PAPER

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Ptolemy's experiments on refraction in science class

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Abstract

In this paper, the inclusion of history and philosophy of science in science teaching is proposed with the goal of depicting pre-service primary teachers' perception of the role of historical experiments in learning science and the nature of science. In order to achieve this, a teaching–learning sequence was designed and conducted in the context of an Introductory Physics Laboratory Course following the integrated approach to teaching the nature of science. Ptolemy's experiments on refraction and the combination of his advanced and erroneous views contributed to pre-service primary teachers' conceptualization of the empirical and tentative nature of science and the relationship between mathematics and science. The majority of the pre-service primary teachers perceived the history of science as important in understanding scientific concepts and aspects of the nature of science.

Keywords: nature of science, integrated approach, Ptolemy's experiments

1. Introduction

The discourse that advocates the use of history of science (HoS) in science teaching has a long history, starting from Mach and Duhem more than a century ago [1, 2], and followed by the emblematic work of Heilbron [3], Holton and Brush [4] and Holton [5, 6] who introduced HoS in the physics textbooks and encouraged the integration of HoS into science teaching. The main arguments are related to (i) a deeper understanding of the subject matter, meaning that the HoS may reveal the important context of the considered fragments of knowledge; (ii) how learning in science education relates to the growth of scientific knowledge; and (iii) understanding of nature of science (NOS) in terms of methodological, philosophical and cultural aspects of science [7].

A review of literature in science education reveals at least three views of understanding NOS. The first one is the consensus view, which attempts to include only those domain-general NOS aspects that are the least controversial. This view, also known as 'general aspects' conceptualization of NOS, supports emphasis on seven key aspects or tenets deemed appropriate for school science that include (1) tentativeness of scientific knowledge, (2) observations and inferences, (3) subjectivity and objectivity in science, (4) creativity and rationality, (5) social and cultural embeddedness in science, (6) scientific theories and laws, and (7) scientific methods [8–10]. This conceptualization has been criticized as being insufficient and even as misrepresenting science. Critics suggest that a more complete picture of science should be communicated to teachers and students, rather than a list of general aspects to NOS. Here comes the second view, family resemblance approach (FRA) to NOS [11], which is based on the ideas of Wittgenstein, addressing the unity of science without sacrificing its diversity. According to FRA, science is viewed as a cognitive epistemic system [12] which encompasses processes of inquiry, aims and values while it is a social-institutional system which encompasses professional activities, scientific ethos and social certification. Therefore the FRA can accommodate for both the domain-general and the domain-specific features of science, e.g. many science domains rely on data collection and observation (domain-general), while experimentation is restricted to some domain, e.g. astronomy (domain-specific) [13].

According to Kampourakis [14], 'general aspects' conceptualization of NOS provides an effective starting point for teaching about NOS. The suggestions made by the critics of the 'general aspects' conceptualization of NOS are, nevertheless, useful in order to explore how teaching about NOS can move beyond general aspects to context-specific ones. NOS instruction must include elements from history and philosophy of science that are relevant to school science and comprehensible by students. Kampourakis [14] argued that the 'general aspects' and 'family resemblance' conceptualizations of NOS are complementary and continuous, proposing developmental pathways in teaching about NOS that might start from the former and end up to the latter conceptualization.

In a similar context, Niaz [15, 16] supports the integrated view; this view claims for an integration of domain-general and domain-specific aspects of NOS if we want students to understand 'science in the making'.

Various examples from HoS are provided to show how understanding 'science in the making' is important in order to facilitate students' conceiving of alternative interpretations of experimental data, the competition among rival theories and explanations.

2. History of optics in science teaching

Along with mechanics and astronomy, optics is one of the oldest areas of scientific exploration; it addresses the reality experienced directly through sense perception [17]. History of optics is a fruitful field of ideas regarding light and vision. A large amount of research papers has been published regarding the historical approach to teaching reflection, refraction and the nature of light and vision [17, 18]. History of optics has offered the context in which several theories and pre-theory ideas of light and vision have been developed. Such ideas include the conceptions of light in the Hellenic period as well as the theory of rays developed during the Hellenistic, medieval European and Muslim periods prior to the scientific revolution of the seventeenth century. What follows includes the ray theory of the 17th century, Newton's color rays, Huygens' pressure waves, particle-wave debate which led to the domination of Newton's conception of particles in the 18th century, the wave theory of the 19th century and photon optics of the 20th century.

Galili in his review [17] proposed teaching optics using HPS-based materials. According to him, the first who used HoS in science education addressed the elements of 'correct' knowledge (Type-A), meaning topics that are not in question. Mihas [18] developed a special optics curriculum units based on Type-A reconstructions. However, the history of optics contains more than Type-A knowledge. It also includes Type-B knowledge, knowledge which emerged and was later refuted, being replaced by more advanced accounts. This knowledge is often seen as irrelevant and undesirable in science classes, as 'incorrect' ideas may be a source of confusion for students, who, being immature, are unable to resolve discrepancies in the subject matter [17]. On the other hand, Type-B knowledge is usually relevant, if not identical, to students' ideas and misconceptions. This interpretation legitimizes addressing Type-B knowledge in teaching using the history of optics, since it facilitates conceptual change, leading eventually to scientific understanding.

In addition, HoS and especially Type-B knowledge has a beneficial impact on teaching NOS; students' coping with the historical conceptual difficulties creates an opportunity to learn about the nature of scientific knowledge. One of the central features of scientific knowledge is mathematics. History of optics provides episodes that highlight the complex and multi-faceted role of mathematics in knowledge production. Euclid, Archimedes and Ptolemy were the first to introduce mathematics in the description and explanation of optical phenomena.

Starting with Euclid, he introduced the geometrical concept of rays of light and vision, an idea that facilitated the description of optical phenomena. At the same time, he supported the erroneous idea of active vision, a much older idea, which coexisted with his successful geometrical schemes. Lindberg [19] gave us a brief and comprehensive overview of the first ideas on active vision and optics. The theory of active vision dealt with the idea that objects are seen by rays of light emanating from the eyes. This idea goes back to Pythagorean school and is continued through Empedocles ideas that visual perception involves the reception of effluences from the object in the eye. The theory of the two emanations, one from the eye and one from the visible object which meet and coalesce somewhere in the intervening space to produce visual sensation, reached its full development with Plato. After Felix Platter and Johannes Kepler, the role of the eye has been understood and we know that the vision of an object depends, among others, on the fuction of the eye, including the role of the retina and the optic nerve. The idea of active vision, though, still remains in the literature through some phrases as 'to throw an eye on something' and reminds us of the development of scientific ideas.

