Journal of Turkish Science Education, 2022, *19*(1), 306-331.
DOI no: 10.36681/tused.2022.123

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Development of the High School Wave Optics Test

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ABSTRACT
In this paper, we described the development of the High School Wave Optics Test (HSWOT). Firstly, 56 conceptual, multiple-choice items with a single correct answer and three distractors were created. Next, we conducted an initial review of the items which resulted in reducing the item pool to 44 highest quality items. Validity evidence and feedback on the quality of these 44 items were collected through an expert survey and small-scale item try-out which included 3 subject-matter experts and 13 high school students, respectively. This process helped us to reduce our item pool to 30 technically improved conceptual items, which were eventually administered to 164 high-school students, from Kazakhstan. Finally, a Rasch analysis of the students' answers resulted in a 24-item scale for measuring conceptual understanding in high-school students. The item reliability proved to be good, person reliability was acceptable, and the difficulty of items was approximately person-independent. All distractors were chosen by at least 5% of students and 8 distracters were chosen by more than 35% of students. We could conclude that HSWOT may be effectively used for measuring conceptual understanding in advanced high-school physics courses and for identifying students' misconceptions in wave optics, in general.

ARTICLE INFORMATION
Received:
08.06.2021
Accepted:
23.01.2022

KEYWORDS:
Wave optics, test development, Rasch analysis, conceptual understanding.

Introduction

Students' conceptual understanding of physical processes significantly contributes to the way they perceive the surrounding world. Such knowledge helps students in everyday life, in choosing a career, as well as in solving problems related to physical phenomena (Basu et al., 2009; Elby, 2001). Therefore, one of the main tasks of modern physics education is to help students to develop a good understanding of key physics concepts (Balta & Eryilmaz, 2020; Voronov & Gerashchenko, 2018). In this regard, teachers need high-quality tools to identify possible gaps in students' understanding, which is very important for facilitating students' learning.

Approaches to Assessing Students' Conceptual Understanding

Until this time, educational researchers have developed various techniques for identifying students' misconceptions (e.g., oral questioning, written questioning, think-aloud). Probably the most economical way for assessing students' conceptual understanding is to use multiple-choice tests. This kind of test is convenient because it is typically associated with a high level of assessment objectivity and it is very easy to administer to large groups of students. Furthermore, earlier studies showed that well-designed multiple-choice tests are very effective in identifying students' misconceptions (Haladyna, 2004).

Tests may be developed within the classical test theory or within the probabilistic test theory framework (Liu, 2010; Mešić et al., 2019a). Within the classical approach to test development, one starts from the assumption that persons' observed scores on a set of tasks consist of these persons' true scores on the measured construct and a measurement error which is considered the same for all included persons. On the other hand, at the heart of the probabilistic approach to test development is making statements about outcome probabilities of certain manifest variables (e.g., how probable is it that a certain person correctly solves the given task). The simplest and most widely applied probabilistic test model is the Rasch model (Liu, 2010). Similarly, to other probabilistic models, and unlike classical test theory models, the Rasch model has the following features, if data fit the model (Hambleton et al., 1991):

1) Item difficulties are not dependent on the specific sample of persons from the given population
2) Persons' ability estimates are not dependent on the specific sample of items from the given item pool
3) The test model is expressed on the level of an item
4) Measurement error is not constant across item difficulty estimates nor person ability estimates

Compared to other probabilistic test models, the Rasch model is more practical because it allows for high-quality measurement even for sample sizes as low as 100 persons (Mešić et al., 2019a).

The Rasch approach to test development within the context of physics education has been thoroughly described by Mešić et al. (2019a). They recommend the test development procedure to consist of the following activities:

1. Delineating the construct that should be measured
2. Operationalizing the construct through learning goals
3. Developing items related to these learning goals
4. Checking for content validity – expert survey
5. Item try out – small scale student survey
6. Final field survey
7. Rasch calibration

It should be noted that most of these activities are common for both, classical and probabilistic test theory procedures of test development (Kaltakci-Gurel, 2021). In fact, in all of the approaches, it is important to define and operationalize the measured construct, as well as to conduct validity studies and to run a trial study on a smaller sample of students before conducting the final field study. However, the parameter invariance property of Rasch models and the property of representing persons' ability estimates and item difficulties on the same scale, make the Rasch approach more powerful for measuring and analyzing students' understanding of physics.

The Wave Concept Inventories

Researchers have developed many diagnostic tests to check students' misconceptions from different areas of physics (Test, 2020). However, the results of our literature review show that there is no research-based instrument for measuring the conceptual understanding of wave optics in high school students. This claim is based on the review of several popular wave concept inventories.

The Wave Diagnostic Test by Wittmann (1998) was developed to understand students' thinking about basic wave concepts. The Mechanical Wave Conceptual Survey developed by Tongchai et al. (2009) was used to identify students' alternative conceptions such as mechanical waves, wave propagation, wave superposition, wave reflection, and standing waves. The Four-tier Geometrical Optics Test developed by Kaltakci-Gurel et al. (2017) was about geometrical optics. The Mechanical Waves Conceptual Survey 2 was developed to assess students' understanding of basic wave concepts such as propagation, superposition, reflection, standing waves (Barniol & Zavala, 2016). The Wave

Concept Inventory (Thoads & Roedel, 1999) was developed to assess students' understanding of wave phenomena such as visualization of waves, mathematical depiction of waves, and wave definitions.

However, High School Wave Optics Test (HSWOT) is about waves optics, and it includes assessment goals related to topics such as coherence, Huygens-Fresnel principle, two-wave interference, optical grating, and single slit diffraction. Moreover, many of the developed inventories about waves are at a college and university level while HSWOT is at a high school level.

Students' Ideas About Wave Optics

For developing a high school wave optics test it is important to understand students' ideas about wave optics. Light is one of the more popular phenomena in physics because almost all living beings get acquainted with light from their birth and learn about the environment with the help of light. However, even though it helps us to see the world around us, light is very complex and vague for the human imagination.

In fact, earlier research has shown that wave optics is very demanding, even for top university students (Ambrose et al., 1999; Coetzee & Imenda, 2012; Colin & Viennot, 2001; Maurines, 2010; Mešić et al., 2019a; Salibašić-Glamočić et al., 2021). Concretely, students find it very difficult to develop a functional model of the wave optics phenomena (Mešić et al., 2016). Thus, many students believe that the transmission of light through a single slit depends on the amplitude of the sinusoidal wave of light (Ambrose et al., 1999) or that a wider light beam contributes to a wider central maximum diffraction pattern (Mešić et al., 2019b). In addition, they think that diffraction happens as a result of a superposition of the two secondary waves that originate at the two edges of the slit (Ambrose et al., 1999).

Generally, many of the identified misconceptions are a result of the fact that students often tend to apply the ray model of light to wave optics phenomena, as well as a result of a misunderstanding of the Huygens-Fresnel principle (Ambrose et al., 1999; Kartalopoulos, 2003; Maurines, 1999; Mešić et al., 2019b; Mešić et al., 2021; Michelini et al., 2017). Some of the misconceptions result from misinterpretations of the sinusoidal wave representation. Concretely, in the study of Steinberg et al. (1996), some students conceptualized the sinusoidal representation as a trajectory of photons: when the sinusoid does not fit through the slit, photons simply hit the wall of the single-slit mask and are reflected. In other words, some students tend to apply a mechanistic view to wave phenomena. This is in line with the claim by Wittmann et al. (1999) who recognized that common misconceptions about the wave nature of the light are associated with the fact that it is difficult for students to imagine how light waves interact. In fact, students try to answer wave optics questions, relying on their knowledge of mechanics. For example when thinking about the interaction of light waves, they imagine the interaction of mechanical objects, which results in the idea that two "colliding" wave impulses will reflect from each other instead of interfering with each other.

Other possible sources of the above-mentioned students' difficulties are the absence of intuitive models in wave optics, the way this area of physics is presented in textbooks, and the way we describe some optical phenomena in everyday life (e.g. describing the color of a table as an intrinsic characteristic of the table itself) (Mešić et al., 2016; Silverman, 2008).

The Aim and Significance of the Research

Research on learning and teaching about waves is relatively scarce (Bezen & Bayrak, 2020). One of the reasons for this may be related to the fact that for some of the areas of wave physics currently there are no research-based assessment instruments, which significantly complicates the conduction of high-quality experimental studies. Therefore, we aimed to develop an assessment instrument that is suited for measuring high school students' conceptual understanding of wave optics. In fact, the physics education community currently lacks such an instrument. This research is important because the developed instrument may be used for a more valid and reliable assessment of outcomes of innovative teaching approaches in wave optics. Generally, the newly created conceptual items may be very useful for sparking insightful classroom discussions about selected wave optics phenomena which could facilitate the development of conceptual understanding.

