LO4 and LO5.

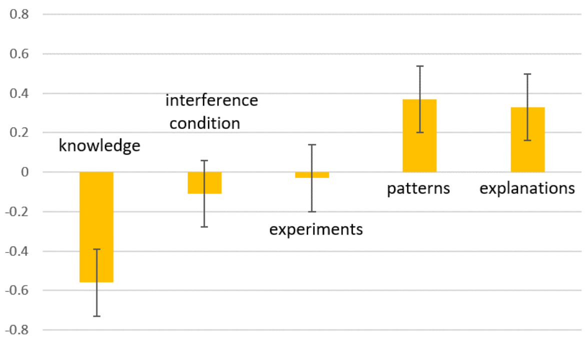


Fig.2: Partial credit score for five *item_groups*, where each *item_group* corresponds to a group of items probing a single LO. The vertical scale is in logits (0 logits corresponds to the average item difficulty, negative values to less difficult, and positive values in logits to more difficult items).

5.1.1. **LO1[2]:**

The easiest item for this sample was the first item of the test, Q1, where students were asked to count how many wavelengths is there on a sine wave. The majority of students (N=123) knew this. The second easiest item, Q5, was solved by 112 students, who knew that light diffraction shows us that light is a wave. Interestingly, 31 students thought that light diffraction shows that light is a transversal wave. Item about calculating path length difference from sources to point T, Q8, seemed to confuse the students, because only 59 students knew what path length difference was (the difference of the distances of each light source to the point T). The most frequently chosen distractor was that the path length difference is the difference of the wavelengths of the waves.

5.1.2. **LO2:**

Items Q3 and Q13 showed that the majority of the students knew that for destructive interference to occur, troughs of one wave must meet with the crests of another wave. On item Q3, 63 students knew how to express this condition by words (the path length difference equals an odd number of half-wavelengths.), while 54 of them simplified this to the path length difference being equal to an *odd number of wavelengths*. On item Q13, the majority of the students (N=97) recognized that at a given point there would be a destructive interference, but 31 of them miscalculated the path length difference for this point.

5.1.3. **LO3:**

Item Q10 asked students about the pattern on the screen if the width of the 1 cm wide slit was narrowed to 1 millimeter. The majority of the students knew that this would result in a wide central maximum and multiple horizontally aligned minima and maxima, but the second most prevalent option was that on the screen there would be only a fraction of the initial laser *dot*.

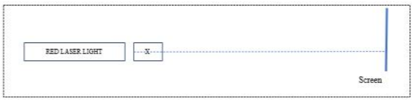
Item Q11 asked students to predict which optical grating would produce maxima that are more apart on the screen: grating with 100 or grating with 300 lines per millimeter. The majority of the students (N=61) thought that the grating with 100 lines per millimeter would produce maxima that are more apart than maxima produced by the grating with 300 lines/mm (N=55).

5.1.4. **LO4:**

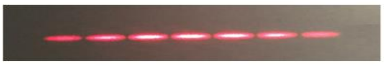
The most difficult item (Q15), as shown in Fig. 1, is the item probing the learning outcome LO4. Students were expected to recognize that a given pattern is obtained with laser light incident on a double slit (Fig. 3). Only 29 students knew how the pattern was produced, while most of the students (71) thought this pattern was obtained with laser light incident on an optical grating. In item Q18, students should have recognized the pattern that laser light produces on optical grating, and they were offered four different patterns to choose from (narrow slit diffraction pattern, double-slit interference pattern, less narrow diffraction pattern, optical grating pattern). Here, the majority recognized the correct pattern (73), but it is interesting to point out that the most frequent wrong choice, that 39 students have chosen, was the double-slit interference pattern (the same pattern used for Q15).

[2] The English version of CSWO with distribution of Croatian high school students' answers can be found on this web page: https://journals.aps.org/prper/abstract/10.1103/PhysRevPhysEducRes.18.010103

Q15. The figure shows an experimental setup with an unknown optical element X.



The following image was obtained on the screen with that setup:



What was used as element X in the experimental setup?

A. An optical grating.
B. A very wide slit.
C. A very narrow slit.
D. Two very narrow slits.

Fig.3: Item 15, the most difficult item for students.

5.1.5. LO5:

Item Q9 examined student knowledge of real life application of wave optics and asked students for the reason behind colors on the soap bubbles. The majority of the students knew that interference of light is involved in creating these colors (N=75), but the second most prevalent option was that the refraction of light creates these colors because the soap bubble acts like a glass prism (N=54).

