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History of Science and Conceptual Change: The Formation of Shadows by Extended Light Sources

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Abstract This study investigates the effectiveness of a teaching conflict procedure whose purpose was the transformation of the representations of 12–16-year-old pupils in Greece concerning light emission and shadow formation by extended light sources. The changes observed during the children's effort to destabilize and reorganise their representations towards a model that was compatible with the respective scientific model were studied using three groups of pupils belonging to different age groups. The methodological plan implemented was based on input from the History of Science, while the parameters of the geometrical optics model were derived from Kepler's relevant historic experiment. The effectiveness of the teaching procedure was evaluated 2 weeks after the intervention. The results showed that the majority of the subjects accepted the model of geometrical optics, i.e. the pupils were able to correctly predict and adequately justify the experimental results based on the principle of punctiform light emission. Educational and research implications are discussed.

1 Theoretical Background

1.1 History of Science and Science Education

The reference point shared by the manifold theoretical views on Science teaching and learning, which are characteristic of the tasks suggested by Science Education researchers, is the established conviction that knowledge is not transferred. Rather, it is formatted in thought within the framework of specially organised teaching initiatives, through which pupils are led to construct systems of meaning and mental/cognitive tools for approaching

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the physical world (Osborne and Wittrock 1983; Wheathley 1991). Within the context of such speculations and relevant inquiries, increased research interest has been observed over the past few years with a view to enriching Science curricula with elements from the History of Science, not by merely making reference to historical events, dates and biographies, but by incorporating historical data into knowledge construction operations. Suggestions related to the contribution of the History of Science to Science Education cover a fairly wide application range (Matthews 1992; Seroglou and Koumaras 2001). In an attempt to codify the different research trends, as these have been and are still being shaped in this field, using as a criterion the direct or indirect part that History of Science (H.S.) plays in Science teaching, one can distinguish two main axes of approaching the matter, which are not mutually exclusive: (a) making educational use of the H.S. as a means of teaching and learning Science and (b) implementing the H.S. as a research and methodological tool in Science Education.

In the first case, the H.S. stands in the foreground of the teaching process, since physical concepts are approached through the historical context of their development. Supporters of the 'historical approach in science teaching' have been producing studies and implementing courses from the 1950s to date (Holton 1952; Conant 1957; Klopfer and Cooley 1963; Brush 1969; Kipnis 1993; Galili and Hazan 2001), voicing the conviction that, through contact with the origin and historical evolution of scientific ideas, pupils approach scientific methodology; comprehend the nature of scientific theories as historical entities bearing a beginning, a peak and an end; become interested and involved; acquire a positive outlook towards science, and—finally—a framework for understanding physical phenomena. In the second case, research interest focuses on the psychological dimension of learning procedures. Researchers attempt to decrypt the operations governing the formation and variation of scientific theories, using the H.S. as a guide, so as to convey the historical 'lessons' to teaching practices for the construction of contemporary knowledge by pupils. The epistemological views that form the starting point of this trend are those which recognise the existence of remarkable similarities between the construction of scientific knowledge within an individual and the historical development of ideas in science (Wiser and Carey 1983; McDermott 1984; Wandersee 1986; McCloskey and Kargon 1998; Robin and Ohlsson 1989). In this perspective, the H.S., even without its direct or explicit presence in the teaching process, can play an important part:

(a) As a dependable research tool for determining focus areas of research interest, in an effort to scan and locate students' representations (Steinberg et al. 1990; Benseghir and Closset 1996; Dedes 2005).
(b) As a useful methodological tool for decoding cognitive activities and utilising them in the processes of conceptual change (Driver and Easley 1978; Champagne et al. 1982; Nersessian 1989).
(c) As a source of inspiration for activities and experimental situations in producing educational material (Greenslade and Howe 1981; Bradley 1991; Teichmann 1991; Seroglou et al. 1998).

1.2 Light Emission by Extended Light Sources in the Evolution of Scientific Thought

In calculation-type optics exercises requiring prediction of the shape and calculation of the size of the shadow cast by an opaque object placed in front of a point light source, problems are solved relatively easily by applying the fundamental principle of geometrical optics, i.e. the principle of rectilinear propagation of light: the (imaginary) straight lines starting from

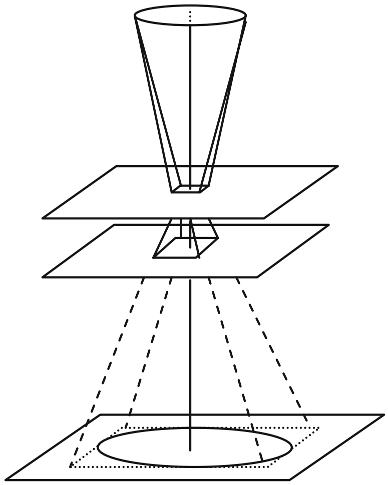

Fig. 1 Schematic representation of Aristotle's 'optical puzzle'

the source and extending to the object's outline form the shadow's constant shape, while its size depends on the distance between the object and the impression surface. In the case of an extended light source, however, the problem becomes more complex, as the shape of the shadow no longer remains constant. While at relatively short distances the shadow bears the shape of the opaque object, at long distances its shape changes and becomes that of the source. Looking at the History of Science, one sees that this problem has occupied scientists and philosophers ever since antiquity. Aristotle, in his work *Problems*, considered by many as a pseudepigraph,[1] ascertains a similar optical phenomenon: when sunlight passes through random-shaped apertures created by tree foliage, it produces an image on the ground which changes shape according to the aperture's distance from the ground. Thus, while at a short distance the image bears the shape of the aperture, as is expected according to the rectilinear propagation of sunrays, nonetheless at greater distances the image assumes the seeming shape of the sun, i.e. it becomes circular (Fig. 1).

