Ninth grade students' mental representations of the refraction of light: didactic implications

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The study of students' mental representations of physics concepts and phenomena constitutes a central part of physics education research, as they play a decisive role in teaching. In the study presented here, we investigate 213 ninth grade students' mental representations of the phenomenon of refraction, after they were taught about it in school. The empirical data was gathered through an interview using 3 tasks which involved the evaluation of hypothetical situations. The research data included mental representations that cause difficulty in the comprehension of refraction.

Keywords: Refraction; light; students' mental representations.

El estudio de representaciones mentales de estudiantes sobre conceptos de Física y fenómenos, constituye una parte central de la investigación en educación física, dado que desempeñan un papel decisivo en la enseñanza. En el estudio aquí presentado, se investigan 213 representaciones mentales de estudiantes de noveno grado sobre el fenómeno de la refracción, tras haberles sido enseñado en la escuela. Los datos empíricos fueron recolectados a través de una entrevista utilizando 3 tareas que involucraron la evaluación de situaciones hipotéticas. Los datos de la investigación incluyeron representaciones mentales que causan dificultades en la comprensión de la refracción.

Descriptores: Refracción; luz; representaciones mentales de estudiantes.

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1. Theoretical Framework

The study of students' understanding of optical phenomena has produced, over the past 30 years, a considerably developed area of research in the field of Science Education. Phenomena and concepts such as light as an entity, rectilinear propagation, shadow formation, vision, and image formation are the most common research topics. They are always addressed within the context of a Geometrical Optics model, which is based on the hypotheses regarding point sources of light and isotropic beam propagation, and constitute the dominant model used in education for children aged from 5-6 to 15-16 [1].

The work that has been done regarding scientific models which have been suitably transformed for the requirements of education offers significant advantages, of which perhaps the most important is the constancy of reasoning schemas which allow students' thought three important functions: description, interpretation and prediction [2-6]. The Geometrical Optics model possesses these features without deviations in terms of a wide range of phenomena and offers a most suitable framework for education [7]. But there are problems included in the primary and low secondary education curricula, such as reflection and refraction, whose descriptions and predictions can be based on the concept of the ray and whose explanation requires the use not of Geometrical Optics but of Wave Optics. The model of Wave Optics is introduced at the end of secondary education, whereas the study of refraction begins in primary education. Thus, the phenomenon is approached based on Snell's law, which is used to describe the relationship between the angles of incidence and refraction when referring to light passing through a boundary between two different isotropic media, such as air and water.

Research on the way in which students up to the age of 15 approach refraction shows great difficulty in the understanding of the phenomenon.

Certain initial studies examined the mental representations of refraction formed by students aged 12-15 based on ordinary, everyday problems such as, for example, the effort to see a piece of plasticine at the bottom of a container of water [8,9] (Andersson & Kärrqvist, 1983; Bouwens, 1987). The categorization of the children's answers produced two general categories of representations. The "concrete" ones, in which students refer only to the objects presented (the plasticine, the water, the container) and the "abstract explanations" which the students answered in terms of reflection or used so-called "vision rays", *i.e.*, they assumed that the light is transferred from the eyes to the object. A very small number of students gave an explanation based on refraction.

Singh & Butler [10] gave high school and university students various refraction problems, in which refracted light encountered concave, convex and plane surfaces. Based on the answers given, the researchers categorized and studied students' representations, and saw that, for most of the study's subjects, refraction in the various problems was tackled in a way which was related to each problem, and that whatever, if any, categorizations were made were based on superficial characteristics. Thus, for example, the students approached prisms, parallel or curved surfaces without applying the law of refraction as a general principle, which would allow the solving of similar problems; moreover, they were unable to appreciate that a beam of light falling upon the interface of two media undergoes partial refraction and partial reflection.

By studying projects conducted by high school and university students on the formation of virtual images by a triangular prism based on refraction, Galili, Bendall & Goldberg [11] arrived at the conclusion that high school and university students were unable to apply a general rule towards the interpretation of the images. They simply invoked refraction, but were unable to draw rays in the prism and to functionally utilize the concept.