Item Q22 asked students for the explanations of the pattern produced by the optical grating, and the majority of the students (N=77) knew that each slit on the grating was considered to be a new point source of the waves that interfere and create the pattern on the screen, but some students (N=39) thought that each slit produces its own maximum on the screen or that (N=32) light is refracted on the optical grating.

6. Discussion

It is evident that students confuse geometrical optics with wave optics (i. e. connecting every case of dispersion of white light to glass prism or invoking geometrical optics phenomena (such as refraction of light) to explain wave optics phenomena (optical grating pattern). Conditions for the destructive interference are sometimes simplified: the path length difference is equal to the odd number of wavelengths instead of the odd number of half wavelengths, and students struggle with defining and calculating the path length difference.

Recognition of the patterns seems to cause difficulties for the students. The reason could be that, in a very short time, students are shown multiple patterns that are quite alike to the untrained eye. If features of the patterns are not properly observed and discussed, they might not be perceived as important. Also, patterns of basic wave optics phenomena are quite dependent on the equipment used. For example, if laser light is incident on a double slit, there will be multiple maxima on the screen, equally spaced and with similar intensity. If white light is incident on a double slit, the obtained pattern is not something that can be easily connected to the previously mentioned pattern: white central maximum and multiple colorful spectra on each side of the central maximum. Even though the main characteristics of such patterns should be the same, they cannot be easily spotted at all. Also, in the double slit experiment, we usually have a pattern that is a combination of two patterns: interference on two slits, and diffraction on each slit. Depending on the width of each slit, the diffraction pattern is more, or less noticeable.

Since this is the continuation of our research of students' difficulties with wave optics, it is interesting to stress out the similarities and differences between Austrian and Croatian samples, which can be best seen when examining the graph with estimated difficulties of groups of items belonging to the same LO (for Austrian students this is shown in Fig. 5 and for Croatian students the data can be found in the [1] or in the footnote[3]).

For the Austrian sample, the items belonging to the LO1 were the easiest group of items, and the same is for the Croatian sample. For both samples, items belonging to the LO2 and LO3 are more difficult than items belonging to LO1, and for both samples items belonging to the LO4 and LO5 are the most difficult groups of items. However, for the Austrian sample, we cannot differentiate the mean difficulties of LO2 and LO3, and LO4 and LO5.

The trend of the increasing difficulty of groups of items is evident for both samples, but for Croatian students, we can differentiate five different levels of difficulties, while for Austrian sample we can differentiate only three. Those differences might be explained by the differences in physics curriculums of the two countries. In Croatia, teachers are mostly oriented toward numerical exercises, so there is not much time to properly conduct experiments during the class. In Austria teachers usually dedicate more time to experiments, than to numerical exercises. Secondly, the timing of teaching might have influenced the results too because Croatian students took the test before the pandemic, and Austrian students took the test during the pandemic, when they had remote teaching. Preparing and showing students basic experiments from wave optics (i.e. Young's experiment) is difficult even during contact teaching (for example, appropriate darkening of the room), but during remote teaching it is even more difficult.

[3] https://journals.aps.org/prper/article/10.1103/PhysRevPhysEducRes.18.010103/figures/5/medium

7. Conclusion and implication for teaching

The CSWO is a new diagnostic instrument that has been, for now, applied to two populations of high school students in two countries in two very different settings: one pre-pandemic (in Croatia) and one during the pandemic (in Austria). The school year 2020/21 was very difficult because (most of the) teaching was remote and online due to the pandemic, especially during winter and early spring, when teaching of wave optics usually took place.

Regardless of the way of teaching (online or contact), the test results showed that basic phenomena of wave optics are very challenging topic for high school students. The most difficult items for students seemed to be the items where students should have recognized basic wave optics phenomena and items with explanations of those phenomena.

One way to tackle these difficulties is putting more emphasis on experiments. If students are asked for detailed observations of basic wave optics patterns during teaching, their attention will be directed to the most prominent features of patterns, thus making it easier to differentiate between very similar patterns later. Asking students to predict the outcome before an experiment might also increase students' curiosity, thus making them observe the pattern more carefully. It is also possible to create a teaching environment where students' hands-on experiments can be included (or giving students the chance to independently explore appropriate simulations or animations in online or remote teaching). Students' hands-on experiments can be used as experiments to test hypotheses or to investigate relation between variables, and the results of these experiments can serve as a basis for the explanations of phenomena, that will be created with guidance and help of the teacher. If students are included in all these steps, perhaps their understanding of basic wave optics phenomena will increase and deepen.

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Appendix

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