The theories of vision developed by atomists, Pythagoreans, Plato, Stoics and Galen are almost devoid of mathematics. The first exposition of a mathematical theory of vision is found in Euclid's *Optics*, who based geometrical theorems on seven postulates. Euclid's way of thinking with his innovative and simultaneously fault ideas on vision could be introduced in science class in order to highlight the development of scientific knowledge and the role of mathematics.

The history of the sine law offers another example of the relationship between mathematics and science. Ptolemy was the first to tackle the issue of a law of refraction [18, 20, 21]. His data did not fit the absolute proportionality between the angles of incidence and the angles of refraction of visual rays. Ptolemy tried to adjust his data to a quadratic dependence [22]. However, the sine law which truly describes the corresponding angles of incidence and refraction was not obtained by Ptolemy. Although Alhazen in his *Book of Optics* came closer to discovering the law of refraction, he did not take this step [23]. The Persian scientist Ibn Sahl in 984, in his manuscript *On Burning Mirrors and Lenses*, used the refraction law to derive lens shapes that focus light with no geometric aberrations [24]. The law was rediscovered by Thomas Harriot in 1602 [25], who however did not publish his results although he had corresponded with Kepler on this very subject.

According to Smith [21] Ptolemy's failure was due to the fact that he only used spatial (geometrical) considerations of the vision-light path, while the key to the true account of refraction, the explanation, was to treat the problem using temporal (kinetic, physical) considerations, as Descartes and others did much later. Thus, obtaining the correct mathematical account in Hellenistic physics was impeded by an inappropriate physical approach: geometry and numbers were not enough [17]. On a pedagogical level, Ptolemy's example provides a fruitful ground for considering the relationship between mathematics and science in a period that optics had a long way to run: the nature and propagation of light and the 'mechanism' of vision were some of the problems waiting to be solved.

3. Integrated view of understanding NOS—the case of Ptolemy's experiment on refraction

Integrated view of understanding NOS which was introduced and analyzed by Niaz [16], came to reconcile two traditions in teaching and learning NOS: the domain-general and domain-specific view on NOS. Niaz [16] suggested that students understand 'science in the making' through the integration of the two traditions and argued that the success of the integration depends upon students' interaction with and conceptualization of the heuristic principles which the domain-specific aspects are based on. Such an integration is proposed through a specific schema:

(a) Elaboration of a theoretical framework based on presuppositions, guiding assumptions, hard-core beliefs, and previous experience.
(b) Formulation of research questions.

(c) Operationalizing heuristic principles.
(d) Designing experiments.
(e) Understanding nature of science.

This schema serves as an outline of how the specific science content can be organized around domain-general and domain-specific aspects of science [16]. The case of Ptolemy's experiments on refraction is presented below. In order to teach the empirical and tentative nature of science and the relationship between science and mathematics, Ptolemy's experiments on refraction are proposed.

4. The purpose of the study

This research aimed to explore pre-service primary teachers' perceptions of the role of historical experiments in developing scientific explanations and more sophisticated conceptions of specific aspects of NOS. We propose that the historical experiments of Ptolemy on refraction be used in order for pre-service primary teachers to become familiar with the phenomenon of refraction and aspects of NOS such as the empirical and tentative features of science, and the relationship between science and mathematics.

5. Research methodology

5.1. General background

Fieldwork was carried out in Athens, in the Department of Primary Education at the National and Kapodistrian University of Athens during the winter semester of 2018–2019. This research is qualitative descriptive. The research aimed to examine how pre-service primary teachers perceive the role of history of science in developing scientific explanations and an understanding of aspects of NOS as well. Learners participated in a historically based laboratory teaching–learning sequence on optics and especially Ptolemy's experiments on refraction, following Niaz's schema, as described in the next section. The instruments used were participants' reflective diaries, their worksheets and an open-ended questionnaire which allowed for in-depth examination of their perceptions. All the participants responded to the same set of questions included in the questionnaire. Qualitative content analysis was applied for the analysis of the data.

5.2. Sample of research

The sample consisted of 55 second-year university pre-service primary teachers, 50 females and 5 males, who undertook an Introductory Physics Laboratory Course (IPLC). The IPLC is comprised of five rotating self-standing 2 h laboratory exercises once a week: (1) taking measurements, (2) mechanics, (3) optics, (4) static electricity, and (5) heating. Pre-service teachers were divided into three teams of 18, 18 and 19 persons whose members worked in pairs and attended the IPLC. Convenience sampling—a non-probability sampling technique—was used to create sample as per ease of access and proximity to the researchers [26].

Regarding their scientific training and science knowledge, most of the pre-service primary teachers enrolled in the department had chosen the Humanities orientation during their final two years of upper secondary school. According to the Greek curriculum, during the last 2 years of secondary school, students may choose their orientation (e.g. Science, Technology, Humanities). Science classes are mandatory at every grade in secondary school, except final year for those who choose the Humanities orientation. As for the academic background of the pre-service teachers, they attended an Introductory Physics Course (IPC) during the same semester as the IPLC. However, when they participated in the Optics laboratory exercise, they had not yet been taught the corresponding theory through the IPC. Their answers were therefore taken to be independent of the IPC and to derive from either the laboratory exercises or previously acquired knowledge.

5.3. Teaching–learning sequence and educational material

A historically based teaching and learning sequence was developed according to Niaz's [16] schema for integrated approach to NOS.

(a) Elaboration of theoretical framework: Ptolemy followed Euclid's Optics and Catoptrics which were mainly based on geometrical

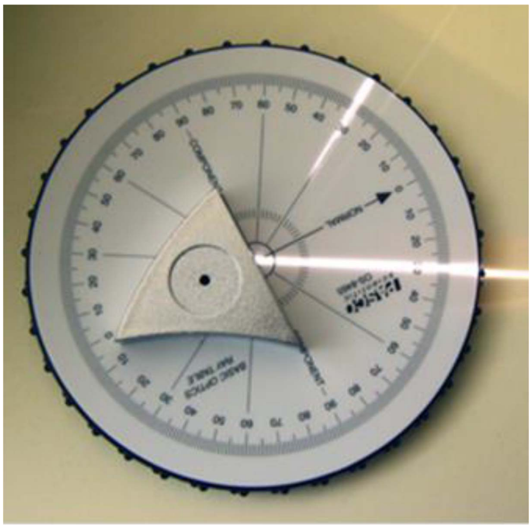

Figure 1. Experiment of catoptric reflection.