The scientific community has unsuccessfully puzzled over the explanation of this phenomenon over some 2,000 years, revealing not only a large number of alternative interpretative approaches, but also a series of theoretical schematizations exceeding the scope of the particular problem and verging on fundamental principles and axioms of optics (Lindberg 1968, 1970). A common feature among all these approaches is the notion of a 'continuous' way of emitting light when it originates in extended sources (Lindberg 1987). At the turn of the seventeenth century, Johannes Kepler adopted the principle of punctiform analysis (see Fig. 2), as formulated by the Arab Al Haytham in his work *On the Shape of the Eclipse* (Straker 1971, p. 555).

Thus, he performed a mechanistic representation of the phenomenon in three dimensions, providing the definitive solution to the 'mystery':

> Since I was unable to understand the very obscure sense of the words from a diagram drawn in a plane, I had recourse to seeing with my own eyes in space. I set a book in a high place, which was to stand for a luminous body. Between this and the pavement a tablet with a polygonal hole was set up. Next, a thread was sent down from one

[1] Aristotle*: Problems*. Trans. W. S. Hett (1952) & E. S. Forster (1963). Hett places the author within the second century B.C., as a later representative of the Peripatetic School.

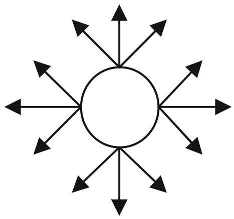

Fig. 2 Al Haytham's principle of punctiform analysis

> corner of the book through the hole to the pavement, falling upon the pavement in such a way as to graze the edges of the hole, the image of which I traced with chalk. In this way a figure was created upon the pavement similar to the hole. The same thing occurred when an additional thread was added from the second, third, and fourth corner of the book, as well as from the infinite points of the edges. In this way, a narrow row of infinite figures of the hole outlined the large quadrangular figure of the book on the pavement. It was thus obvious that this was in agreement with the demonstration of the problem, that the round shape is not that of the visual ray but of the sun itself, not because this is the most perfect shape, but because this is generally the shape of a luminous body (Kepler 1604/2000, p. 56).

Kepler considered the luminous body as the composition of an infinite number of luminous point-elements, each of which radiates independently, rectilinearly and isotropically in all directions According to this view, and mentally replacing the hole with a small obstacle, each luminous point produces a shadow that, due to the rectilinear propagation of light, will bear the shape of the obstacle. If one attempts a dynamic depiction and supposes that a luminous point-element travels the circumference of a luminous object, then the respective shadows of the obstacle partially overlap and are distributed along the circumference of a shape corresponding to the luminous object and located on the ground (Fig. 3).

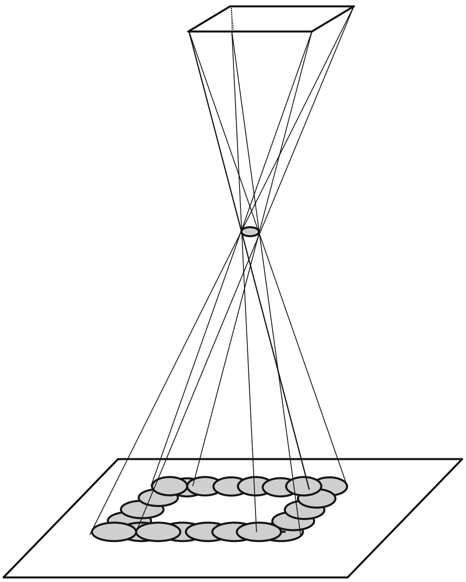

Fig. 3 Kepler's crucial experiment

As the distance between the obstacle and the ground lessens, the degree of overlap of the shadows dominates the degree of decrease in their size, so that the overall shadow gradually coincides with the shape of the obstacle. On the contrary, as the distance between the obstacle and the ground increases, the degree of spreading of the shadows dominates the degree of increase in their size (i.e. the degree of overlap), so that the overall shadow gradually coincides with the shape of the source.

By applying his model of analysis to similar problems (i.e. mechanism of vision, lens images), Kepler formulated a consistent conceptual interpretative framework and set the basis of modern geometrical optics. The holistic mode of radiation emission was definitively abandoned, while the luminous mathematical point-element radiating rectilinearly in all directions was established as the new emission 'unit'. The light propagation model depicted by a pyramid whose base is the total surface of the light source lost its methodological usefulness and was replaced by an inverted pyramid whose apex was every point of emission and whose base was the object underlying the light (Lindberg 1992). Finally, in approaching and studying optical phenomena, the equal contribution of the entire 'quantity' of light replaced views about privileged power and propagation in preferential directions.

1.3 Pupils' Representations Concerning Shadow Formation by Extended Light Sources

It is within the scope of this speculation that this research project takes place. In the research field of Science Education and in the domain of optics in particular, the vast majority of studies conducted on children's representations concerning light phenomena assumes dimensionless light sources, i.e. point sources (Guesne 1978; Andersson and Kärrqvist 1983; Eaton et al. 1984; Palacios et al. 1989; Ramadas and Driver 1989; Boyes and Stanisstreet 1991; Selley 1996; Langley et al. 1997; Hosson and Kaminski 2002). However, since the chapters taught on optics include topics whose understanding requires the use of extended light sources (i.e. pinhole images, formation of shadows, mirror images, mechanism of vision, lens and prism images), this has led to the development of a (limited) number of research initiatives based on this latter assumption. The findings of these studies prove that—even following school instruction—pupils still approach such phenomena through representations which deviate, more or less, from the accepted scientific models. In searching for the interpretations that these new representations lead to, as these are documented in the relevant literature and confirmed by our own preliminary research (pre-test), we discover that pupils' interpretative schemata are largely dependent on the way in which children perceive light emission when coming from extended light sources (Fawaz and Viennot 1986; Rice and Feher 1987; Goldberg and McDermott 1987; Galili et al. 1993; Galili 1996). After codifying the pupils' alternative approaches, three representation categories emerge:

(i) Representations of a holistic mode of light emission and propagation in a preferential direction (i.e. the source emits light as a whole and the light rays carry its shape in the direction that 'matters' to the problem at hand, which is in our case the horizontal direction) (see Fig. 4a).
(ii) Representations of a radial mode of emission (i.e. irrespective of its shape, the source emits light as if it were a spherical surface whose every point emits a single ray of light perpendicular to its surface. In effect this is a mechanistic transference of the radial emission of the 'point' source model, which is arbitrarily and notionally enlarged to dimensions comparable to the extended source) (see Fig. 4b).
(iii) Representations of a combinative mode of emission (i.e. simultaneous emission in both the aforementioned ways) (see Fig. 4c).