Methods

Student Sample and Curriculum

The data used in this study were collected from a group of students from Nazarbayev Intellectual Schools (NIS) sponsored by a state-funded, non-profit company in Kazakhstan. The system of NIS has been initiated in 2009 with an aim of introducing new educational procedures before their induction into the public school system. NIS experience is widely used to update the school curricula content in Kazakhstan.

The schools are accepting students through testing and have a vying application process while aiming to be available to all sectors of the public. The entrance exams are offered in both Russian and Kazakh. Students take the exam after graduating from the 6th grade and graduate from these schools in the 12th grade. The schools are spread throughout the country (21 schools in 17 different cities). Many have boarding services and the schools are tuition-free with meals, uniforms, and lodging free of charge as well (NIS, 2020).

Most schools apply the same curriculum based on Cambridge AS and A Level. Teaching is trilingual, in Kazakh, Russian and English, transitioning entirely to English by the 11th and 12th grades. Class sizes generally start with 5 up to 20 pupils, equipped with student laptops, electronic smartboards, and state-of-the-art services.

Many international teachers are recruited in English language, Mathematics, Chemistry, History, Biology, Physics, Information technology etc. The aim of hiring international teachers is to conduct classes in English, mentor local teachers informally and present them with best educational practices, provide master classes, observe lessons, do team-teaching, etc. Furthermore, contributing to curriculum development, preparing students for university entrance tests, and conducting SAT courses are some of the other activities expected from international teachers.

Wave optics is taught in 11th grade in NIS. There are six hours of physics each week and four weeks are allocated to teach wave optics to 11th graders. Along with lecturing, problem-solving, laboratory work, formative and summative assessments are included during these four weeks. We collected the data from the 12th graders who were previously taught the topic. A total of 13 students completed the HSWOT for the pilot study and 164 students for the main study. These 164 students were from 14 different NIS schools and had an average score of 4.57, in their last quarter of the 2020-2021 academic year in a 5-point grading system.

The Development of HSWOT

The development of the HSWOT, which lasted approximately six months, started with the identification of the key ideas (See Appendix A) which, in our view, operationally define the conceptual understanding of wave optics.

The key ideas have been stated for several sub-topics: basic wave optics concepts and principles (Huygens-Fresnel principle, coherence), two-wave interference, single slit diffraction, diffraction grating, and combined topics.

The second step was composing an item pool that could be potentially used for measuring wave optics understanding in high school students. Most of the items were created specifically for this occasion, whereby inspiration for the creative process was often found in the freely available simulations of wave optics phenomena. However, some of the items were also adapted from earlier research on the conceptual understanding of wave optics students (Mešić et al., 2019a). We initially selected/developed a pretty large number of 56 items.

In the third step, we worked on adding, removing, and revising items. We iteratively worked on improving the quality of the item pool. After the first review of the items, along with the amendment of items, we removed 15 items and added four new items. For instance, we simplified many items for better understanding because our population was not native English speakers. Further, we improved the quality of some figures and some distractors. We removed several items because they were above high school students' knowledge of wave optics.

The very early version of the test composed of 44 items with the following distribution across sub-topics: basic wave optics concepts and principles (Huygens-Fresnel principle and coherence) (8 items), two wave interference (23 items), a diffraction grating (3 items), single slit diffraction (6 items), and combined topics (4 items).

We associated each item with an explicit learning goal (See Appendix A) which facilitated the discussion of the results and made it easier to connect the items with misconceptions/difficulties identified in earlier research.

In the fourth step, we prepared an expert view form and sent it to three experts; one experienced high school physics teacher, one researcher that previously prepared and winners of international physics Olympiads, and one university professor that teaches and publishes on wave optics. Experts reviewed each item in terms of the following queries:

1. *What is the correct answer?*
   A B C D
2. *Does it measure understanding of wave optics?*
   Yes. No.
3. *Is this item physically correct?*
   Yes. No. (Please explain what is wrong)

Not at all	*Very much*	⟵⟶
4. *The item is clear.*		
5. *I like this item.*		
6. *The item matches the cognitive level of the target students.*		

We aimed to utilize reviewers' comments for purposes of selecting a 35 high-quality items set. We used the following criteria:

1. Distribution of items across sub-topics should be approximately as follows: Basic concepts and principles – 15 % (i.e. 6 items to be selected), Two-wave interference – 50 % (i.e. 17 items to be selected), Diffraction grating – 10 % (i.e. no items should be removed if good ratings; one more item should be developed), Single slit diffraction – 15 % (i.e. 5 items to be selected), Combined topics – 10 % (i.e. 3 items to be selected)
2. Then we used experts' opinions as an orienteer in selecting the highest-quality items from each of the sub-topics. The way this has been done may be illustrated with an example of the two-wave interference sub-topic:
   a. Firstly, we selected items with like ratings higher than 4.6. There were 14 such items for the two-wave interference sub-topic and we needed to select 3 more items in order to fulfill the earlier described distribution criterion.
   b. Secondly, we decided to remove those two-wave interference items with "Cognitive match" lower than 4.6. As a result, the two of nine remaining items were removed.
   c. Finally, we could freely select three items out of the remaining seven two-wave interference items for inclusion in the 35-item test. This was done based on our general impression and perceived originality of the item. Thus, we arrived at the desired number

of 17 two-wave interference items and the same procedure could be repeated for selecting items in other sub-topics.

Besides utilizing the reviewers' comments for selecting a smaller set of high-quality items, their comments were also utilized for purposes of increasing the readability and clarity of items in general.

In the fifth step of the test development process, we conducted a pilot study to check whether students understand our items as intended. Along with a single correct answer and three distractors, we offered the following additional choices for each item:

e) *I don't know the answer.*
f) *I think the answer is:*
g) *Write the words you did not understand in this question:*
h) *Is this question confusing?*
   1. *No.*
   2. *Yes, (please explain what is confusing)*
i) *How confident are you in your answer to this question?*
   1. *I am not confident in my answer at all.*
   2. *Mostly I am not confident.*
   3. *I am somehow confident.*
   4. *I am completely confident.*
j) *Are you familiar with the content covered in this question?*
   1. *Yes, I learned it in my physics course.*
   2. *Yes, I learned it by myself.*
   3. *No.*
k) *How much mental activity did you spend in answering this question?*
   Very little → 1 2 3 4 5 6 7 8 9 10 → Very much
l) *What is the difficulty level of this question?*
   Very easy → 1 2 3 4 5 6 7 8 9 10 → Very difficult

Thirteen students completed the test and based on their responses we further improved the quality of our items and removed five more items of a relatively low quality. Following criteria were applied to remove inappropriate items:

1. The distribution of items across sub-topics was an important criterion once again. There were five sub-topics and five items to be removed. The two-wave interference was the largest sub-topic and consequently, we decided to remove two items from it. Three items were to be removed from the remaining four sub-topics; approximately, one item per sub-topic.
2. Firstly, for each of the subtopics, we wanted to identify those items that have at least one problematic characteristic. To that end, we applied the following selection filter in the SPSS software (proportion correct<0.2) or (proportion who answered they do not know>0.2) or (proportion who answered they are confused >0.2) or (average confidence rating < 2.5).
3. Secondly, for each sub-topic, the items were ranked with respect to "proportion of students who answered that they do not know the answer", "proportion of students who answered they are confused", "how confident the students were in their answer". All three variables were coded in a way that lower ranks represent more desirable item characteristics. Then we developed a composite variable in which ranks for the three earlier mentioned variables were summed. The obtained composite variable contains combined information about the quality of each item, mostly related to the degree of knowledge-based answering versus guessing answers. Items with the highest values of the composite variable were removed.

Data Collection

For purposes of collecting the validity evidence, data were collected from experts. Data were also collected from a small group of students for purposes of small-scale item try-out (pilot study).

Finally, a large-scale field study has been conducted for purposes of Rasch calibration of our instrument. The Microsoft Word form of the test was sent to experts to revise, add/delete, and comment on the items. In both, pilot and final study, the test was administered online through Google Forms.

Two weeks were given to experts to resubmit their reports. Similarly, in the pilot study, the test was posted online for two weeks and students were reminded two times to complete the test.

In the final field study, the test (See Appendix B) remained online for three weeks, and students were reminded three times to complete the test. The link for the test was sent to heads of the physics teachers in NIS schools and they were requested to share it with teachers in their departments.