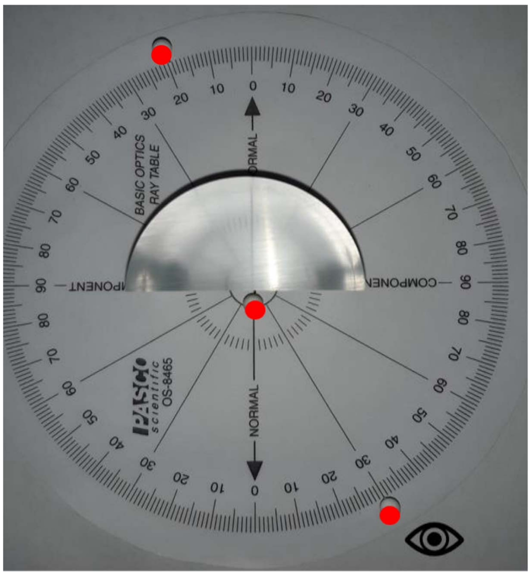

Figure 2. Ptolemy's experiment on refraction for angle of incidence 30°.

schemes; regarding the law of catoptric reflection, the angle of the reflected ray is equal to the angle of the incident ray.

Pre-service primary teachers verified the law by conducting a laboratory experiment and were introduced to Euclid's geometrical approach to optics (figure 1).

(b) Formulation of research questions: However, Ptolemy went beyond Euclid in that he was also trying to determine the necessary conditions for accurate perception of an object's true location. In other words, what is the relationship between angles of incidence and angles of refraction? At this point, one can see the astronomer's concerns coming to the fore [27].

Pre-service primary teachers came to face the same question in the laboratory and conducted their research in order to answer it.

(c) Operationalizing heuristic principles: Smith [21] has pointed out that Ptolemy expected to find a linear relationship between the angle of incidence and the angle of refraction. This apparently reasonable expectation led him to error regarding the law of refraction. Moreover, Ptolemy maintained the conceptual framework of his predecessor, Euclid, regarding the visual rays.

(d) Designing experiments: Ptolemy carried out experiments to investigate the refraction of light while passing from air to glass, from glass to water and vice versa. He added a semicircle of glass to the bottom half of one disk and sighted through the glass. He then proceeded to find the angle of refraction for the glass/air and the glass/water boundary as he did for the water/air boundary. He also discussed refraction at the air/ether boundary and its problems for astronomy but dismissed the possibility of determining the values [27].

Pre-service primary teachers conducted experiments on refraction in two phases. First, they followed Ptolemy's method, and measured the angle of refraction for the air/glass boundary (figure 2). Then, they conducted an experiment on refraction for the air/glass boundary using a light source (figure 3). Due to the principle of reversibility of light, the two experimental approaches, the one based on ray of vision (figure 2) and the

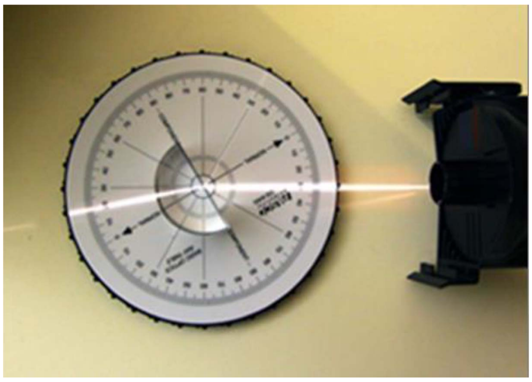

Figure 3. Experiment of refraction using a light source.

other based on ray of light (figure 3), are expected to give the same results. That means that the mathematical model of light, what we call geometrical optics, entails no contradiction.

(e) Understanding nature of science: Pre-service primary teachers were asked to compare the data that they had gathered in the first phase with the corresponding Ptolemy's table and found that they were similar. They were also asked to put the data on a rectangular angle system and make a hypothesis about the relationship between the angle of refraction and angle of incidence. In this way, participants were explicitly involved in the procedures of Ptolemy's experiment that had to do not only with the empirical and tentative nature of science but also with Ptolemy's heuristic principles, such as the 'proportionality' of angle of incidence and angle of refraction. More than that, participants were urged to observe that Ptolemy's experiment was based on his idea of active vision, allowing them to place directly their eye at one point of the disc in order to 'see', when the method with the light source is in some way more indirect and needs to shift the place of the observer. They were also asked to confirm Snell's law, after they had taken data using a light source. This was followed by a discussion on the role of mathematics to the 'science in the making'.

The teaching–learning sequence, which included Niaz's schema for teaching NOS through history of optics is described in detail in the worksheet in appendix A.

5.4. Instruments

Regarding the research data, all participants completed a worksheet (appendix A) and a reflective diary (appendix B) during their laboratory exercise. Moreover, an open-ended questionnaire was completed by them at home (appendix C). The instruments included open-ended questions in order to examine participants' perceptions of the role of history of science in learning scientific concepts and processes and certain aspects of NOS to be depicted.

The worksheets were designed according to Niaz's schema and included the phases that have already been mentioned in the above section. They included open-ended questions and experimental activities and were not analyzed in terms of drawing conclusions, as participants' answers were usually influenced by the instructor/researcher (the first author) who had a guiding and facilitating role during the teaching-learning process (appendix A).

Pre-service primary teachers' reflective diaries were also collected at the end of the laboratory exercise, in which they kept notes on three questions. The first question asked the participants to identify the aspects of the teaching–learning procedure that they found to be the most interesting, while the second one asked for key elements of the whole procedure that facilitated their understanding of the phenomenon of refraction. The third question asked about which part of the process helped the participants understand the relation between mathematics and physics (appendix B). This data enabled the researchers to ascertain whether participants found historically based material to be both interesting and facilitating in understanding the science content and NOS.

Regarding the questionnaire, it consisted of six open-ended questions asking for participants' opinion on the value of teaching optics through history of science, on the activity they perceived to be the most helpful in conceiving refraction, on the role that Ptolemy's theory of active vision played in designing his experimental apparatus and the benefits of it, on the relationship between mathematics and physics and particularly on Ptolemy's attempt to express a mathematic law, and on the value of having a mathematical formulated law (appendix C).

The 55 questionnaires coupled with the corresponding participants' answers in their reflective diary (response rate 100%) were used for data analysis. In order to avoid bias that might result from the presence of the instructor-researcher who had a guiding role in the teaching–learning procedure, worksheet answers were included in the analysis only as a secondary data source, in order to support the information coming from the other two data sources.