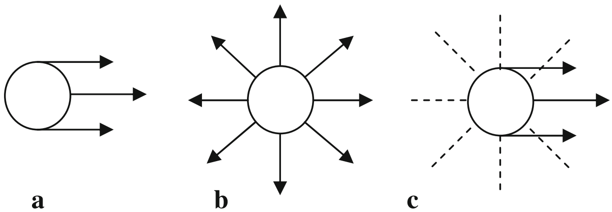

Fig. 4 Schematisation of children's representations concerning light emission by extended light sources

The aim of this paper is to present the results of a teaching intervention based on the involvement of the subjects in experimental activities with a view to transforming their representations concerning the formation of shadows by extended light sources. In the light of social constructivism, this transformation requires and presupposes the disarrangement of the existing cognitive structure; this can be achieved under conditions of social interaction, not in the sense of the general influence of various social factors, but in the sense of an organised teaching procedure with predetermined characteristics (Doise and Mugny 1981; Lemeignan and Weil-Barais 1993; Perret-Clermont et al. 2004). At a methodological level, representatives of this research movement adopt intervention strategies which initially aim at destabilising the pupils' representations, since—in certain topics—these representations prove to be extremely resistant to teaching (Gunstone and White 1981; McCloskey 1983; Howe et al. 1990). To this end, they suggest creating teaching conflict procedures through which the subject's predictions under a given experimental situation are confronted with the sensory findings which arise from the execution of the experiment and which contradict previous assumptions (Lefebvre and Pinard 1972; Sydner and Feldman 1977; Nussbaum and Novick 1982; Champagne et al. 1985). Thus, when the correct scientific model is then presented and elaborated, it may benefit learning by favouring the development of representations and the logical systemisation of ideas (Ravanis 2005).

The History of Science is used in this effort as a tool for creating teaching-learning situations. Experimental settings whose cognitive content is derived from the History of Optics are thus utilized in teaching. This is attempted in the destabilization of the subjects' representations as much as it is in their restructuring. Thus, during the first stage of the procedure, appropriate conflict conditions are created during experimental situations inspired by the History of Optics, by confronting the subjects' predictions and the results of these situations, with an aim to imbalance the spontaneously formatted representations. During the second stage, the use of historical data and their didactic transformation form the basis for constructing the experimental situations as well as the intervention strategy: through organising and rearranging the same materials based on Kepler's relevant historic experiment and through appropriate guidance on the researcher's part, it is attempted to reorganise representations and construct a scientific model.

2 Methodology

2.1 The Sample

Forty eight students (24 boys and 24 girls) took part in this study, coming from 10 different schools and evenly distributed into three age groups. Sixteen pupils were in the Fifth Grade of primary school (approximately 11 years old), 16 were in their second year of junior high school (approximately 14 years old) and 16 were in their first year of secondary high school (approximately 16 years old). It should be noted that pupils in Greece are taught topics related to shadows' formation during the fifth year of primary education as well as in the second year of junior high school. The teaching of these topics in these particular school years makes it possible:

(a) for the students to acquire some basic knowledge regarding the behaviour of light, which is a prerequisite for their participation in the study,
(b) to detect the representations present, either pre-existing or created under the influence of the teaching procedure,
(c) to check whether any positive influence of the school teaching may retain its power in the course of time (i.e. 2 years after the last teaching intervention).

The schools were chosen so as to ensure that pupils with different socio-economic backgrounds would be included in the sample. The selection of the pupils was made in cooperation with their teachers, so that pupils from the top, middle and bottom levels of the achievement range would be represented in the sample.

2.2 Data Collection

The only children that took part in the study were the ones who expressed alternative representations after the pre-test. Two subjects from the third age group recognised the correct scientific model during the pre-test and were thus not included in the experimental procedure. Moreover, students from the sixth grade of primary school and the second year of junior high school participated in the study directly after having been taught the relevant topics on optics at school. Data were collected through individual semi-structured interviews which lasted approximately 45–50 min and comprised open-end questions adjusted to the empirical content of specific experimental situations. Interviews took place in a specially designed room in the children's school, since the specific experimental situations necessitated conditions of darkness in order for the results to be clearly visible. Predictions, descriptions and interpretations were formulated verbally and recorded by a tape recorder (i.e., with the children's consent), as well as marked on schematic reproductions of the experimental settings (see Fig. 5). The researchers also used special protocols which permitted any relevant non-verbal responses to be encoded. The interviews were analyzed by studying both the transcribed text and the schematic reproductions and protocol in writing.

2.3 The Process

2.3.1 First Stage: Pupil Involvement in Teaching Conflict Procedures

During this stage, pupils had to deal with three tasks which were formed based on the empirical content of Aristotle's 'optical paradox'. The tasks were purposefully chosen in an attempt to create cognitive disequilibrium in the children's existing representations. Thus, the task sequence was such that the results of each following task would provide the subjects with the opportunity to realize the inadequacy of their previous interpretative scheme. During the process, subjects were asked—in this order—to make predictions, justify them, verify or disprove them by activating the source and, finally, provide new justifications and make comparisons with the original predictions.[2]

[2] A similar type of arrangement is used by Wosilait et al. (1998) in their research on image formation by extended light sources. However, the teaching procedure they propose clearly differs from the one followed in this paper, since the theoretical basis of the authors is not related to the historical origins of the phenomenon.

2.3.1.1 Task 1a The following items were placed in the following order along a school desk: a quadrangular fluorescent light source with dimensions 10 cm × 10 cm, shaped by a glass tube with a cross-section of 1 cm; an opaque circular obstacle of 1 cm in diameter (i.e., small compared to the dimensions of the source) located at the same height as the centre of the quadrangular source; and, finally, a projection screen (Fig. 5).