In China, in a study in which they highlighted significant difficulties in the matter of understanding refraction among junior high school students, Chen, Chang & Guo [12] identified the problems in students' representations as being related to: "(a) the inability of the primary level science curriculum to provide students with a systematic introduction to these concepts; (b) the misinterpretation of daily experience; (c) linguistic problems, such as misunderstanding of words or phrases; and (d) inappropriate connection and inference to a new context" (p. 311).

In their study of 11- and 12-year-old students' representations of refraction, Keawkhong *et al*. [13] in Taiwan asked their subjects, based on a simple experimental situation, to create diagrams which would illustrate the path followed by rays of light. The results showed that the students were unable to use the simple laws of refraction, even though they had been taught Geometrical Optics. These results were confirmed by other student examples.

Another study which was conducted in India [14] examined the representations formed by students aged 16-20 concerning a series of properties of light. The topics addressed included refraction, which was studied through the creation of the reflection of the filament of a light bulb on a screen via a convex lens. Their answers made it clear that, when discussing the creation of the reflection, students do not take into account the refraction of the light through the lens, drawing the diffusion of the light as a straight line, with no deviation.

A very small number of studies concerns teaching interventions, with an aim to change the mental representations of refraction.

Harrison & Treagust [15] used an analogy in order to work with tenth grade students. "The analogy likened a ray of light as it passes from air into glass to a pair of wheels that changed direction as they rolled obliquely from a hard onto a soft surface" (p. 1291). Their results were satisfactory and they concluded that it is especially important for educators to have planned at which precise moment of their teaching activity they will introduce the analogy which facilitates students' conceptual understanding.

In an attempt to avoid students' representations, McDermott *et al*. [16] first used the wave model in the teaching of refraction, and then introduced the concepts of geometrical optics. This method introduces the wave fronts (without invoking Huygens' principle) and then the rays which are vertical in relation to the wave fronts. Once the students work with refraction using the wave model, they combine the teaching of refraction in Optics with the teaching of real and imaginary reflections.

In a study by Aydin [17], an effort was made to transform the mental representations of geometric optics formed by second-year teacher candidates by using conceptual change texts. After systematically tracing the students' misconceptions of refraction, which were compatible with the ones we encountered in the research we presented, 90 university students were split into an experimental group and a control group. Special texts were then created which were based on these misconceptions and were intended to lead to conceptual change. These texts were used as teaching material for the students of the experimental group. As far as the control group was concerned, the lesson consisted of simple lectures, of the type used in traditional teaching methods. Following the two different teaching interventions, a questionnaire consisting of multiple-choice questions was given to the students of both groups. The study showed that the conceptual change texts are more effective than the traditional teaching method towards eliminating students' misconceptions regarding geometric optics.

However, the research which has been conducted internationally to this day on the documentation of students' representations of refraction is limited and fragmentary. It usually focuses on older students, *i.e*., after the 11th grade, and the tasks employed are often quite complicated for students who then prove unable to tackle even the most fundamental application of the laws of refraction. In addition, matters of refraction are often combined with matters of vision, a fact which often causes confusion due to the combination of various misconceptions with respect to the role of rays in the propagation of light and in vision.

Arguably, these difficulties, which are documented in this study, could be due to the effort to create reasoning schemas in students' minds outside the Geometrical Optics model which students are systematically taught and work on. In the study presented here, we tried to study students' representations after they have been taught refraction twice - once qualitatively and once semi-quantitatively. That is to say, we studied 9th graders' representations with respect to the second law of refraction, Snell's law, which, in the curricula considered most suitable for students of this age, studies the relation between the angles of incidence and refraction when a ray of light passes from one medium to another, *i.e*., in the case of our study, when it passes from air to glass and vice versa.