Instructions for the test and each item in HSWOT were divided into different sections of Google Forms, and it was mandatory to answer each section. Thus, for a student to submit her/his answers, they had to provide answers for all the items in the test.

Each participant voluntarily completed the test. Ethical approval for the study was obtained from the ethics committee of NIS at which we collect data.

Data Analysis

Data that has been collected through our Google Forms survey has been automatically saved in a Microsoft Excel sheet. For purposes of facilitating further statistical analyses, we copied all students' answers to SPSS. Then we started the process of data analysis.

Firstly, we checked for unusual response strings. In that way, we identified 7 students who selected the same answering option for all or nearly all wave optics items. These students were deleted from our database.

In the next step, we used our answer key to recode the database in order to prepare it for Rasch analyses. Correct student answers have been coded with a "1" and incorrect answers with a "0".

Next, the Rasch calibration was conducted, during which we used the Winsteps 4.0 software to obtain the Rasch ability measures for the 157 included persons and Rasch difficulty measures for our 30 items (Linacre, 2017).

This initial analysis showed that the infit and outfit statistics for all our items were below 1.2 which indicated excellent item fit (Wright & Linacre, 1994). However, person reliability was only 0.41 and several items had a point measure correlation below 0.2. These values indicate weak discriminating power (Abdullah et al., 2016; Yao et al., 2016). Consequently, we started to iteratively remove items with the lowest point measure correlations. After having removed six items in six subsequent calibrations, all items proved to have point measure correlations above 0.2 and person reliability increased from 0.41 for the 30 items scale to 0.49 for the 24 items scale. However, an inspection of student measures showed that for two persons outfit statistics above 1.3 were detected. We deleted these persons from our database and repeated the Rasch calibration procedure. The repeated procedure has shown that all items and persons had infit and outfit statistics below 1.3, as well as that point measure correlations for all remaining 24 items, were above 0.20.

Finally, we had a database consisting of 24 items and 155 persons which has been used for all subsequent scale quality analyses.

Results and Discussion

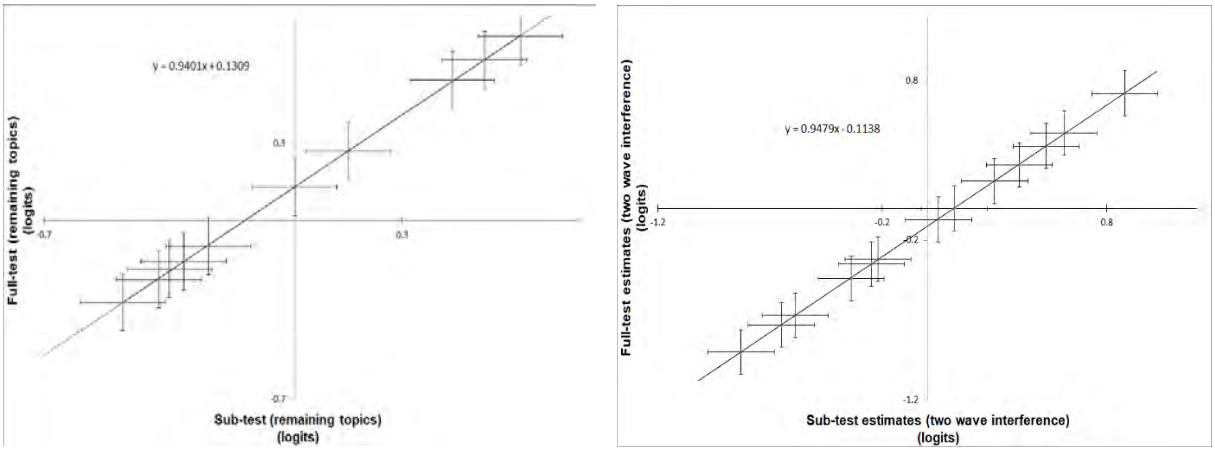
Unidimensionality and Local Item Independence

Firstly, we wanted to check whether for our data the Rasch model assumptions of unidimensionality and local independence of items are met (Hambleton et al., 1991). For these assumptions to be met, our items should reflect a single construct and there should be no substantial relationships between residuals (Linacre, 2017). Here, residuals are defined as differences between observed data (correct or wrong answer) and data expected based on the Rasch model.

For checking the unidimensionality assumption we used Bejar's method (Bejar, 1980; Ding, 2014; Mešić et al., 2019a). The item pool has been divided into two groups: two-wave interference items and items from the remaining four subtopics. Next, we ran a Rasch calibration in which item difficulty measures were estimated for all 24 items (full-test estimates). Thereafter, we ran two separate calibrations for the two groups of items (sub-test estimates). Finally, we cross-plotted the full-test and sub-test estimates for the two groups of items (Figure 1).

Figure 1

Cross-plot of Item Difficulties for Two Groups of Items; Crosses Represent Standard Errors



Evidently, the slope of the obtained trendlines was close to 1, which suggests that combining items from different subtopics does not distort the metrics. Consequently, a slope close to 1 is an indicator that our data are essentially unidimensional (Ding, 2014; Mešić et al., 2019a).

The assumption of local independence of items was checked by investigating standardized residual correlations for different pairs of items. The largest negative standardized residual correlation was observed for item pairs 12 and 15; it amounted to -0.31. The largest positive standardized residual correlation was observed for item pairs 11 and 13; it amounted to 0.24.

Linacre (2017) points out that residual correlations above 0.7 indicate a violation of the local independence of items assumption. Since highest correlation we encountered was 0.31, we can conclude that our data met the assumption of local independence of items.

Reliability

For our data, the person reliability coefficient amounted to 0.49 and the item reliability coefficient amounted to 0.82. According to Linacre (2017), a person reliability coefficient of 0.5 means that it is possible to discriminate maximally two performance levels in the given person sample, whereas an item reliability coefficient of 0.8 allows us to discriminate maximally three "performance" levels in the given item sample. In other words, our scale was not very sensitive in distinguishing between low and high performers in our student sample, but at the same time, the obtained item difficulty hierarchy may be considered as relatively stable.

In fact, the Cronbach's alpha (a classical analog for person reliability) for our data amounted to 0.53 which is low, but acceptable (Bowling, 2005, p. 397). Such relatively low-reliability coefficients have already been reported for some other research-based instruments, such as the Quantum Mechanics Conceptual Survey for which McKagan et al. (2010) reported a Cronbach's alpha of 0.44. They pointed out that low values of Cronbach's alpha most probably result from the fact that an instrument aims at measuring multiple concepts, which was also the case in our study (e.g., coherence, interference, diffraction, etc.).

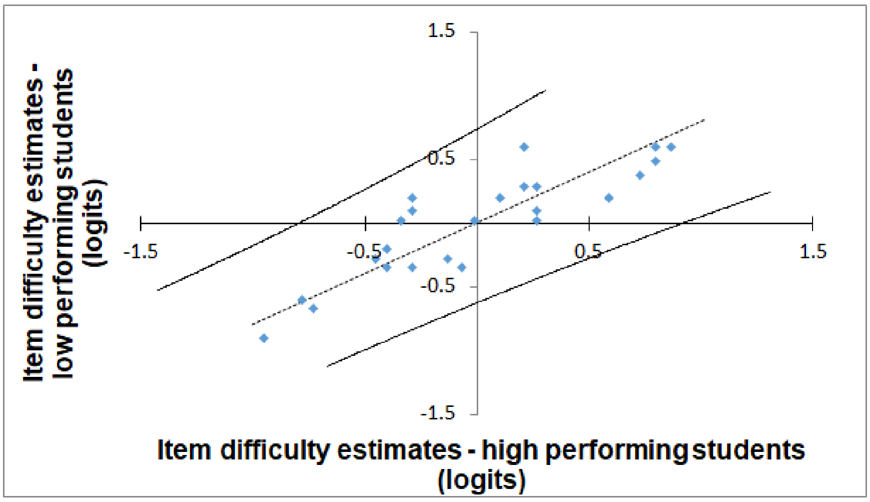
Item Fit Statistics and Item Difficulty Invariance

For our 24 items, the infit mean square (MNSQ) statistics ranged from 0.91 to 1.06, whereas the outfit mean square (MNSQ) statistics ranged from 0.87 to 1.10. No item had a standardized (ZSTD) infit or outfit statistic outside the range from -2.0 to 2.0. Thus, we could conclude that the item fit was excellent for our data (Wright & Linacre, 1994). This is an important finding. In fact, Wright and Panchapakesan (1969) assert that in situations where guessing cannot be neglected or items measure different abilities, items may not fit together. Thus, excellent item fit statistics obtained in our study provide further evidence that most students approached test solving responsibly and that our 24-item scale measures a single construct.