The source–obstacle distance was 80 cm while the obstacle-screen distance was 5 cm. While the light source was kept deactivated, the subject was first asked to predict the results on the screen as well as on the obstacle surface and to justify these predictions by tracing the light path on the schematic form of the optical system. The dialogue that ensued contained the following sequence of questions:

"Can you predict what you'll be seeing on the screen if we turn the lamp on?"

In the event in which the subject predicted the formation of a shadow, we proceeded as follows:

"Can you indicate more or less where the shadow will appear on the screen?"

"What will be the shape and the size of the shadow?"

"To what do you think the shape of the shadow is due?"

"Will the obstacle be lit, and if yes, in what way?"

"In what way do you think the light will be emitted from the source in order to give us the lit result you have predicted?"

"Can you draw exactly what it is that's going on in this illustration?" (here they were given the schematic reproduction of the experimental setting).

In the event in which the subject did not predict the formation of a shadow, the dialogue continued on the basis of the three last questions.

Subjects adopting the holistic mode of emission predicted that a lit rectangle with the same dimensions as the source would appear in the centre of the screen, while the front surface of the obstacle (i.e. the one towards the source) as well as the rest of the screen would remain unlit. "What we'll see on the screen is the square … because the source is square … I don't think the rest of it will be lit because the light travels this way [shows a horizontal motion] … and so the obstacle won't be lit" (S. 47). Subjects adopting the second representation category (i.e. the radial mode of light emission) correctly predicted that a dark spot would appear in the centre of the screen, while the obstacle would be uniformly lit. "… the light travels this way [draws lines extending radially from the source, as if it were a sphere] … and we'll see the shadow of the obstacle on the screen … because one of the rays doesn't pass through the obstacle, so we'll see its shadow" (S. 25). Finally, subjects actuated by the combinative mode of emission predicted that the quadrangular image of the

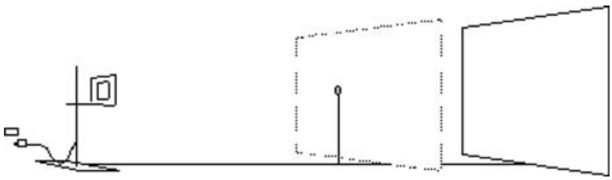

Fig. 5 Schematic representation of the optical system in Tasks 1a and 1b

source would appear on the screen with a dark spot at its centre, while the rest of the screen as well as the obstacle would only be faintly lit. "… we'll see the shape of the square on the screen … and the shadow of the obstacle will be right here in the middle [shows the center of the square] … the screen will be uniformly lit, but slightly less … it is being lit by the source but the square will be stronger, it'll stand out" (S. 13). Following this, the light source was activated, causing a dark spot with the same dimensions as the obstacle to appear on the screen, while the rest of the screen as well as the obstacle were uniformly lit. The child was then reminded of his/her own original prediction and asked for an explanation and, if the prediction was disproved, for a new justification. The contradiction between predictions and results occurring for part of the sample caused the representations of holistic and combinative emission to be rejected and led the subjects to unanimously (100%) adopt the radial interpretative scheme, which in this particular task exhibits absolute explanatory adequacy.

2.3.1.2 Task 1b The light source was deactivated and the screen drawn away from the obstacle to a distance of 30 cm. This time, the subjects' answers were all compatible with the radial mode of emission, as all the children predicted that a dark spot would appear at the centre of the screen and the obstacle along with the rest of the screen would be uniformly lit. Then the light source was activated and the dark quadrangular image of the source appeared on the screen. The explanatory adequacy of the radial emission mode was severely injured; however it still detained the subjects from recognising the correct scientific model. The majority of the children (58.70%) was lead to an interpretational impasse, while a significant percentage of them (41.30%) maintained the characteristics of the radial mode of emission, yet interpreted the shape that appeared not as a result of the opaque obstacle obstructing the path of the light beam but as an imprint of the shadow of the source itself (Fig. 6).

2.3.1.3 Task 1c The light source was then deactivated once again and, without modifying the relative distances, a small opaque object was placed in front of the lower side of the quadrangular source, so as to modify its shape into the form of an upright Π. No change was observed in the prediction stage, since all the children predicted the formation of a dark upright Π on the screen, without being able to provide adequate justification. Following that, the source was reactivated once more and the image of an inverted dark Π appeared on the screen. Thus, conflict conditions escalated, since by now the interpretation of the result did not agree with any of the interpretative schemas that had been suggested this far, except that of punctiform emission. Only one subject (Sub. 40) recognised the characteristics of the correct scientific model, while all the other children declared they were unable to interpret the result and were thus led to a situation of cognitive destabilization.

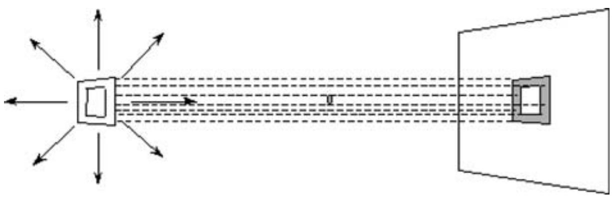

Fig. 6 Shadow as property of the light source

2.3.2 Second Stage: Teaching Intervention

At this stage, in order to achieve reorganisation of the pupils' representations, Kepler's historic experiment was utilized in an educational manner so as to gradually guide the children to perform the experiment cooperatively within an interactive environment. To this end, a special optical device was constructed, which provided the possibility of 'decomposing' the extended light source into a certain number of 'point' sources. This device consisted of an array of eight tiny halogen light bulbs with dimensions 1 cm × 1 cm (12 V, 20 W), evenly placed along the sides of an imaginary quadrangle with dimensions 10 cm × 10 cm; i.e., equal in size with the quadrangular fluorescent light source used in the previous experiment. Each light bulb could be independently activated through an improvised control console, causing a shadow on the screen which bore the shape of the obstacle at that time. Each time the overall shape of the shadow resulted as a synthesis of the shadows of each 'point' source. Only subjects who had failed to approach the correct scientific model during the previous stage participated in this teaching intervention. These children had to deal with two new tasks.