5.5. Data analysis

In the present study, qualitative content analysis method was used to analyze the data. The texts for analysis were given to a second coder along with the analytical rules, such as units, coding agenda, category definition and level of abstraction for inductive formation [28]. The points of disagreement with the second coder were recorded by a third coder. Quantitative steps of analysis, i.e. percentages, the so-called descriptive statistics, helped quantify the findings and provide a clearer picture of participants' perceptions of the role of the historical experiments in understanding science content and NOS aspects [29]. The trustworthiness of this research study was checked by implementing accordant quality criteria: credibility, confirmability, dependability, and transferability. Credibility was established through triangulation of the data collection instruments; the questionnaires, the reflective diaries and the worksheets which were used supplementary as a secondary data source. Peer debriefing was also used to increase the credibility of the data analysis. The approaches that researchers used to increase confirmability were documentation and control of bias, while coding agreement was another strategy used to enhance dependability. Moreover, the criterion of descriptive adequacy, one aspect of transferability, was applied. A thorough description of the context in which the IPLC was undertaken was provided, so that readers can determine the extent to which the findings of the case being examined can be applicable to alternative settings [30].

6. Limitations

Data for this research were collected from a particular Department of Primary Education (that of the National and Kapodistrian Univesity of Athens). The inherent bias in convenience sampling [31], due to under-representation of particular subgroups in the sample, does not allow trustworthy inferences to be made about the intended population.

7. Results

The first findings revealed that most pre-service primary teachers deemed Ptolemy's historical experiment of refraction very helpful in understanding both the phenomenon of refraction, as well as some aspects of NOS, such as the empirical and tentative character of science and the relationship between mathematics and science (table 1). Participants realized that even if Ptolemy could not formulate a scientifically accepted mathematical formula, he developed an experiment holding great historical value. They were able to grasp the idea that although Ptolemy adopted the erroneous idea of active vision, his account on refraction and the corresponding experiment is of great historical, cultural and scientific value. They had the opportunity to recognize Euclidean-Ptolemaic heuristics on Optics that influenced Ptolemy's way of thinking. Learners came to realize that Ptolemy was not merely collecting and assessing bare facts with an open mind. He may have expected that the angle of incidence and the angle of refraction would be constantly proportional. Gradually students became familiar with the idea that obtaining the correct mathematical law in Hellenistic years was impeded by an inappropriate physical approach, in the sense that geometry and numbers were not 'enough'. All of them recognized that 'we' had to wait for some centuries after Ptolemy's era for the formulation of a precise law for refraction, the so-called Snell's law.

Regarding the first question of the questionnaire 'Did you find the historical perspective of the lesson useful in understanding reflection and refraction? If yes, in what ways?' the majority of the participants (84%) answered that the historical perspective was very helpful in understanding how the scientific ideas changed over time and

Table 1. Pre-service teachers answers in the questionnaire.

1st Question: Did you find the historical perspective of the lesson useful in understanding reflection and refraction? If yes, in what ways?		
Answers	Frequency	Percentage (%)
The historical perspective was very helpful in understanding how the scientific ideas were developed.	46	84
The historical perspective was helpful (no elaboration)	9	16
2nd Question: Which particular activity facilitated you the most in understanding refraction?		
Answers	Frequency	Percentage (%)
Ptolemy's historical experiment on refraction (the one with the pins)	50	91
Angle of refraction measurement using a light source	5	9
3rd Question: Do you think that Ptolemy's active vision played a role in designing the experiment?		
Answers	Frequency	Percentage (%)
Ptolemy's theory of active vision influenced positively the construction of the particular experiment.	34	62
Ptolemy's theory of active vision is not recognized as important.	21	38
4th Question: In your opinion, what are the specific benefits, resulting from this experimental procedure?		
Answers	Frequency	Percentage (%)
The specific experiment offered simplicity and a unique observation of the phenomenon.	44	80
The experimental procedure is helpful (no elaboration)	11	20
5th Question: What is the value of having a mathematical formulation of law?		
Answers	Frequency	Percentage (%)
The mathematical relation is also predictive, in that if we know the refractive index of the material, we can calculate the refraction angle for any incidence angle without performing the experiment.	34	62
No answer regarding the value of law. Only description of Snell's law	12	22
Mathematical law is very important (no elaboration)	9	16
6th Question: Suppose you want to find the angle of refraction that corresponds to an angle of incidence of 37° in an air to glass interface. Which approach would you follow? Ptolemy's experiment or Snell's law of refraction?		
Answers	Frequency	Percentage (%)
Snell's law because it leads to fast and accurate results	44	80
Snell's law is preferable only for a given refractive index. Otherwise Ptolemy's experiment is better	11	20
Total	55	100%

were developed. Particularly, a participant (P26) answered: 'Ptolemy followed Euclid's steps. He went on to investigate the refraction of light for the sake of being an astronomer. He was trying to explain and calculate the actual position of the stars. It was Snell that managed to formulate the law that Ptolemy failed to. I am wondering, how else would we have entered the real world of science if we had not previously opened the door to history?'. Moreover, participants focused on Ptolemy's difficulties with refraction and stated that they faced the same difficulties. This was 'a relief' for them making their difficulties seem more manageable and expected. A minority of pre-service teachers (16%) answered positively that the historical perspective was helpful in understanding reflection and refraction, but they gave no further explanations.

Regarding the second question 'Which particular activity facilitated you the most in understanding refraction?' most pre-service teachers (91%) found very helpful Ptolemy's historical experiment for refraction (figure 2), the one with the pins, recognizing that this particular experimental set facilitates the observation of refraction even in room light. The position of the three pins play an important role as no additional light is needed in order for the refracted light to be observed. They found extremely interesting the fact that the pins seemed collinear when viewed through the interface and non-collinear when viewed from above. In her own words, a participant (P37) said: 'Ptolemy was a genius because he found the way to observe the change of direction of light using three pins. This idea is great, especially when it comes from an astronomer who is looking for the true position of the stars'. Some pre-service teachers (9%) found that the most helpful activity for understanding refraction was to measure the refraction angle using the light source, due to its accuracy and convenience.