An important feature of Rasch difficulty estimates is that they are independent of the student sample if data fit the Rasch model (Bond & Fox, 2015). For purposes of checking whether this feature holds for our data, we ranked our students with respect to their Rasch ability measure and divided the student sample into a relatively high-performing subgroup (77 students) and a relatively low-performing subgroup (78 students). Next, we separately calibrated our 24 items for these two subgroups and created a cross-plot of obtained item difficulties (Figure 2).

Figure 2

Evidence for Item Difficulty Invariance; A 95% Confidence Band Is Shown



It has been found that the differences between item difficulty estimates obtained for the two subgroups of students are not statistically significant. The difficulty estimates may be considered as independent from the student sample.

Person-item Targeting

Person-item targeting may be most adequately evaluated by inspecting Wright's map which shows the distribution of items and examinees along the same unidimensional logit scale (Figure 3).

The Rasch ability of examinees as well as the difficulty of items increases when we move from the bottom to the top of Wright's map. Linacre (2017) points out that ideally the items should be targeted, i.e., lined up with persons, and items should have even spread, with no gaps, along the vertical axis.

Wright's map for our 24 items and 155 students shows that the test proved to be very difficult for most of the sampled high school students. If we know that even the most able university students have substantial difficulties with understanding basic wave optics concepts (Ambrose et al., 1999), these findings are not surprising, at all. This could also explain why the person reliability coefficient was relatively low for our student sample: simply, there was a large group of students whose wave optics ability was below the difficulty of all 24 items. Consequently, for this subgroup of students, our 24 items scale did not allow for reliable discrimination of wave optics abilities, i.e., it did not allow for reliable ranking of students along with the wave optics ability construct. We can conclude that, if we aim to rank the students with respect to their wave optics understanding, our 24 items scale works best when administrated to students from the upper half of ability distribution, e.g., with students from advanced physics courses in high schools or honors courses. On the other hand, if our aim is only to identify students' misconceptions, then preciseness of students' ranking is of secondary importance, and it is more important that our distractors work well. Some authors point out that distractors may be considered to work well if each of them is chosen by at least 5 % of students (Kline, 2015), which was the case for all the distractors in our study.

Figure 3

Wright's Map for Inspecting Person-Item Targeting

```
MEASURE    Person - MAP - Item
                  <more>-<rare>
                        +
                   .    -
                        -
                        -
                   .    -
                        -
    1                   +
                        -T
                        -
                   #    -   ITEM12   ITEM30
                        -   ITEM22
                        -   ITEM2
                   # T- 	ITEM16
                        -S  ITEM11
                   .    -
                        -   ITEM20   ITEM27
                  .#    -   ITEM10   ITEM17   ITEM18
                        -
    0            ###    +M  ITEM14
                        -   ITEM19   ITEM24
                 ### S- 	ITEM21   ITEM26
                        -   ITEM23
             .######    -   ITEM13   ITEM28   ITEM6
                        -S  ITEM15
           #########    -
                        -
                        -   ITEM4
         .##########    -   ITEM7
                        -
         .########## M-T    ITEM8
   -1                   +
                        -
          ##########    -
                        -
                        -
            .#######    -
                        -
                      S-
               #####    -
                        -
                        -
                        -
   -2         .#####    +
                        -
                        -
                      T-
                  ##    -
                        -
                        -
                        -
                        -
                        -
   -3                   +
                  <less>-<freq>
```

Generally, if we look for some pattern in the hierarchy of item difficulty, one may note that the lowest difficulty is associated with the requirement to relate zero path-length difference between two waves with the occurrence of constructive interference (item 8). Next, there are items in which students had to predict how a change in color of light would influence the interference/single slit/grating pattern (e.g., items 13, 15, and 20). Finally, in some of the most difficult items students had to overcome the misconception that increasing slit width/slit separation or decreasing slit-screen distance results in wider fringes (e.g., items 12 and 22).

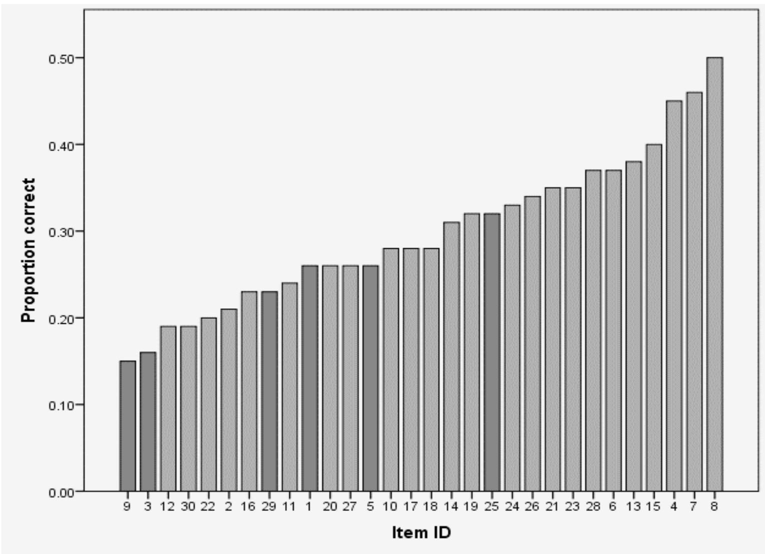
Item-level Analyses

Although our primary aim was to develop a scale for purposes of measuring understanding of wave optics in high school students, we strongly believe that our items may be generally a valuable tool for identifying misconceptions in wave optics and for providing concrete contexts for conceptual discussions about wave optics phenomena.

In practice, identification of concrete students' difficulties and conceptual discussions largely happen at the level of individual items. Therefore, in this paper, we also provide item-level analyses. The proportion of correct answers for all 30 field-tested items is presented in Figure 4.

Figure 4

The Proportion of Correct Answers for the 30 Field-Tested Items



Red-colored are the bars for items that were excluded from the HSWOT scale but can be informative for the identification of misconceptions.

Generally, the three most difficult items for our students proved to be items 3, 9, and 12, whereas the three least difficult items were items 8, 7, and 4.

In item 8 students simply had to associate zero path length difference between two waves with constructive interference and it seems that most high-school students manage to correctly handle this task. When it comes to item 7, the students were required to predict how a double-slit interference pattern changes if the slits are rotated by 90°. In other words, solving this item is facilitated by visuospatial intuitive reasoning which could explain why it was relatively easy for our students (Mešić et al., 2016). Finally, in item 4 students were asked about the distribution of light intensity in the space between the illuminated double-slit mask and screen. Many students correctly recognized that intensity of light changes according to a regular pattern. However, up to 30 % of students wrongly believed that in the space between double-slit and screen the waves only constructively interfere which results in the constant intensity of light in this region of space. It is interesting to note that similar misconceptions were earlier identified in geometrical optics. Concretely, in the context of lenses, Goldberg & McDermott (1987) noticed that many students cannot conceive an image as existing in space, independent of the surface.

Item 9 proved to be the most difficult. It is interesting to note that it was very similar to the easiest item, i.e., item 8. Again, the students were shown two point sources and they were required to think about the superposition of light at point A which was at an equal distance from the two sources. However, this time it was pointed out that the two sources emit waves of different wavelengths and consequently at point A there is a superposition of two incoherent waves. This means that the amplitude of the resulting wave in point A changes over time; generally, such sources cannot generate a stable interference pattern of non-uniform intensity. In spite of that, approximately 41 % of students answered that, like in item 8, constructive interference will happen at point A.

Item 3 proved to be also very difficult for students. In that item, students were shown a wavefront representation of a two waves interference. Approximately, 39 % of students chose option "c" which reflects the misconception that at points where wavefronts do not intersect there is no interference at all. This once again shows that we must be very careful when introducing visual representations in order to avoid the development of misconceptions (Mešić et al., 2016).

Finally, in item 12, 33.5 % of students believed that increasing slit separation results in wider interference fringes and 39.4 % of students believed that wider fringes are a result of decreasing the slits-screen distance.

Generally, our wave optics-related items proved to be very effective in uncovering students' misconceptions. In fact, all distractors have been chosen by more than 5 % of students. Furthermore, in 8 out of 30 items some distracters were chosen by more than 35 % of students (Table 1).