2. Research Methodology

2.1. Research Questions and Tools of Analysis

Our research questions aimed at the systematic documentation of the elements which determine students' mental representations of refraction. In addition, they allow us to discuss the possibilities of teaching a phenomenon of Physics outside the limits of the dominant work model. There are three basic questions which we studied in terms of children's thinking vis-à-vis refraction:

- Can they predict and explain the path of a ray of light moving from a thinner to a denser medium?
- Can they predict and explain the path of a ray of light moving from a denser to a thinner medium?
- Do they associate the path of the refracted ray with the angle of incidence?

We will study these questions based on the students' answers which, after we have categorized, we will present in tables of frequency and examples of answers.

2.2. Sample

A total of 213 students (102 boys and 111 girls) aged 14-15, from 10 different classes took part in this study. The students were attending the ninth grade of school (the 3rd grade of secondary school). It should be noted that all socioeconomic strata (low, middle, and high) and subject genders were equally represented in the sample. Greek students are first taught certain absolutely qualitative phenomena related to refraction in primary school and then they are taught Snell's law in the second year of secondary school (8th grade). For the "interpretation" of refraction we used the idea of the change in the speed of light when it passes from one optical medium to another.

2.3. Tasks

The children's mental representations were studied through a questionnaire with 3 tasks which referred to the issues we mentioned earlier. Each question asked the students to predict the path of a ray of light after it had fallen on a smooth, plane interface of two media, and then to justify their opinion. The questionnaire was filled out individually and eponymously. We will now present these three tasks.

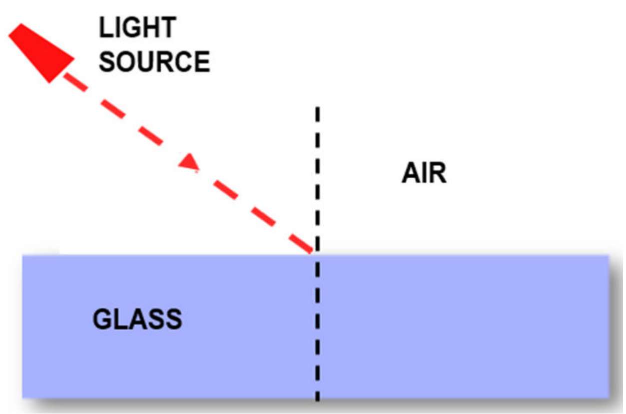

FIGURE 1. The path of the ray from the air into the glass.

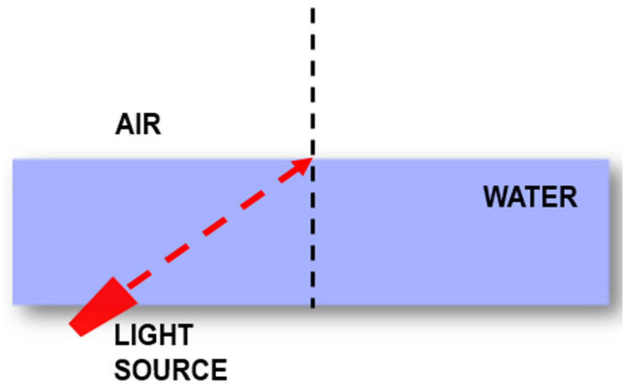

FIGURE 2. The path of the ray from the water into the air.

2.3.1. *Task 1*

"A thin ray falls obliquely on the smooth and plane surface of the glass plate of Fig. 1. Draw on Fig. 1 the path of the ray through the plate and justify this path" (see Fig. 1).

2.3.2. *Task 2*

"The light source is now in the water, as in Fig. 2. On the figure, draw the path of the ray and justify this path" (Fig. 2).

In this task, students had to draw the path of the ray and then justify their prediction. The ray of light passes from a dense transparent medium to a thinner one. It was pointed out to the students that the light source is in the water and that the ray falls obliquely on the water-air interface. If the students predicted that the ray wouldn't come out of the water, they only drew it in the water. Through this task we checked refraction from a denser to a thinner medium, as well as the event in which the students knew and chose the phenomenon of total reflection.