Regarding the third question 'Do you think that Ptolemy's idea of active vision played a role in designing the experiment?' most of the pre-service teachers (62%) had the opinion that Ptolemy's theory of active vision influenced positively the construction of the particular experiment, for as much as Ptolemy thought that the ray is emitted by the humaneye, enters the glass, and then it is refracted. In a participant's (P7) words: 'Ptolemy's experiment is based on a abandoned theory, but it is appropriate for understanding refraction. If the pins are viewed through the air/glass boundary they seem to be collinear. If they are viewed top-down they are not. I understood what is going on'. In other participant's words (P18): 'Ptolemy's theory of active vision helped the development of his experimental set for investigating refraction. It would not be the one without the other'. Some participants (38%) did not recognize Ptolemy's theory of active vision as important. They just mentioned that this particular theory has been abandoned explaining that the light is emitted by the bodies and not by the eyes.

Regarding the fourth question 'In your opinion, what are the specific benefits resulting from this experimental procedure?' most participants (80%) answered that the specific experiment offered simplicity in that someone can see with his/her own eyes that the pins appear to be collinear when viewed through a glass to air interface and non-collinear if they are seen top-down. Pre-service teachers supported the view that it is not possible to observe refraction in the same way when conducting the experiment with a light source. Particularly, the participant P13 said: 'Through this experimental procedure we deeply understand the refraction phenomenon. The experimental procedure is very simple and offers opportunities for deeper understanding. The fact that we are trying to explain how the pins seem to be collinear if seen through the interface and they are not if they are seen top-down, help us understand the relation between angle of incidence and angle of refraction'. Most of the pre-service primary teachers expressed an extra benefit of this experimental set that had to do with the fact that only simple everyday materials and not technologically advanced equipment supplies were used. Some participants (20%) simply reiterated that Ptolemy's experiment helped them, but without explaining the reasons.

Regarding the fifth question 'What is the value of having a mathematical formulation of law?' most pre-service teachers (62%) responded that the mathematical relation is predictive in that for a given refractive index, the refraction angle for any incidence angle can be calculated. Some participants suggested that a powerful advantage of the mathematical law is the calculation of the speed of light in glass or any other material, with a given refractive index. Some participants (16%) admitted that the law is valuable without explicitly explaining why. Finally, some participants (22%) just described Snell's law without arguing for its importance.

Regarding the sixth question 'Suppose you want to find the angle of refraction that corresponds to an angle of incidence of 37° in an air to glass interface. Which approach would you follow? Ptolemy's experiment or Snell's law of refraction?' Most participants (80%) answered that they would choose Snell's law that leads them to fast and accurate results, since with Ptolemy's tables they could only approximately find that angle. Few participants (20%) answered that they would use Snell's law only in case they knew the refraction index, otherwise they would do the Ptolemy's experiment.

Regarding the reflective diaries (table 2), a lot of participants (44%) thought that the most interesting phase of the teaching—learning sequence was the implementation of Ptolemy's experiment on refraction. The reason for that was not limited

Table 2. Pre-service teachers' answers in the reflective diaries.

1st Question: What did you find most interesting about the teaching—learning process?		
Answers	Frequency	Percentage (%)
The implementation of Ptolemy's experiment for refraction.	24	44
The fact that Ptolemy was studying and trying to quantify the phenomenon of refraction based on the abandoned theory of active vision.	18	33
The fact that they made the graphs of Ptolemy and their own measurements on the same coordinate system.	11	20
Measuring the refraction angle with the angular disc and the light source.	2	3
2nd Question: What facilitated you the most in understanding the phenomenon of refraction?		
Answers	Frequency	Percentage (%)
Using Ptolemy's experimental set (without any light source) followed by the corresponding experiment using light source confirming Snell's law.	44	80
Ptolemy's experiment (no elaboration)	11	20
3rd Question: What facilitated you the most in understanding the relation between mathematics and physics?		
Answers	Frequency	Percentage (%)
The activity of developing a mathematical relation between the angles of incidence and the angles of refraction, like Ptolemy did.	45	82
There is a strong relationship between physics and mathematics (tautology)	10	18
Total	55	100%

to the fact that the experiment was very helpful in understanding refraction. More than that, they liked Ptolemy's idea 'per se', and they found very interesting the fact that Ptolemy's research was triggered by the fact that he was an astronomer aiming to find the real position of stars. Participants appreciated the fact that Ptolemy found the way to do the research 'here on earth'. Finally, some of them argued that it requires only simple materials and supplies, which make it much more interesting.

In addition, a significant number of pre-service teachers (33%) was interested in the fact that Ptolemy was studying and trying to quantify the phenomenon of refraction based on the erroneous theory of active vision. That is, the scientist's ingenuity also contained elements that are no longer scientifically acceptable today. Specifically, a participant said (P23): 'Ptolemy argued that light is emitted from the eyes, which is wrong. But it is striking to see how through this error he made such a profound analysis of the phenomenon of refraction'.

For some participants (20%), the most interesting phase of teaching was making the graphs of angles of incidence and refraction on the same coordinate system, based both on Ptolemy's and their data. They found it extremely interesting to compare the accuracy of their measurements with that of Ptolemy, as well as to try to figure out what the form of the graph was like. Some of the pre-service teachers were really impressed by the fact that although at first, they considered the angle of incidence and the angle of refraction as proportional, they had an impression that something was going wrong with this thought. When they realized that the proportionality was between the sine values of the angles and not the measures of the angles, their concern was confirmed.

Few participants (3%) found measuring the refraction angle with the angular disc and the light source (figure 3) to be the most interesting phase of the teaching sequence. These participants argued that it was interesting because refraction is clearly revealed using the light source.

Regarding the second question of the reflective diaries 'What facilitated you the most in understanding the phenomenon of refraction?' most pre-service teachers (80%) argued that the experiment that helped them the most in understanding the phenomenon of refraction was Ptolemy's experimental set (figure 2), followed by the corresponding experiment using light source (figure 3) confirming Snell's law. Participants highlighted that although Ptolemy's experiment was based on the erroneous theory of active vision, it helped them empirically understanding the phenomenon of refraction.

Some pre-service teachers (20%) argued that the experiment that helped them the most in understanding refraction was Ptolemy's experiment without however explaining their view.

The last question of the reflective diary was the following: 'What facilitated you the most in understanding the relation between mathematics and physics?'. Most pre-service teachers (82%) supported that the activity that helped them the most was the one where they, like Ptolemy, attempted to develop a mathematical relation between the angles of incidence and the angles of refraction and eventually failed. The participants claimed that this activity was thought-provoking and prepared the ground for introducing Snell's law. In other words, through this teaching sequence, they understood both the phenomenon of refraction and the relation between physics and mathematics.

Some participants (18%) answered, using a tautology, that there is a strong relationship between physics and mathematics without further elaborating on that.