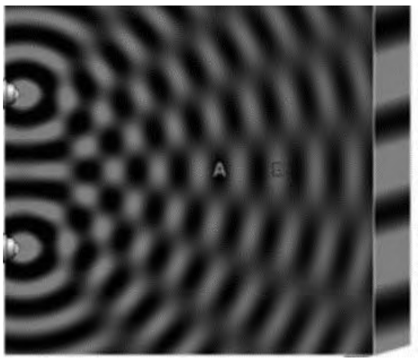
Table 1

Results of the Distractor Analysis

Item 1	Item 2	Item 3	Item 5	Item 9	Item 12	Item 22	Item 30
A	C	C	C	B	C	D	C
35.5%	47.7%	38.7%	47.7%	40.6%	39.4%	37.4%	35.7%

Figure 5

Item 5 Illustration



As we can see, the most powerful distracters were identified for items 2 and 5. In item 5 students were shown the wavefront representation of double-slit interference for a fixed amount of time. Also, points A and B which both lie on the direction $\theta=0°$ and are separated by $\lambda/2$ were shown (Figure 5). The students were asked what we would observe in points A and B if the screen was moved to these points.

Almost 48 % of students answered that a dark fringe would be observed in A and a bright one in B.

However, it should be noted that at both points the path length difference between the two interfering waves is zero and consequently a bright fringe would be observed. The students should be led to observe that even at positions of bright fringes the resultant wave periodically becomes zero, as is the case for point A at the given instant of time. However, the intensity of light is not determined by this instantaneous state of the wave (i.e., electromagnetic field), but by the square of the amplitude which is constant over time for the interference of coherent waves at a fixed point in space.

In item 2 students were asked why was it important to first pass the white light through a small hole before it illuminates the double-slit in the double-slit interference experiment. From the history of physics, we know that is precisely how we achieve good spatial coherence of light (Hecht, 2017). Spatial coherence is a measure of a correlation between the phases of a light wave at different points transverse to the direction of propagation (Malik & Singh, 2010). By passing the wave through a small hole, only a small part of the wavefront is let through the hole and for this part of the wave, the correlation between the phases of light at different points of the wave is substantial. However, the minority of students recognized the increase of spatial coherence as an explanation. In fact, nearly 48 % of students believed that the primary role of the small hole is to focus light on the slits. Nevertheless, probably it could be said that at the hole an opposite process happens: according to Huygens's principle, each point of the hole becomes a source of secondary waves and light diffracts behind the hole which means that the students' answer cannot be considered as correct.

Limitations of the Study

An important limitation of this study is related to the fact that the final field study has been conducted through an online survey in which we were not able to control testing conditions (e.g., time of testing, cheating, etc.) as we could have done if there was a paper-and-pencil administration of the test. However, the fact that item fit was excellent indicates that careless guessing of answers was not a serious issue in our study (Wright & Panchapakesan, 1969) which suggests that most students solved the test responsibly. Furthermore, it should be noted that the distribution of students' answers on individual items was not random and many misconceptions could be identified which additionally speaks for the fact that the answers provided by students were informative.

Another important limitation of this study is that the reliability for our 24-item scale was barely acceptable. As we could see earlier, this only means that we must be careful when using sum scores (composite scores) for our HSWOT scale. Particularly, we should avoid using this scale for ranking low-competence high-school students concerning their understanding of wave optics. A more reliable ranking may be obtained when the scale is used with high-school students of above-average competence (e.g., honors courses).

Conclusions

Currently, there are no research-based scales for measuring the understanding of wave optics in high-school students. In this study, we aimed not only to develop such a scale but also to provide the physics education community with new, original conceptual items about wave optics phenomena.

Eventually, we managed to develop a 24-item scale calibrated within the framework of Rasch formalism. The scale measures a single construct which is the understanding of wave optics. It is characterized by good item reliability. When it comes to person reliability, it is recommended to use the scale with high-school students of above-average competence (e.g., honors courses).

Generally, the developed conceptual items proved to be powerful in detecting students' misconceptions. In addition to identifying misconceptions that are known from earlier studies, we also managed to detect some misconceptions that were not reported in earlier research, namely:

- Interference happens only at places where the shown wavefronts intersect,

- If at some point in space, at an instant of time, the electromagnetic field is zero, at that point necessarily a dark fringe is observed,
- The role of the small hole in a double-slit interference setup with white light is to focus light on the slits.

The findings from our research implicate, that powerful mental models about wave physics phenomena cannot be developed based on verbal representations and mathematical formalism alone (Greca & Moreira, 1997). It is important to combine multiple representations which may: activate complementary learning processes, constrain the room for misinterpretation and help to construct deeper understanding (Ainsworth, 2008). However, the different representations of waves (e.g., wavefronts, oscillating vectors, sinusoids) must be introduced very carefully if we want to prevent the development of misconceptions about wave physics phenomena. Multiple representations should be only combined after we are sure that students have a good understanding of each individual representation. Some of the approaches that earlier research found to be promising for the development of powerful mental models about wave physics phenomena are the 5E model of inquiry-based learning (Bezen & Bayrak, 2020), sensor-based labs, and modeling (Buongiorno et al., 2018), establishing analogies combined with the hands-on introduction of the wave representations (Wosilait et al., 1999). It should be noted that the assessment instrument developed in our study allows for a more objective comparative evaluation of the different approaches to teaching wave optics.

In our future studies, we intend on investigating the type of student population for which our set of conceptual items allows the most reliable measurements of wave optics understanding.

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Appendix A

These goals are for the very early version of the test - 44 items. We preferred to present them here for the readers who want to have information about the learning goals we used to develop our test. Many of the items were removed during the test development process. The values in the parenthesis are the ID of the items in the final student survey presented in Appendix B.

Goals (key ideas)	Coherence; Huygens-Fresnel principle	Two wave interference	Optical grating	Single slit	Combined topics
It is possible that Light+Light=No light		Item 1			
Differences in wavelengths affect the degree of coherence; Superposition of two waves with different wavelengths leads to a resulting wave whose amplitude continuously changes which influences that a stable interference pattern of non-uniform intensity cannot be observed	Item 2 Item 12 (9)				
Passing light through small apertures may increase (spatial) coherence, and passing light through color filter may improve temporal coherence	Item 3 (2) Item 44 (29)				
Maxima can be observed all along antinodal lines and a point between two wavefronts does not have to be an interference minimum; Zero resultant electric field in a point at a certain time instant does not necessarily mean that in that point we will observe a dark fringe.		Item 4 (3) Item 6 (5)			
Waves do not interfere only on the screen but also in the space between slits and screen.		Item 5 (4)			
Zero resultant electric field in a point of space at a certain time instant does not necessarily mean that in that point the phase difference of interfering waves is an odd multiple of π.;		Item 7			
<u>In two wave interference</u>, dark fringes correspond to phase difference π and path difference $n*\lambda/2$ (n-odd integer); Bright fringes correspond to 2 π phase difference and path difference $n*\lambda$ (n-even integer); Not only path length difference, but also the initial phase difference matters! Higher order of maximum corresponds to larger path difference.		Item 8 (6) Item 10 (8) Item 13 (10) Item 14 (11) Item 28			
If you rotate the double slit, the interference pattern gets rotated, which is due to the fact that now light diffracts along the vertical axis.		Item 9 (7)			
Two waves with differing amplitudes can interfere to give a stable, non-uniform pattern, but no absolute destructive interference can occur.		Item 11			
Two coherent waves that propagate in opposite directions can result in a standing light wave.		Item 15			
If light is not perpendicularly incident on the double slit there is a difference in initial phases of the secondary waves and the central maximum is not anymore at zero diffraction angle.		Item 16			
In wave optics, small path difference need NOT be neglected!		Item 17			

Changing λ, slit separation, slit width, screen separation or optical medium affects width and separation of fringes. Moving the screen from/towards slit does not change the diffraction angle at which minima and maxima can be seen!		Item 18 (12) Item 19 (13) Item 21 (15) Item 22 (16) Item 27 (19) Item 29 (20)	Item 24 (17)	Item 34 (22) Item 35 (23) Item 39	Item 25
Polychromatic light can also give a diffraction pattern whose characteristics depend on mixing of colors.		Item 20 (14)	Item 26 (18)		
More slits means sharper fringes.			Item 23		Item 32 (21)
Light from incandescent bulb has a low degree of coherence.	Item 30				
Coherence of light may be improved by applying a color filter or by passing light through a small aperture.	Item 31				
All points reached by a wave become sources of new waves and their superposition affects the appearance of the screen; Vertical length of the slit may influence vertical length of fringes (more/less point sources along vertical direction)	Item 41 (1) Item 42 (28)	Item 33			
The ratio λ/a and λ/d determines the location of minima/maxima in single-slit diffraction and double-slit interference, respectively.				Item 36 (24) Item 37 (25) Item 40 (27)	
Single slit pattern is characterized by a wider central fringe, whereas in double-slit interference patterns all fringes should (ideally) be of same width. Optical grating patterns are typically characterized by very narrow fringes.					Item 38 (26)
When a double slit is illuminated with light from a source of finite size, whether the waves from the two slits are spatially coherent also depends on the between slit separation					Item 43

Appendix B

Here we present the version of the instrument used in the final student survey. Correct choices are highlighted with green color.