2.3.3. *Task 3*

"We now place the light source vertically to the surface of the glass plate. Draw the path of the ray after it falls on the glass surface and justify your choice" (Fig. 3).

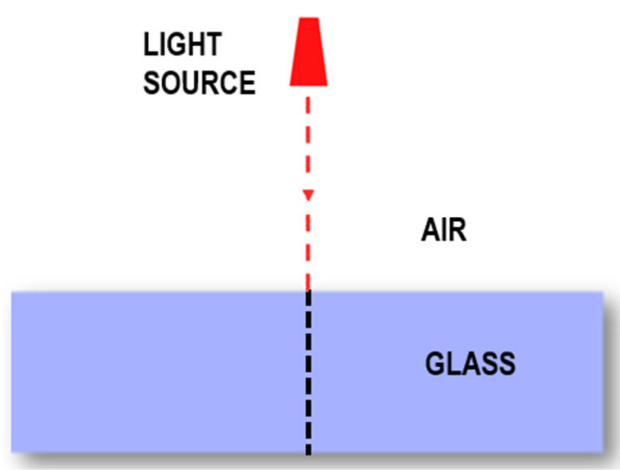

FIGURE 3. The vertical incidence of the ray from the air on the glass.

TABLE I. Frequency of subjects' answers to Task 1

	Frequency	Percentage
(a) the beam will converge with the vertical line with sufficient justification	12	5.6
(b) the beam will converge with the vertical line with insufficient or no justification	15	7
(c) the beam will diverge from the vertical line with insufficient or no justification	18	8.5
(d) The ray will continue to move rectilinearly with insufficient or no justification	123	57.7
(e) The ray will not enter the glass plate because it is reflected or diffused	45	21.1

In this task, students were asked to draw the path of the ray of light when it fell vertically on the air-glass interface.

3. Research Results

3.1. Task 1: Students' representations for the passing of a ray of light from air into glass

Students' answers tracked in Task 1 seem to confirm the research literature. Indeed, this Task clearly illustrates the difficulty most children have in predicting the path of the ray, even though they have been taught about this subject. But what is even more important is the difficulty they have in justifying their answer using arguments drawn from the context of the school teaching of refraction (Table I).

a) The first category comprises the answers of 12 students who drew a ray converging. The argument these children used to defend their drawing involved the passing of the light from the thinner to the denser medium or the fact that, in refraction, the ray of light converges in order to pass as quickly as possible. These are answers whose arguments were drawn from what the students have been taught in school. For example: "The thin beam of light won't keep moving straight but will turn a little bit in order to pass more quickly through the glass plate" (S.134).

b) The second category comprises 15 answers for which either no justification was offered, or the justification for the convergence of the ray to the vertical line was not based on arguments which are compatible with the laws of refraction. For example: "The ray will approach the vertical line because it's changing its medium of propagation" (S. 60).

c) A small number of students drew the ray as diverging from the vertical line. These answers are related to a certain representation of refraction, but they are not compatible with the teaching framework. Out of these 18 students, the 9 who justified their drawing either invoked the change of speed through the glass medium, or vaguely invoked the nature of the glass. For example: "The path of the ray through the plate diverges from the vertical line because the glass is a solid" (S. 128).

d) More than half the children thought that the path of the ray of light would not change, and thus it would continue to move rectilinearly through the glass plate too. These answers were mainly related to the material the plate is made of. Indeed, 72 students of this group attributed their interpretation to factors related to the nature of the glass plate. For example: "The ray will continue on the same path because glass is a transparent material and the ray won't have any difficulty passing through it" (S. 62); "The beam will fall obliquely and will continue in a straight line because glass is a homogeneous material" (S. 47). Four students interpreted the steady path of the ray of light by attributing to it special properties. For example: "The beam of light will pass through the glass in a straight line because a thin beam can go through any kind of material" (S. 51), while the remaining 47 students did not justify their answer.