Findings from the analysis of the questionnaires are in line with the findings from the reflective diaries. Participants made explicit references to the teaching sequence and to particular activities during the laboratory lesson. Such a fact gives evidence for increased credibility through triangulation of data collection and results.

8. Discussion

Data analysis showed that pre-service teachers perceive historical experiments as being helpful in understanding science content and NOS as well. These findings are more meaningful if we consider the fact that participants were fully engaged in a historically based teaching and learning sequence. Their answers were given in the historical context of Ptolemy's work on refraction. They had the opportunity to investigate Ptolemy's measurements for angles of refraction and develop their own hypothesis about the relationship between angles of refraction and incidence. They also had the opportunity to think about Ptolemy's theory of active vision and the role it played in the development of his experimental set for refraction. In other words, in this study pre-service teachers had the opportunity to explain in detail the reasons for supporting or not history of science in science teaching.

This study is in line with previous study [32] which indicates that teachers—including student teachers, elementary teachers, middle school teachers, and high school teachers, believe that teaching history of science is an important part of their science instructional program. The additional value of the present study is that the participants were students themselves and participated in a historically based laboratory instruction. Their experience helped them express their perceptions of the role of history of science in learning science content and NOS as well.

Psillos' paper [32] 'Is the history of science the wasteland of false theories?' can shed light on the role of Ptolemy's abandoned theory of active vision. The results revealed that pre-service teachers found the theory of active vision both interesting and helpful in understanding refraction. More than that, most of them found theory of active vision interesting in developing the idea of how scientific ideas develop. On the other hand, theory of active vision can be currently found in history of science books and not in textbooks, even though it was the dominant theory for quite some time and enjoyed explanatory and predictive success. Participants received active vision theory with appreciation and cultivated what Psillos [32] calls 'scientific conscience': critical appraisal of one's own theory; sensitivity to the strengths and limitations of scientific inquiry; openness to criticism and correction; responsiveness to epistemic values and theoretical virtues; sensitivity to the historical complexity and the philosophical implications of the scientific enterprise.

However, this belief is not necessarily congruent with instructional practices related to the teaching of the history of science. Most teachers in Wang's study believe that history of science is important, however, they often have limited instructional materials [33], and inappropriate training. By integrating history of science with daily science instruction, teachers will facilitate their students to develop a culturally and socially relevant view of science, and ultimately produce more scientifically and culturally literate citizens.

9. Conclusions

This study aimed at investigating the pre-service primary teachers' perceptions related to the role of historical experiments in developing scientific explanations and NOS as well. For that purpose, an integrated approach to teaching NOS was implemented based on History of Optics and particularly Ptolemy's experiments on refraction. The first findings revealed that pre-service teachers perceived history of science as being important in developing scientific explanations and in providing a better understanding of the empirical and tentative aspects of the NOS as well as the relationship between mathematics and physics. Participants characteristically said that historical experiments, such as Ptolemy's, can shed light on human's way of thinking and on the ways in which scientific concepts can be developed through accepted and abandoned theories alike. Moreover, participants, after their experimentation with Ptolemy's data, considered History of Science as very important in revealing the relationship between physics and mathematics.

The findings of this study reveal a practical application worthy of future study and practice, since it is about the implementation of an integrated approach to NOS [16] in pre-service teachers education and pre-service teachers' perceptions of the role of the historical experiments in their learning NOS. What pre-service teachers found to be interesting and helpful was not a result of their personal background knowledge but a result of their experience in the lab. Pre-service teachers are future primary teachers who may or may not use history of science in their own classes depending also on their own experience. The present study provides evidence that suggests that pre-service teachers who are offered historical based laboratory experiences perceive history of science as helpful and motivating in teaching and learning science.

Consequently, what this study suggests for future consideration is increasing the historically based physics laboratory exercises using Niaz's schema for an integrated approach to teaching NOS [16], in order for the pre-service teachers to ascertain that history of science is not only helpful but necessary in teaching science content and NOS as well.

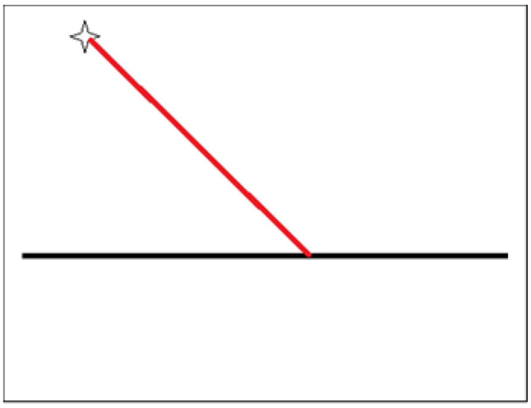

Figure A1. Schematic optical representation.

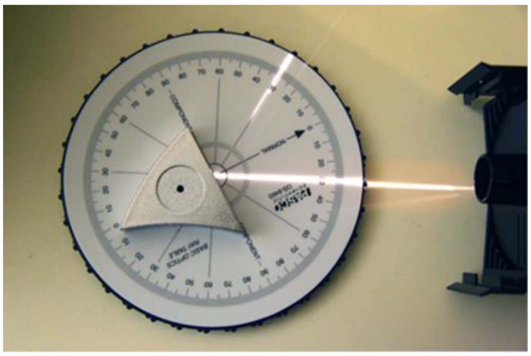

Figure A2. Experimental set of reflection.

Appendix A: Worksheet (completed in class)

A. Reflection

Phase of hypotheses/ elaboration of a theoretical framework based on presuppositions

1. Can you make a hypothesis regarding the beam path in figure A1? Draw and describe the path.

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2. Identify the incidence ray, the normal and the reflected ray and the corresponding angles.

3. Place the mirror surface at the location shown in figure A2. Put the light source in such a position that rays fall on the mirror. Observe the ray of incidence and the ray of reflection.

Table A1. Reflection measurements.

Angle of incidence	Angle of reflection
30°	
45°	
50°	
60°	

4. Complete the table.

5. Compare the angles of incidence and the corresponding angles of refraction. What do you observe?

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The first explicit formulation of the law of reflection, stating the equality of the angles of incidence and reflection of sight or visual rays is to be found in Euclid's Optics.

6. Do your measurements verify the law of reflection? If not, why do you think that happens?

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B. Refraction

Formulation of research questions

Do you think that the boy in figure A3 sees the light source in the right position? Can you think of a possible explanation for why this is happening? Can you describe similar phenomena?