Item 1

A laser beam of wavelength 650 nm is perpendicularly incident on a slit of width 20 μm and height 2 cm. Which processes will occur after the light encounters the slit?

a) The edges of the slit will become sources of secondary waves, whose superposition will result in the occurrence of bright and dark fringes on the screen.
b) All the points between the two edges of the slit will become sources of secondary waves, whose superposition will result in the occurrence of bright and dark fringes on the screen.
c) The point at the centre of the slit will become a source of secondary waves which will result in the occurrence of one bright, vertical fringe on the screen.
d) The edges of the slit, as well as the point at the centre of the slit will become sources of secondary waves whose superposition will result in the occurrence of bright and dark fringes on the screen.

Item 2

In double-slit experiments with white light, light is firstly passed through a small hole before arriving at the two slits (Figure 1). What is the role of passing the light through the small hole first?

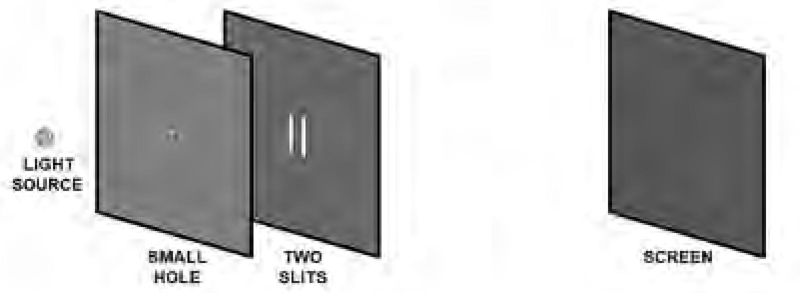


Figure 1

a) To reduce the intensity of light.
b) To obtain relatively coherent light.
c) To focus the incoming light onto the double slit.
d) To obtain monochromatic light.

Item 3

Two identical, mutually coherent point sources 1 and 2 start to emit waves at the same instant (see Figure 2). Which of the following best describes the situation at points A and B?

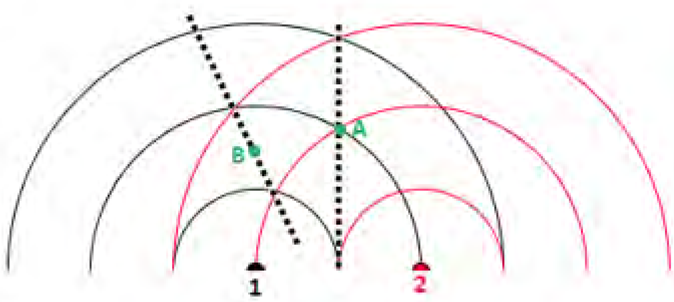


Figure 2

a) At point A there is a bright fringe and at point B there is a dark fringe.

b) Both at point A and B there would be bright fringes.
c) At point A there is a bright fringe, whereas at point B there would be no interference at all.
d) At point A there is a dark fringe and at point B there is a bright fringe.

Item 4

Laser light is incident on a double slit which results in the occurrence of bright and dark interference fringes on the screen. Which of the following is true regarding the intensity of laser light in the space between the slits and the screen?

a) The intensity is zero.
b) There is a constant and non-zero intensity.
c) There is constant intensity which corresponds to complete constructive interference.
d) The intensity is changing from point to point according to a regular pattern.

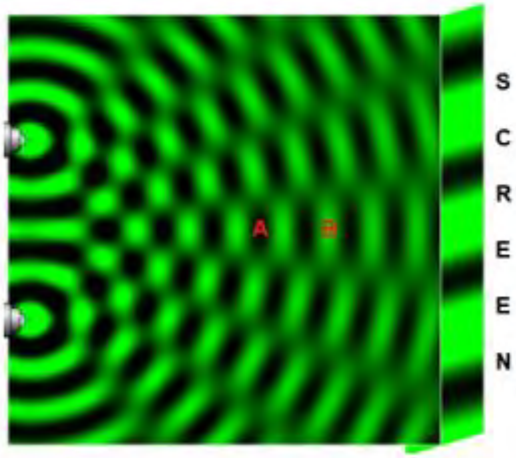


Figure 3

Item 5

Figure 3 illustrates the interference of two coherent waves at a certain instant of time. Screen with the resulting interference pattern is also shown in Figure 3. What would we observe in points B and A if we move the screen to these points?

a) In both points we would observe a bright fringe.
b) In both points we would observe a dark fringe.
c) In point A we would observe a dark fringe and in point B a bright fringe.
d) In point B we would observe a dark fringe and in point A a bright fringe.

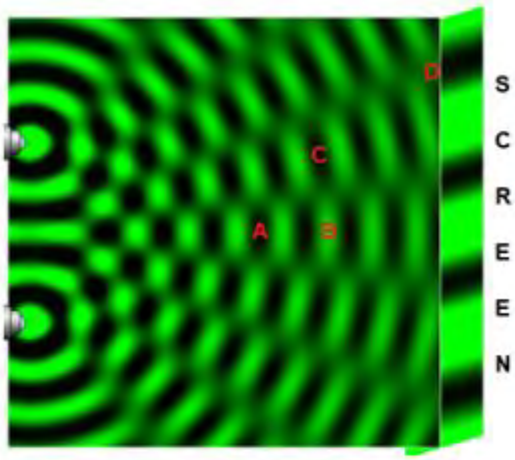


Figure 5

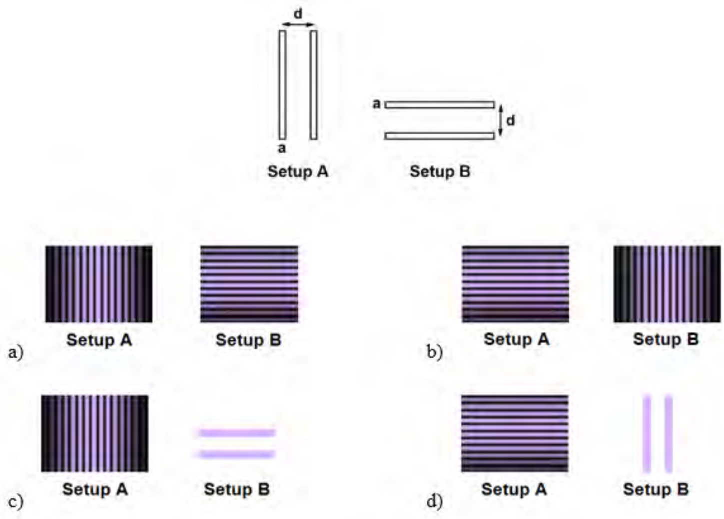
Item 6

Figure 5 illustrates the interference of two coherent waves at a certain instant of time. Screen with the resulting interference pattern is also shown in Figure 5. What is the path difference of interfering waves at point D?

a) $7\lambda/2$
b) $8\lambda/2$
c) $5\lambda/2$
d) $3\lambda/2$

Item 7

Laser light is perpendicularly incident on a double slit (Setup A). The setup is then modified by rotating the slits by 90° (Setup B). Which pair of interference patterns best represents the appearance of the screen for Setup A and Setup B?



Answer is A

Item 8

Two mutually coherent point sources 1 and 2 start to emit light waves which have same initial phases (see Figure 6). Which of the following is true regarding the interference at points A and B?

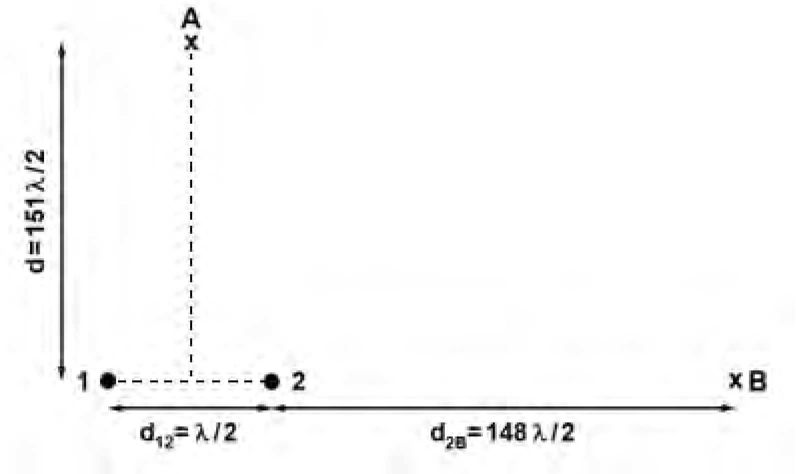


Figure 6

a) Point A is a maximum and point B is a minimum.
b) Point B is a maximum and point A is a minimum.
c) Interference maximum occurs in both points.
d) Interference minimum occurs in both points.