2.3.2.1 Task 2a The setting was modified by replacing the fluorescent source with the improvised one and by placing an obstacle at a distance of 50 cm from that. The screen remained behind the obstacle, at a distance of 80 cm from the source (see Fig. 7).

In cooperation with the subject, one of the tiny light bulbs was chosen at random and a prediction was requested. Then the light bulb was activated and the dark spot was marked on the screen. After the circular shape of the spot was established, the corresponding shape of the obstacle was pointed out and the rectilinear propagation of light was verified. This was followed by successive and independent activation of the remaining light bulbs, immediately followed each time by the direct verification or disproval of the predictions. Following that, all the light bulbs were successively activated and each remained permanently lit, so as to gradually form the quadrangular shape of the shadow as the sum of the eight dark spots. Finally, the lower-middle and then the lateral-middle light bulbs were deactivated successively and independently, so that the extended source assumed the shape of an upright and then a sidelong Π, respectively. This modification allowed the children to interpret the inversion of the shape of the shadow onto a vertical as well as a horizontal plane, which is observable only in the case of a non-symmetrical light source.

2.3.2.2 Task 2b The obstacle remained in place while the screen was drawn nearer to the diaphragm to a distance of 5 cm. Following the same methodological approach (prediction—immediate validation—discussion—guidance—interpretation), the remaining light bulbs were then activated successively. The virtually total overlapping of the circular dark spots caused, as an overall result, a circular shadow with the same dimensions as the obstacle. The screen was then slowly drawn away from the diaphragm and placed in its initial

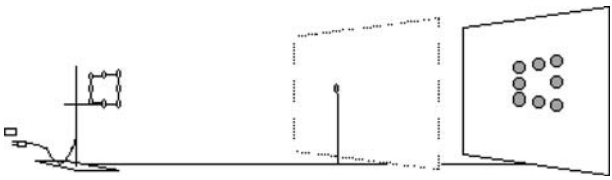

Fig. 7 Schematic representation of the optical system in Tasks 2a and 2b

position. The increase in the dispersion of the dark spots as well as their size was established through collaborative discussion, while the one-to-one relation between each element of the source and its corresponding shadow was demonstrated.

3 Results

In order to check the effectiveness of the intervention, certain tasks were used which had the same cognitive presuppositions and yet different empirical content with respect to the tasks of the previous stages. Thus, the rectilinear fluorescent source was replaced in all tasks by a cross-shaped one, while the circular obstacle was replaced per child by another with different shape (i.e. triangular or rectilinear). Changing the source shape was the safest way of verifying whether the children had assimilated the characteristics of the correct scientific model, since during the post-test they were asked to apply the constructed representations to situations different to those under which they were constructed. The investigation into the representations that were finally constructed took place 15 days later, again through personal interviews, whose structure remained the same as that of the initial stages: the subjects were asked to provide predictions, descriptions, interpretations and justifications, both verbally and diagrammatically—this time, naturally, without the chance to verify or disprove them. Discussion during justification was particularly careful and thorough, given the risk that correct answers might spring from mechanistically reproducing and transferring the results observed during the previous stages to the new empirical data. In order to minimize this risk, the tasks chosen and developed were those whose results had not been sensory-detected during the teaching intervention.

Table 1 presents the children's representations on the mode of light emission by extended light sources prior to and following the entire process, classified by age group.

4 Analysis of Findings

From the results of the post-test, as recorded in Table 1, it can be seen that restructuring of representations was achieved to a percentage of 37.5%, 68.8% and 57.1% for the first, second and third age group, respectively. Furthermore, a significant percentage of subjects in every age group (37.5%, 6.2% and 14.3%, respectively) maintained the radial interpretative scheme in the end. From a conceptual point of view, the radial scheme could be considered as the one nearest to the correct scientific model, as it contains the seed of the punctiform emission view. Indeed, according to this scheme, each point of the source emits autonomously (if not isotropically) in space, while the radiation propagates in all directions without there being any privileged dependencies which might indicate concentrations of an intuitive nature. Thus, the construction of representations of this kind presupposes decentralising from the subjective viewpoint of privileged propagation and refers to the activation of logical mental operations which mark representational progress. By adding up these two percentages by age group, the total progress is found to be 75.0%, 75.0% and 71.4%, respectively.

On the basis of this particular reasoning, statistical elaboration of the data was carried out. The subjects were evaluated as to the change in their performance according to an ordinal scale which comprised four categories: progress, relative progress, stagnation and regression. With a view to checking the changes in the students' responses, their alternative representations were classified into two categories after having been evaluated and

Table 1 Frequencies of pupils' representations of light emission by extended light sources

Mode of light emission	Sixth grade of primary school ($N = 16$)				Second year of junior high school ($N = 16$)				Frist year of secondary high school ($N = 14$)			
	Pre-test		Post-test		Pre-test		Post-test		Pre-test		Post-test	
	Subjects	*N*	Subjects	*N*	Subjects	*N*	Subjects	*N*	Subjects	*N*	Subjects	*N*
Punctiform		0	*3, 7, 10, 11, 13, 14*	6		0	*17, 19, 20, 23, 26, 27, 28, 29, 30, 31, 32*	11		0	*35, 38, 41, 43, 44, 45, 47, 48*	8
Holistic	*1, 2, 8*	3		0	*17, 18, 21, 32*	4		0	*38, 40, 42, 47*	4		0
Radial	*9, 12, 14, 15*	4	*1, 2, 5, 6, 8, 9, 15, 16*	8	*19, 20, 22, 25, 27, 28*	6	*21, 22, 25*	3	*35, 36, 43, 45, 46, 48*	6	*36, 40, 42*	3
Combinative	*3, 4, 5, 7, 10, 13, 16*	7		0	*23, 24, 26, 29, 31*	5	*24*	1	*34, 39, 41, 44*	4	*39*	1
Other	*6, 11*	2	*4, 12*	2	*30*	1	*18*	1		0	*34, 46*	2