The first who not only observed refraction phenomena but also conducted related experiments was the astronomer Claudius Ptolemy (108–170 AD). Ptolemy dealt with refraction and claimed in his Astronomy that the position of a star is apparent due to the refraction of light by the atmosphere. He experimented with the relation between the angles of incidence and the angles of refraction by examining the refraction of rays 'coming out of the eye'! Ptolemy's experiments are among the first experiments in the history of the natural sciences!

Ptolemy's experimental set is similar to the one in figure A4. Ptolemy 'seeing' through the air–water separating surface, placed a sign in the water so that the three points would look collinear as he looked through the air–glass surface.

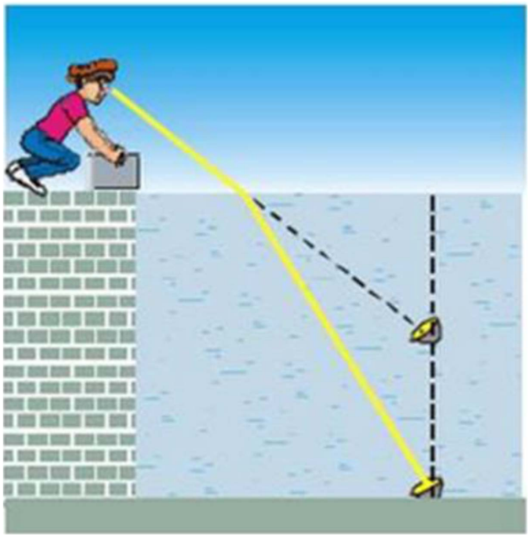

Figure A3. Apparent depth.

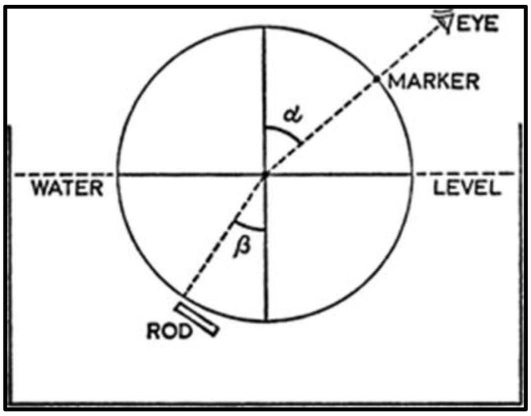

Figure A4. Ptolemy's experimental set.

Let us follow Ptolemy's steps…

Designing experiments

7. On your laboratory bench, you can find a semicircular glass block, fastened in the angular disc, in order to measure angles easily. Have two pins placed at two points (A and B), so that an angle of 10° be formed. Place another pin at C point, so that points A, B and C be collinear, if they are seen through the air/glass boundary.

8. Measure the angle that BC forms to the perpendicular line: ………………………

Table A2. Measurements according to Ptolemy's experiment.

Angle between AB and the perpendicular	Angle between BC and the perpendicular
0°	
10°	
20°	
30°	
40°	
50°	
60°	
70°	
80°	

Table A3. Ptolemy's measurements on refraction.

Angle between AB and the perpendicular	Ptolemy's angle between BC and the perpendicular
0°	0°
10°	7°
20°	13° 30'
30°	19° 30'
40°	25°
50°	30°
60°	34° 30'
70°	38° 30'
80°	42°

9. Repeat the procedure for the measurement of the following angles in the table below (table A2).

In table A3, you can see what Ptolemy's measurements for the corresponding angles in a glass air refraction are.

Operationalizing heuristic principles

10. Compare your results with Ptolemy's measurements and write down your observations.

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11. On the same axis system, make the two graphs, using Ptolemy's data and your own data.

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12. Compare the two graphs and write down your observations. What is the type of the graph (linear, parabola, trigonometric, etc)?

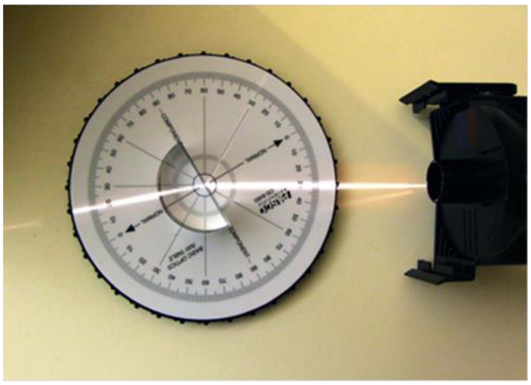

Figure A5. Experimental set for refraction.

Table A4. Refraction measurements using the laser source.

Angle of incidence	Angle of refraction
$\theta_1 = 30°$	
$\theta_2 = 40°$	
$\theta_3 = 50°$	
$\theta_4 = 60°$	

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Understanding NOS

13. Ptolemy failed to mathematically calculate the angle of refraction. His measurements did not end to a mathematical equation (law). Such a mathematical description was Snellious and Descartes' achievement 1500 years later and is known as Snell's law of refraction. Place the semicircular glass block in the position specially designed for it. Put the light source in such a position so that the light fall exactly in the center of the semicircular glass with an angle of incidence of 30°, and the incident and reflected ray appear on the disc, as shown in figure A5.

Several tests may be required to achieve the desired result. Before proceeding, ask the supervisor to check the experimental set. Then measure the angle of refraction θ using the angular disc. Repeat the procedure and complete table A4.

Table A5. Calculating the fraction.

Fraction
$\sin(\theta_{in})_1/\sin(\theta_{ref})_1$
$\sin(\theta_{in})_2/\sin(\theta_{ref})_2$
$\sin(\theta_{in})_3/\sin(\theta_{ref})_3$
$\sin(\theta_{in})_4/\sin(\theta_{ref})_4$

14. Using the provided trigonometric table, find the sine of angle of incidence and the angle of refraction. For every pair of angles, calculate the fraction, and complete table A5. What do you observe?

15. Calculate the average of the above values $\sin(\theta\text{in})/\sin(\theta\text{ref}) = \ldots\ldots$

16. The ratio you calculated above is characteristic of any material and is called refractive index. The ratio you calculated in the previous step is equal to the refractive index n of the glass. The literature reports that the refractive index of ordinary glasses ranges between 1.52 and 1.62, while in some special glasses it can take values above 1.70. According to the value of the refractive index you calculated for that piece of glass, what kind of glass do you think it is? An ordinary or a special one?

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17. Can you calculate the angle of refraction, if the angle of incidence is 50°? Could you do that using Ptolemy's measurements?

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18. Given that light propagates in vacuum with 3×10^8 m s^{-1}, calculate the velocity of light in the glass, using the refractive index you found in activity 15.

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19. We have another material with $n' = 1{,}2$. Does the light propagate slower, faster or the same? What is the significance of refractive index?