e) In a significant number of answers, the ray did not enter the glass plate, while the 28 students who justified their answer attributed the lack of refraction to the nature of the glass plate which is denser than air. Out of these, 22 believed that the ray would reflect off the surface of the plate. For example: "The path of the ray will be reflected because glass is denser and so the ray cannot enter" (S. 10). Six students drew the light being diffused after the incidence of the ray on the pate. For example: "The ray changes path to the side because it is reflected off the surface of the glass" (S. 150). The remaining 17 students did not justify their answer.

3.2. Task 2: Students' representations of the passing of a ray of light from water to air

The reasoning formulated by the students in their answers to Task 2 lies within the same framework as that formulated in Task 1 (Table II).

TABLE II. Frequency of subjects' answers to Task 2

	Frequency	Percentage
(a) The ray will diverge from the vertical line with sufficient justification	13	6.1
(b) The ray will diverge from the vertical line without any justification suggested	29	13.6
(c) The ray will converge with the vertical line with insufficient or no justification	21	9.9
(d) The ray will continue to move rectilinearly with insufficient or no justification	121	56.8
(e) The ray will not exit the water	29	13.6

a) The first category comprises the answers of 13 children who drew the ray as diverging from the vertical line and who sufficiently justified their choice using arguments such as the results of the change of the medium in refraction; the increased density of the water compared to that of the air; or the exiting from the water to the air. For example, "In the water it will follow a straight path since the light is traveling in a homogeneous space; from the moment it exits, there will be a certain divergence due to refraction" (S. 93).

b) The second category comprises the drawings of 29 students which are compatible with the context of school teaching but are not accompanied by justifications.

c) A small number of students drew the ray as converging with the vertical line as it exits from the water. At this point we should acknowledge the effect of the teaching of refraction, although the approach is inadequate. Six students justified their choice with arguments related to refraction or the different speeds of the ray in the water and the air, but without correctly using the referential knowledge. For example "The ray will change path and will converge with the vertical line because light travels faster in water than in the air" (S. 141). The remaining 15 students did not justify their answer.

d) As in the case of the ray passing from air to glass, here too just over half the students drew the path of the ray continuing in a straight line as it exited the water into the air. Those students who justified their answer focused mostly on properties they attributed to the water. Indeed, 34 students mentioned that the ray did not meet any obstacles in the water, the water is transparent, or, more vaguely, that the water cannot change the ray's path. For example: "The ray will continue in the same direction because the water is less dense and the ray's particles will pass through it" (S. 204). The remaining 87 students did not justify their answer.

e) In 29 students' drawings, the ray appears to not be exiting the water. Only a few students justified their answers in this case; and indeed without referring to the phenomenon of total reflection. Six students referred to a kind of reflection of the ray off the surface of the water and 3 students thought that the water constituted a kind of obstacle to the exit of the ray of light. For example: "Because water is denser than air, the ray will remain inside and won't be able to get out" (S. 209). The remaining 20 students did not justify their answer.

3.3. Task 3: Students' representations of the vertical incidence of a ray of light from the air on a glass plate

The students' answers given to Task 3 are within the same contexts as that of the previous tasks (Table III).

a) In the first category, 20 children draw the ray as continuing its path without diverging, and justified their choice by the fact of the vertical incidence on the plate. However, a limited number of students suggested justifications that are compatible with the laws of refraction. For example: "The path will be a straight one because the ray is vertical with respect to the glass" (S. 44), "Since there is no angle (0° angle), the ray continues on the same path" (S. 122).