Subjects S.33 and S.37 (16 years of age) did not participate in the experimental procedure because they had recognised the correct scientific model during the pre-test. During the post-test, S.40 predicted results that were compatible with the radial mode of emission classified based on their conceptual consistency with the correct scientific model. The first category consists of representations related to the radial mode of emission, their characteristics not being completely incompatible with scientific theory, but merely resulting from poor application of the principles of geometrical optics. The remaining representations were classified into the second category. Thus, progress is defined as a subject's transition from any alternative representation to that of punctiform emission, while relative progress as the transition to representations of radial emission mode. Regression is defined as the exact opposite transition, while stagnation is marked by a subject remaining at the same level of representation. Differences between the pre-test and post-test are considered statistically significant for a 0.05 level of significance. The statistical check carried out on the data yielded the following results.

In order to evaluate the improvement in class performance following the teaching intervention, a goodness-of-fit test (χ^2) was performed for each age group. From the results of the three tests, it follows that in the 6th Grade of Primary School, 37.5% of the subjects made progress, while 37.5%, 18.8% and 6.3% of them made relative progress, stagnation or regression, respectively ($\chi^2(3) = 4.5$, $p < 0.212$). In the second year of Junior High School, the percentage of subjects that progressed is as high as 68.8%, which is much higher than the percentages of relative progress (6.2%) and stagnation (25%) ($\chi^2(2) = 9.125$, $p < 0.01$). In the first year of Secondary High School, the percentage of subjects who progressed is also significantly higher (57.1%) than percentages pertaining to all other categories, namely 14.3%, 21.4% and 7.1% for relative progress, stagnation and regression, respectively ($\chi^2(3) = 8.29$, $p < 0.04$). The absolute frequencies and performance percentages per class are presented in detail in Table 2.

The above results also reflect the extent of positive impact this particular experimental-teaching procedure had. The extent to which the research objectives we set—i.e. the transition from a spontaneously formatted model to one which bears characteristics approximating the geometrical optics model—were accomplished, constitutes not only a criterion for assessing the chosen method's success, but also a starting point for formulating teaching suggestions with the purpose of improving teaching efficiency at a level of school practice. We believe that the variations observed in the results were determined by the influence and interdependence of two factors: the mental development occurring with age and the time span of the teaching of the relevant topics in class. As indicated by the results, the subjects from the youngest age group face the greatest transformation difficulties. The improvement of transformation percentages with age is, of course, to be expected in this type of intervention. However, the spectacular superiority of the second age group over the other two may be interpreted as a result of the joint influence of both aforementioned factors in as positive

Table 2 Changes in performance and percentages per class

Change in performance	Sixth grade of primary school ($N = 16$)		Second year of junior high school ($N = 16$)		First year of secondary high school ($N = 14$)		Total ($N = 46$)	
	N	(%)	N	(%)	N	(%)	N	(%)
Progress	6	(37.5)	11	(68.8)	8	(57.1)	25	(54.3)
Relative progress	6	(37.5)	1	(6.2)	2	(14.3)	9	(19.5)
Stagnation	3	(18.8)	4	(25.0)	3	(21.4)	10	(21.7)
Regression	1	(6.3)	0	(0.0)	1	(7.1)	2	(4.3)

Percentages not summing up to 100 due to rounding errors a combination as possible. It is widely accepted that pupils in their first year of secondary school are considered as having a higher level of thinking than pupils of the second age group in terms of mental processes. However, the 2-year gap that elapsed since the last time they were taught the relevant cognitive objects seems to have inhibited any further increase in the percentages of the desirable knowledge acquisition.

5 Implications for Teaching

It is known from research in Science Education that, in certain areas of the curriculum, students' alternative representations exhibit significant resistance when 'encountering' scientific knowledge, at least the way it is conveyed in the classroom (i.e. school science). Especially in optics, perceptual data do not contribute to the immediate recognition of the shadow formation mechanism, given that the path travelled by light in space is usually not sensory detectable. Thus, construction of a scientific model entails the ability for deductive mental operations as well as the possibility of processing perceptual data through a mental process of analysis and synthesis, all of which are qualities not yet conquered at these stages of cognitive development. Since the pursued representation transformation requires a framework of cognitive abilities that is of a higher standard than that of spontaneous thought, the teaching intervention should then be based on activities that will lead the children to a reorganisation of their intellectual tools. Thus, in order to reorganise the subjects' representations following the conflict procedure stage, the geometrical optics model was experimentally developed within a learning environment appropriately configured through the mediation of the researcher. Therefore, the issue of cognitive progress was raised here not only in terms of the subjects' activity but also in terms of social interaction. Our objective was to appropriately guide the pupils with a view to discerning the problem's variables and parameters as well as understanding relations between the parameters, so as to facilitate the development of their representations towards approaching the scientific model.

Inasmuch as concerns the extremely weak influence of school teaching, this could be attributed is the absence of any thorough mention of the mechanism of punctiform emission during class. As this model is not explicitly mentioned in the Greek curriculum, neither in primary school nor in junior high school, one may assume that this particular issue would only be mentioned in passing in the classroom. Thus, students' representations continue being based on schemes of emission which are dictated by a one-to-one relation between each point of the source and its corresponding lit result through *one and only one* ray of light (not a light beam). Even under intense conflict conditions (see Task 1b), the radial mode of emission is not doubted, since invoking the concept of the 'shadow of the source' does not pertain to the mode of radiation emission but rather to the source and shadow being connected through a special relationship. This kind of interpretation exhibits a constant frequency of occurrence in studies conducted in the field of didactics with respect to light. The schematic resemblance between shadow and obstacle, especially in cases where the light source lies at a great distance from the object and in conjunction with the inability to recognise light as an entity in space, lead intuitive thought towards comprehending shadows as properties of objects (Piaget and Inhelder 1971; Anderson and Smith 1983; Guesne 1984; Feher and Rice 1988; Langley et al. 1997; Ravanis et al. 2005). In the case at hand, exposing the subjects to an unexpected light result (Task 1b) disarranged the stability of their mental structures and recalled a similar interpretive scheme, transferring, however, this particular property of the objects from the object-obstacle to the source.