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Appendix B: Reflective diary (completed in class)

1. What did you find most interesting during the teaching–learning process?

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2. What did you find most helpful in understanding the phenomenon of refraction?

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3. What did you find more helpful in understanding the relation between mathematics and physics?

Appendix C: Questionnaire (completed at home)

1. During the laboratory meeting, you worked on reflection and refraction; Euclid's law of reflection, Ptolemy's experiments on refraction and Snell's law of refraction. Did you find the historical perspective of the lesson useful in understanding reflection and refraction?

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2. What is the activity you find most helpful in understanding refraction?

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3. Although Ptolemy's theory of active vision is abandoned, during the laboratory meeting you were asked to conduct experiments on refraction following Ptolemy's method using the pins. Do you think that Ptolemy's active vision played a role in designing the experiment?

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4. In your opinion, what are the specific benefits, resulting from this experimental procedure?

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5. Ptolemy failed in formulating a law for refraction. Some centuries later, Snell formulated a mathematical relation (a law) relating the sinus

of angle of incidence to sinus of angle of refraction. What is the value of having a mathematical formulation of a law?

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6. Suppose you want to find the angle of refraction that corresponds to an angle of incidence of 37° in a glass/air boundary. Which approach would you follow? Ptolemy's experiment or Snell's law of refraction? Please, justify your answer.

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References

[1] Mach E 1893/1960 *The Science of Mechanics; A Critical and Historical Account of Its Development* (Chicago, IL: Open Court Publishing Company)

[2] Duhem P 1906/1954 *The Aim and Structure of Physical Theory* (Princeton, NJ: Princeton University Press)

[3] Heilbron L J 1987 Applied history of science *ISIS* **78** 552–63

[4] Holton G and Brush S G 1973 *Introduction to Concepts and Theories in Physical Science* (Cambridge, MA: Addison-Wesley Publishing Co.)

[5] Holton G 2003 What historians of science and science educators can do for one another *Sci. Educ.* **12** 603–16

[6] Holton G 2003 The project physics course, then and now *Sci. Educ.* **12** 779–86

[7] Mathews M 2015 *Science Teaching: the Contribution of History and Philosophy of Science, 20th Anniversary Revised and Expanded Edition* 2nd edn (New York: Routledge)

[8] Lederman N, Abd-El-Khalick F, Bell R and Schwartz R 2002 Views of nature of science questionnaire: toward valid and meaningful assessment of learners' conceptions of nature of science *J. Res. Sci. Teach.* **39** 497–521

[9] Abd-El-Khalick F 2012 Examining the sources for our understandings about science: enduring conflations and critical issues in research on nature of science in science education *Int. J. Sci. Educ.* **34** 353–74

[10] Osborne J, Collins S, Ratcliffe M, Millar R and Duschl R 2003 What 'ideas-about-science' should be taught in school science? A delphi study of the expert community *J. Res. Sci. Teach.* **40** 692–720

[11] Erduran S and Dagher Z 2014 *Reconceptualizing the Nature of Science for Science Education: scientific Knowledge, Practices and Other Family Categories* (Dordrecht: Springer)

[12] Irzik G and Nola R 2011 A family resemblance approach to the nature of science for science education *Sci. Educ.* **20** 591–607

[13] Kaya E and Erduran S 2016 From FRA to RFN, or how the family resemblance approach can be transformed for science curriculum analysis on nature of science *Sci. Educ.* **25** 1115–33

[14] Kampourakis K 2016 The 'general aspects' conceptualization as a pragmatic and effective means to introducing students to nature of science *J. Res. Sci. Teach.* **53** 667–82

[15] Niaz M 2001 Understanding nature of science as progressive transitions in heuristic principles *Sci. Educ.* **8** 684–90

[16] Niaz M 2016 Nature of science in science education: an integrated view *Chemistry Education and Contributions from History and Philosophy of Science* (Cham: Springer)

[17] Galili I 2014 Teaching optics: ahistorico-philosophical perspective *International Handbook of Research in History, Philosophy and Science Teaching*, ed M R Matthews (Dordrecht: Springer) pp 97–128

[18] Mihas P 2008 Developing ideas of refraction, lenses and rainbow through the use of historical resources *Sci. Educ.* **17** 751–77

[19] Lindberg D 1976 *Theories of Vision, From Al-Kindi to Kepler* (Chicago: University of Chicago Press)

[20] Ptolemy C 1940/1966 Refraction *A Source Book in Greek Science* ed M R Cohen and I E Drankin (New York: McGraw-Hill) pp 271–81

[21] Smith A M 1982 Ptolemy's search for a law of refractions: a case-study in the classical methodology of 'saving the appearance' and its limitations *Arch. Hist. Exact Sci.* **26** 221–40

[22] Russo L 2004 *The Forgotten Revolution: How Science Was Born in 300 BC and Why It Had to Be Reborn* (New York: Springer)

[23] Sabra A I 1981 *Theories of Light from Descartes to Newton* (Cambridge: Cambridge University Press)

[24] Rashed R 1990 A pioneer in anaclastics: ibn Sahl on burning mirrors and lenses *ISIS* **81** 464–91
[25] Kwan A, Dudley J and Lantz E 2002 Who really discovered Snell's law? *Phys. World* **15** 64
[26] Dörnyei Z 2007 *Research Methods in Applied Linguistics* (New York: Oxford University Press)
[27] Riley M 1995 Ptolemy's use of his predecessors' data *Trans. Am. Philol. Assoc.* **125** 221–30
[28] Mayring P 2014 *Qualitative Content Analysis. Theoretical Foundation, Basic Procedures and Software Solution* (Klagenfurt: Beltz)
[29] Gay L, Mills G and Airasian P 2012 *Education Research, Competencies for Analysis and Analysis* (Hoboken, NJ: Pearson)
[30] Lincoln Y S and Guba E G 1985 *Naturalistic Inquiry* (Beverly Hills, CA: Sage)
[31] Hedt L B and Pagano M 2011 Health indicators: eliminating bias from convenience sampling estimators *Stat. Med.* **30** 560–8
[32] Psillos S 2010 Is the history of science the wasteland of false theories? *Adapting Historical Knowledge Production to the Classroom* ed P Kokkotas, K Malamitsa and A Rizaki (Netherlands: Sense Publishers) pp 17–36
[33] Wang H A and Cox-Petersen A M 2002 A comparison of elementary, secondary and student teachers' perceptions and practices related to history of science instruction *Sci. Educ.* **11** 69–81

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