Item 9

Two point sources 1 and 2 start to emit waves of different wavelengths and same initial phases (Figure 7). Which of the following is true regarding the situation at point A?

a) The amplitude of the resultant wave changes over time.
b) Completely constructive interference will occur.
c) Completely destructive interference will occur.
d) No superposition of waves will take place at A.

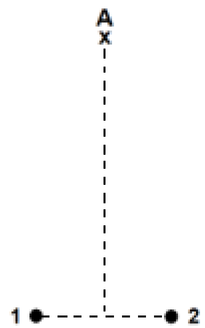


Figure 7

Item 10

Two identical, mutually coherent point sources 1 and 2 emit light waves with a phase difference that corresponds to a half period delay (Figure 8). Which of the following is true regarding the interference at points A and B?

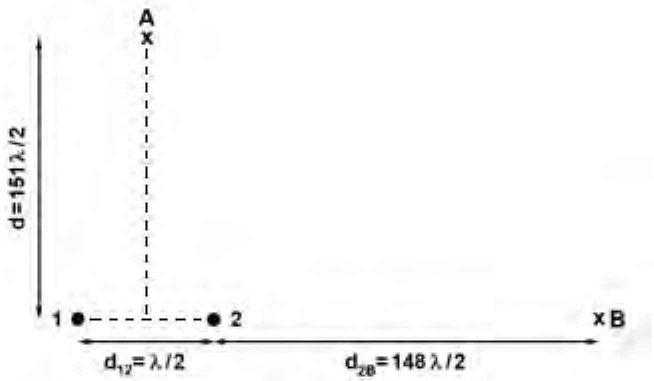
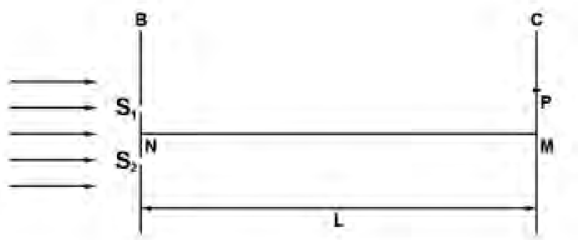


Figure 8

a) Point A is a maximum and point B is a minimum.
b) Point B is a maximum and point A is a minimum.
c) Interference maximum occurs in both points.
d) Interference minimum occurs in both points.

Item 11

Laser light is incident on slits S_1 and S_2. The waves emitted from S_1 and S_2 arrive at point P on the screen with a phase difference of 11π. What will be observed at point P?



a) A bright fringe that corresponds to complete constructive interference.
b) A dark fringe that corresponds to complete destructive interference.
c) From the given information we cannot determine whether there will be a bright or dark fringe.
d) A fringe that corresponds neither to complete constructive nor complete destructive interference, but something in between.

Item 12

Which of the following should be done to change the double slit interference pattern shown in Figure 9a to the pattern shown in Figure 9b? Remark: Central maxima are designated with "+".

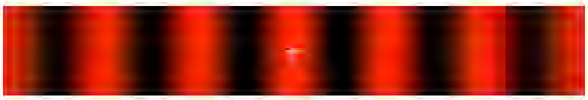


Figure 9a

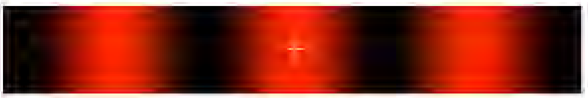


Figure 9b

a) Increase the slit seperation.
b) Cover one of the slits by an opaque material
c) Decrease the distance between the slits and the screen.
d) Decrease the slits seperation.

Item 13

When red laser light is incident on a double slit the first order minima occur at angles of +6.2° and -6.2°, respectively (see Figure 10). How the magnitude of these angles will be affected if red light is replaced with violet laser light?

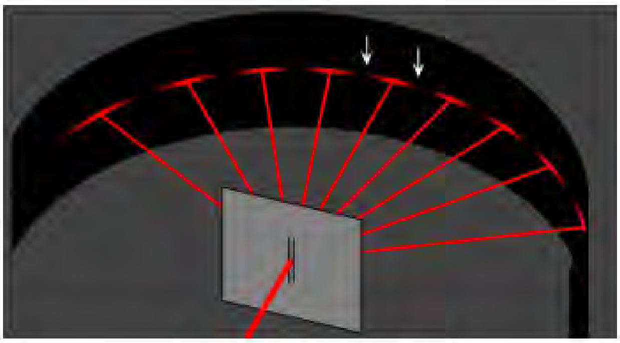
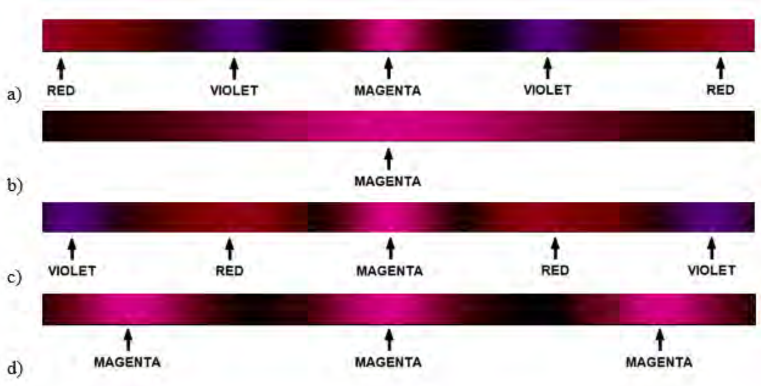


Figure 10 Red laser light setup

a) Will increase.
b) Will decrease.
c) Will remain the same.
d) For violet laser light no interference pattern can be obtained.



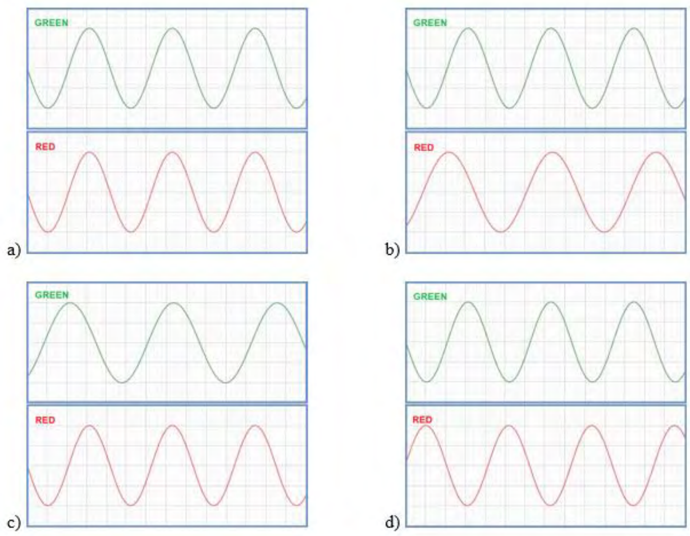
Item 14

Light which consists of wavelength 680 nm and wavelength 400 nm passes through a small hole and thereafter it illuminates a double slit. Which of the following would best describe the appearance of the screen?

Answer is A

Item 15

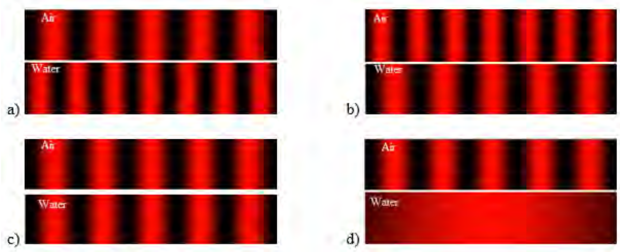
Green laser light is incident on a double slit which results in a typical interference pattern for which a relative distribution of intensity of light is recorded. Then the whole experiment is repeated with only changing the wavelength of light from green light to red light. How would the relative distribution of light intensity compare for these two experiments?



Answer is B

Item 16

Young's double slit experiment is first performed in air and then in water with the same experimental setup. Which of the provided figures best compares the appearance of the screen in air and water?