Besides, pupils' representations are reinforced by the approach adopted in physics textbooks. In these, in computational problems regarding the tracing of shadows, images or patterns, connection of the source with its results is achieved through the presence of certain 'special' rays. The preferential use of the necessary rays may serve purposes of design economy, but nevertheless, at the level of representation formulation, these special rays prove to be exclusively sufficient conditions of the formation of shadows.

Thus, in teaching topics of geometrical optics, it is of paramount importance to overcome this 'obstacle' and reveal the contribution of the entire light 'quantity' to the formation of lit—and therefore also of shadowed—areas. On a practical level, making use of tasks whose cognitive and empirical content is derived from the H.S. may effectively contribute towards tracking pupils' alternative representations. Furthermore, implementing Kepler's theoretical concept (i.e., developing light sources in such a way as renders possible their 'decomposition' into a number of elementary sources) may prove to be an extremely useful instructional material for constructing the model of punctiform emission and for achieving learning objectives with greater efficiency.

Finally, as concerns future perspectives, it would also be of great importance to extend the experiment, as carried out in the present study, to the rest curriculum topics dealing with light emission by extended light sources. Such an attempt would set the perspective of a unified approach in confronting relevant issues, while at the same time accentuating the significant role that History of Science can play in Science teaching. At any rate, of course, only if the appropriate teaching strategy is chosen will it allow for transformation of the intuitive way of thinking and formation of mental models that are compatible with the respective scientific ones. The results of this study indicate that a structured intervention on the part of the teacher between object and subject may decisively contribute to making use of teaching material systematically drawn from the History of Science.

References

Anderson CW, Smith EL (1983) Children's conceptions of light and color: understanding the concept of unseen rays. East Lansing, Michigan State University

Andersson B, Kärrqvist C (1983) How Swedish pupils aged 12–15 years understand light and its properties. Eur J Sci Educ 5(4):387–402

Aristotle (1952) Problems (trans. W. S. Hett). Heinemann, London

Aristotle (1963) Problems (trans. E. S. Forster). Oxford University Press, Oxford

Benseghir A, Closset JL (1996) The electrostatics–electrokinetics transition: historical and educational difficulties. Int J Sci Educ 18(2):179–191. doi:10.1080/0950069960180204

Boyes E, Stanisstreet M (1991) Development of pupils' ideas about seeing and hearing—the path of light and sound. Res Sci Technol Educ 9:223–244. doi:10.1080/0263514910090209

Bradley J (1991) Repeating the electromagnetic experiments of Michael Faraday. Phys Educ 26:284–288. doi:10.1088/0031-9120/26/5/005

Brush SG (1969) The role of history in the teaching of physics. Phys Teach 7(5):271–280. doi:10.1119/1.2351365

Champagne AB, Klopfer LE, Gunstone RF (1982) Cognitive research and the design of science instruction. Educ Psychol 17:31–53

Champagne AB, Gunstone RF, Klopfer LE (1985) Effecting changes in cognitive structures among physics students. In: West L, Pines A (eds) Cognitive structure and conceptual change. Academic Press, Orlando, Florida

Conant JB (ed) (1957) Harvard case histories in experimental science. Harvard University Press, Cambridge

Dedes C (2005) The mechanism of vision: conceptual similarities between historical models and children's representations. Sci & Educ 14(7/8):699–712. doi:10.1007/s11191-005-1928-5

Doise W, Mugny G (1981) Le Développement Social de l'Intelligence. Interéditions, Paris

Driver R, Easley J (1978) Pupils and paradigms: a review of literature related to concept development in adolescent science students. Stud Sci Educ 5:61–84. doi:10.1080/03057267808559857

Eaton J, Anderson CW, Smith EL (1984) Student's misconceptions interfere with science learning: case studies of fifth-grade students. Elem Sch J 84(4):365–379. doi:10.1086/461370

Fawaz A, Viennot L (1986) Image Optique et Vision: Enquête en Classe de Premier au Liban. Bull Union Physicians 686:1125–1146

Feher E, Rice K (1988) Shadows and anti-images: children's conceptions of light and vision. Sci Educ 75(5):637–649

Galili I (1996) Student's conceptual change in geometrical optics. Int J Sci Educ 18(7):847–868. doi:10.1080/0950069960180709

Galili I, Hazan A (2001) The effect of a history-based course in optics on students' views about science. Sci & Educ 10(1–2):7–32. doi:10.1023/A:1008799919970

Galili I, Bendall S, Goldberg F (1993) The effects of prior knowledge and instruction on understanding image formation. J Res Sci Teach 30(3):271–301. doi:10.1002/tea.3660300305

Goldberg FM, McDermott LC (1987) An Investigation of student understanding of the real image formed by a converging lens or concave mirror. Am J Phys 55(2):108–119. doi:10.1119/1.15254

Greenslade TB, Howe RH (1981) A modern use of Volta's electroscope. Phys Teach 19(9):614–615. doi:10.1119/1.2340902

Guesne E (1978) Lumière et Vision des Objets. In: Delacote G (ed) Physics teaching in schools. Taylor & Francis, London

Guesne E (1984) Children's ideas about light. In: Wenham EJ (ed) New trends in physics teaching, vol IV. Unesco, Paris, pp 179–192

Gunstone RF, White RT (1981) Understanding of gravity. Sci Educ 65(3):291–300. doi:10.1002/sce.3730650308

Holton G (1952) Introduction to concepts & theories in physical sciences. Addison-Wesley, New York

Hosson C, Kaminski W (2002) Les Yeux des Enfants sont-ils des «Porte-lumière»? Bull Union Physicians 840:143–160

Howe C, Rodgers D, Tolmie A (1990) Peer interaction in primary school physics. Eur J Psychol Educ 4:459–475