TABLE III. Frequency of subjects' answers to Task 3

	Frequency	Percentage
(a) The ray will continue to move rectilinearly with sufficient justification	20	9.4
(b) The ray will continue to move rectilinearly with insufficient or no justification	89	41.8
(c) The ray enters the glass plate and is diverted with respect to the vertical line with insufficient or no justification	34	16
(d) The ray is reflected vertically with respect to the plate in the opposite direction	51	23.9
(e) The ray is reflected and diffused in different directions	19	8.9

b) The second category comprises 89 students who drew the ray as continuing its rectilinear path even after entering the plate, but either did not justify their answer or justified it insufficiently, referring to the absence of an obstacle or the transparent nature of the plate. For example: "The light will go straight through the glass plate because it's transparent" (S. 72).

c) Here we have the answers of 34 students who believe that the ray will diverge with respect to the vertical line on the surface of the plate. Eleven of these students who justified their answers appeared clearly influenced by the general discussion on refraction, but did not make sufficient use of this referential knowledge. For example: "The ray will bend in both directions because it is falling vertically, and it will also bend for the same reasons" (S. 98); "Because of refraction, because it changes medium" (S. 30).

d) About 1/4 of the students drew the ray as reflecting vertically off the plate and going back. Of these students 29 gave no justification and 22 invoked various processes of reflection. For example: "Because the ray will be reflected and will go back" (S. 21), "The light won't go through the glass because there's not enough of it to go through" (S. 67).

e) This category includes answers in which students drew the ray as falling on the surface of the plate and being diffused in different directions in the air. About half the children gave no explanation, while the rest invoked reflection. For example: "The edge of the glass plate is not transparent and the light is reflected or only goes through the plate a little and makes it semi-transparent" (S. 182), "The light is reflected according to the law of reflection. It will split into two reflections" (S. 33).

4. Discussion

In this paper, we have tried to study 14-15-year-old students' mental representations of refraction. The results show, first of all, that there are difficulties in the construction of mental representations which may lead children's reasoning to the understanding of phenomena of refraction. This finding is compatible with the findings of international research [11-13] (Galili, Bendal & Goldberg, 1993; Chen, Chang & Guo, 2004; Keawkhong *et al*., 2008) and raises questions since in this study focused on the reasoning of children who have already been taught refraction, both qualitatively and according to Snell's law.

In the research presented here, two new questions were studied for the first time: the refraction of light passing from a dense to a thinner medium, and light falling vertically on the surface of the denser medium. In terms of these questions, we did not observe any noteworthy changes from the classical findings of research that examines exclusively the transition of light from a thinner to a denser medium, to which we have referred. As we saw, the difficulties encountered are consistent in all tasks and show that over half the students have absolutely no sense of refraction. Answers which are compatible with the scientific model are given by 5-9% of the students to the three tasks, a fact that confirms the difficulties of creating a systematic reasoning. Also of interest is the difficulty in formulating explanations and arguments for the choices they have made.

However, we should note that refraction, like reflection, is usually part of the teaching of Geometrical Optics, *i.e*., within a framework which does not allow the creation of explanations of these phenomena, since their interpretation is possible within the framework of Wave Optics. In many curricula, including the Greek one, refraction is taught as a process in which the propagation medium and the direction of the light change, while the explanation of the phenomenon is linked to the difference in the propagation speeds light has through different media. In other words, the students have to be able to simultaneously use two models, a task which is extremely difficult, even for university students, according to Colin and Viennot [18]. Moreover, in the case of the students in our sample, the Wave Optics model has not been approached yet in any way.

When we carefully study the answers of students in which difficulties or the absence of arguments is especially pronounced, it seems as if the most important problem we can identify is the choice to teach refraction outside the Wave Optics model. Wave Optics would offer the explanation of the phenomenon, allowing it to take on meaning in the students' mind. But since the students cannot understand the reason for the ray's convergence to or divergence from the vertical line on the incidence surface, we can easily assume that they choose answers without taking into account a rule, given that they are unable to think according to a causal relationship between factors.

The effort to compare the reasoning of students who have been taught refraction as a part of Wave Optics with that of students who have been taught Snell's law in Geometrical Optics will allow us to confirm whether our earlier hypothesis was justified. It is in this direction that our research is now moving.

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