Answer is A

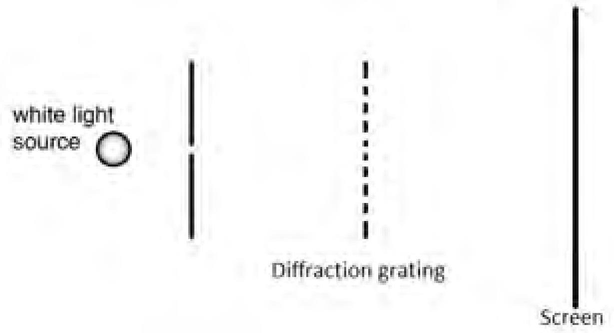
Item 17

Laser light is perpendicularly incident on a diffraction grating. What happens with the diffraction pattern if we increase the screen's distance from the grating?

a) The distance between the fringes will increase.
b) The distance between the fringes will decrease.
c) The intensity of fringes will increase.
d) The fringes will become narrower.

Item 18

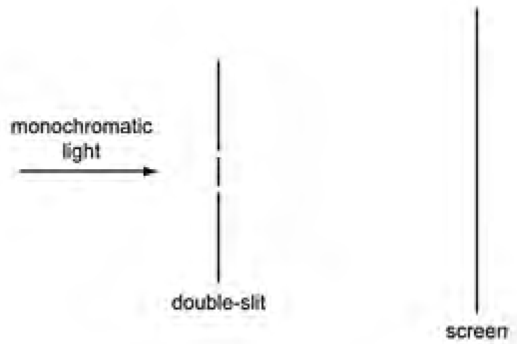
In a laboratory experiment, white light first passes through a narrow slit and thereafter it illuminates a diffraction grating (see Figure). What will be seen on the screen?



a) The central fringe is black with black and white fringes on each side.
b) The central fringe is black with coloured fringes on each side.
c) The central fringe is white with black and white fringes on each side.
d) The central fringe is white with coloured fringes on each side.

Item 19

A student sets up apparatus to observe the double-slit interference of monochromatic light as shown. Interference fringes are formed on the screen. Which change would increase the distance between adjacent interference fringes?



a) Decrease the distance between the two slits.
b) Increase the intensity of incident light.
c) Move the screen closer to the double-slit.
d) Use light of a higher frequency.

Item 20

In a Young's double slit experiment, green laser light is incident on the two slits. Which one of the following changes would cause the fringes to be more closely spaced?

a) Reduce the slit separation.
b) Use red light instead of green light.
c) Use blue light instead of green light.
d) Move the screen farther away from the slits.

Item 21

Laser light is incident on a double slit which results in the typical interference pattern on a screen. Then we start adding new identical slits, while preserving the separation between adjacent slits. How will adding of a large number of new slits affect the bright fringes?

a) Bright fringes will become narrower and more intense.
b) Bright fringes will only become more intense.
c) Bright fringes will become wider and less intense.
d) Bright fringes will become narrower and less intense.

Item 22

Which of the following was done to change the diffraction pattern shown in Figure 13a to the pattern shown in Figure 13b? Remark: The central maxima are designated with "+".

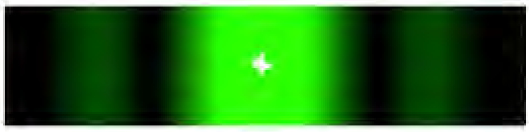


Figure 13a

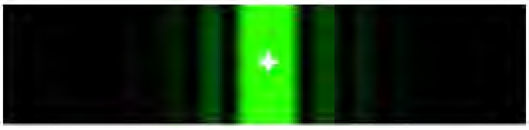


Figure 13b

a) A more powerful laser has been used.
b) The slit width increased.
c) The distance between slit and the screen increased.
d) The slit width decreased.

Item 23

When red laser light is incident on a single slit, the first order maxima occur at angles of +18.1° and -18.1°, respectively (see Figure 14). How the magnitude of these angles will be affected if the screen is moved farther away from the slit?

a) Will increase.
b) Will decrease.
c) Will approximately remain the same.
d) First it will decrease and after some point it won't change anymore.

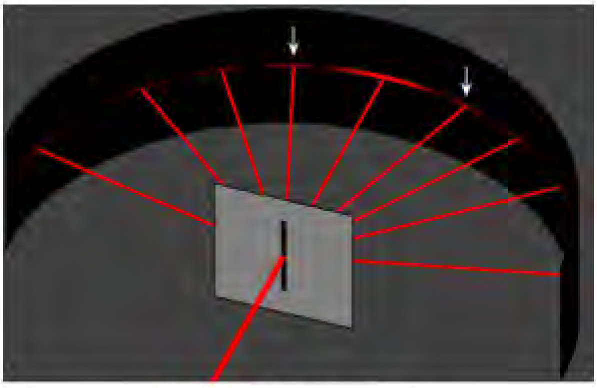


Figure 14 Original setup

Item 24

Laser light of wavelength 400 nm is incident on a slit of width 2 μm. Figure 15 illustrates how this light diffracts. Positions of first order minima are shown. What will happen with the location of first order minima when wavelength of light is increased by a factor of 1.5, and width of the slit is also increased by the same factor?

a) The location of first order minima won't change.
b) The minima will move farther away from the central maximum.
c) The minima will move towards the central maximum.
d) For a slit width of 3 μm there won't be any diffraction minima.

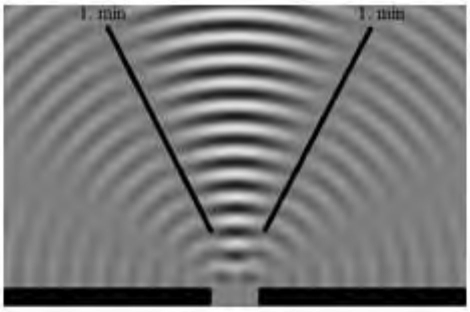


Figure 15

Item 25

A laser beam of wavelength 650 nm is incident on a slit of width 200 nm. Which of the following is true regarding the appearance of the screen placed two meter behind the single slit mask?

a) Alternating bright and dark fringes would appear on the screen.
b) We could observe a small bright spot at the very centre of the screen.
c) We could observe a very wide diffraction fringe along the screen.
d) The screen would be dark, because slit width is lower than wavelength of light.

Item 26

In three different experiments red laser light has been used for obtaining interference and diffraction patterns (see Figure 16). What apparatus has been used in these experiments?

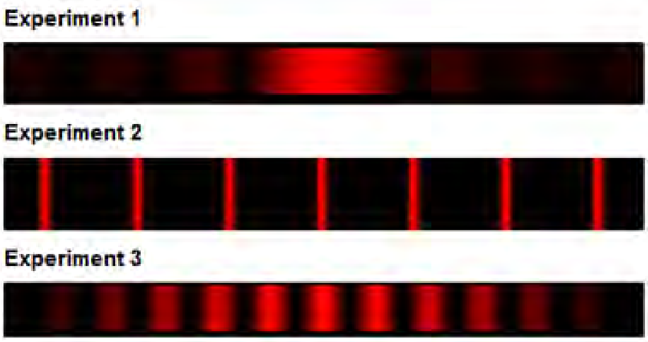


Figure 16 Obtained interference and diffraction patterns

a) Double slit, diffraction grating, and single slit, respectively..
b) Single slit, diffraction grating, and double slit, respectively.
c) Single slit, double slit and diffraction grating, respectively.
d) Double slit, single slit, and diffraction grating, respectively.

Item 27

A laboratory experiment produces a single-slit diffraction pattern with alternating bright and dark fringes on the screen. The slit width is a and the wavelength of light is λ. How does λ compare to a in this situation?

a) $\lambda < a$
b) $\lambda = a$
c) $\lambda > a$
d) Not enough information to compare λ to a.

Item 28

Huygens-Fresnel principle can be used to explain which of the given phenomena?

a) Only interference, diffraction and polarization of light.
b) Only diffraction of light.
c) Only interference of light.
d) Reflection, refraction, diffraction and rectilinear propagation of light.

Item 29

Which of the following procedures would be the best choice to increase the coherence of white light?

a) Passing the light beam through a very thin glass.
b) Passing the light beam through a prism.
c) Passing the light beam through a color filter.
d) Passing the light beam through a diverging lens.

Item 30

Light of wavelength λ is incident on a diffraction grating that has 100 slits. The first-order maximum is observed at point P on a distant screen. What is the path difference between light waves that travel to point P from first slit and 100th slit?

a) λ
b) 100 λ
c) 50 λ
d) 99 λ