Kepler J (1604/2000) Optics: paralipomena to witelo & optical part of astronomy. Green Lion Press, Santa Fe, New Mexico

Kipnis N (1993) Rediscovering optics. BENA Press, Minneapolis

Klopfer LE, Cooley WW (1963) The history of science cases for high schools in the development of student understanding of science and scientists: a report on the HOSC instruction project. J Res Sci Teach 1:33–47. doi:10.1002/tea.3660010112

Langley D, Ronen M, Eylon BS (1997) Light propagation and visual patterns: preinstruction learners' conceptions. J Res Sci Teach 34(4):399–424. doi:10.1002/(SICI)1098-2736(199704)34:4<399::AID-TEA8>3.0.CO;2-M

Lefebvre R, Pinard A (1972) Apprentissage de la Conversation des Quantités par une Méthode de Conflit Cognitif. Rev Canadienne Sci Comportement 7:37–42

Lemeignan G, Weil-Barais A (1993) Construire des Concepts en Physique. Hachette, Paris

Lindberg DC (1968) The theory of pinhole images from antiquity to the thirteenth century. Arch Hist Exact Sci 5:154–176. doi:10.1007/BF00327249

Lindberg DC (1970) The theory of pinhole images in the fourteenth century. Arch Hist Exact Sci 6:299–325. doi:10.1007/BF00417622

Lindberg DC (1987) Continuity and discontinuity in the history of optics: Kepler and the medieval tradition. Hist Technol 4:431–448

Lindberg DC (1992) The beginnings of western science. The University of Chicago Press, Chicago

Matthews MR (1992) History, philosophy and science teaching: the present rapprochement. Sci & Educ 1(1):11–47. doi:10.1007/BF00430208

McCloskey M (1983) Intuitive physics. Sci Am 248:114–122

McCloskey M, Kargon R (1998) The meaning and the use of historical models in the study of intuitive physics. In: Strauss S (ed) Ontogeny, phylogeny and historical development. Ablex Publishing Corporation, Norwood, New Jersey, pp 49–67

McDermott L (1984) Research on conceptual understanding in mechanics. Phys Today 37:24–32

Nersessian NJ (1989) Conceptual change in science and in science education. Synthese 80(1):163–184. doi:10.1007/BF00869953

Nussbaum J, Novick S (1982) Alternative frameworks, conceptual conflict and accommodation: toward a principled teaching strategy. Instr Sci 11:183–200. doi:10.1007/BF00414279

Osborne RJ, Wittrock MC (1983) Learning science: a generative process. Sci Educ 67(4):489–508. doi:10.1002/sce.3730670406

Palacios FP, Cazorla FN, Cervantes A (1989) Misconceptions on geometric optics and their association with relevant educational variables. Int J Sci Educ 11(3):273–286. doi:10.1080/0950069890110304

Perret-Clermont AN, Pontecorvo C, Resnick LB, Zittoun T, Burge B (2004) Joining society. Social interaction and learning in adolescence and youth. Cambridge University Press, Cambridge
Piaget J, Inhelder B (1971) The child's conception of space. Routledge & Kegan Paul Ltd, London
Ramadas J, Driver R (1989) Aspects of secondary students' ideas about light. University of Leeds, Centre for Studies in Science and Mathematics Education, UK
Ravanis K (2005) Les Sciences Physiques à l'École Maternelle: Éléments Théoriques d'un Cadre Sociocognitif pour la Construction des Connaissances et/ou le Développement des Activités Didactiques. Int Rev Educ 51(2/3):201–218. doi:10.1007/s11159-005-1885-x
Ravanis K, Charalampopoulou C, Boilevin JM, Bagakis G (2005) La Construction de la Formation des Ombres chez la Pensée des Enfants de 5–6 ans: Procédures Didactiques Sociocognitives. Rev Rech Educ Spirale 36:87–98
Rice K, Feher E (1987) Pinholes and images: children's conceptions of light and vision. Sci Educ 71(4):629–639. doi:10.1002/sce.3730710413
Robin N, Ohlsson S (1989) Impetus then and now: a detailed comparison between Jean Buridan and a single contemporary subject. In: Hegert DE (ed) The history and philosophy of science teaching. Florida State University, Florida
Selley NF (1996) Children's ideas on light and vision. Int J Sci Educ 18(6):713–723. doi:10.1080/0950069960180605
Seroglou F, Koumaras P (2001) The contribution of the history of physics in physics education: A review. Sci & Educ 10(1–2):153–172. doi:10.1023/A:1008702000098
Seroglou F, Koumaras P, Tselfes V (1998) History of science and instructional design: the case of electromagnetism. Sci & Educ 7(3):261–280. doi:10.1023/A:1008649319416
Steinberg MS, Brown DE, Clement J (1990) Genius is not immune to persistent misconceptions: conceptual difficulties impeding Isaac Newton and contemporary physics students. Int J Sci Educ 12(3):265–273. doi:10.1080/0950069900120305
Straker SM (1971) Kepler's optics: a study in the development of seventeenth-century natural philosophy, Ph.D. Thesis, Indiana University
Sydner S, Feldman D (1977) Internal and external influences on cognitive development change. Child Dev 48:937–943. doi:10.2307/1128344
Teichmann J (1991) History and historical experiments in physics education with special regard to astronomy. Phys Educ 26:46–51. doi:10.1088/0031-9120/26/1/008
Wandersee JH (1986) Can the history of science help science educators anticipate students' misconceptions? J Res Sci Teach 23(7):581–597. doi:10.1002/tea.3660230703
Wheathley GH (1991) Constructivist perspectives in science and mathematics learning. Sci Educ 75(1):9–21. doi:10.1002/sce.3730750103
Wiser M, Carey S (1983) When heat and temperature were one. In: Gentner D, Stevens AL (eds) Mental models. Lawrence Erlbaum, Hillsdale, NJ
Wosilait K, Heron P, Shaffer P, McDermott L (1998) Development and assessment of a research-based tutorial on light and shadow. Am J Phys 66(10):906–913. doi:10.1119/1.18988

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