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RESEARCH REPORT

Historical Controversy as an Educational Tool: Evaluating elements of a teaching–learning sequence conducted with the text "Dialogue on the Ways that Vision Operates"

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This paper describes the development, use, and analysis, of an educational tool inspired by the history of the optical mechanism of vision. We investigated 12-year-old students' reasoning about vision. Most of them explain it as the result of something coming either from the object or from the eye. Moreover, some of them think that light penetrates the eye only when they are dazzled. Such ideas can be found in the ancient and medieval history of science. In particular, the Ancients disagreed about the direction of vision until Alhazen opened the way to a consensus, arguing in the 11th century that light could be a stimulus for the eye. Our tool, a short drama entitled "Dialogue on the Ways that Vision Operates", refers to those historical elements, especially to the controversy over the direction of vision and Alhazen's ideas about light. This text was integrated in a teaching–learning sequence and experimented with six pairs of students aged 12–13. The analysis of this teaching–learning sequence shows that the learning process can take advantage of the opportunity offered to the students to identify themselves with the scientists portrayed in the drama.

Keywords: *Historical Controversy; Optics; Vision*

Introduction

Optics is a field on which there has been a lot of educational research throughout the world. While most of enquiries have been concerned with the analysis of students' reasoning (about the role that light plays in vision, on the forming of optical images,

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about colour, etc.), some have lead to teaching propositions. However, recent studies show that certain difficulties that students face in their first years at school remain with them until university in every country. It has been noticed that students find it hard to use the concept of light in an appropriate way, even in cases where they have a high level of knowledge. The teaching of optics can therefore still be perfected; and it seems necessary to explore different ways to contribute to its improvement.

The use of the history of science is the starting point of a pedagogical reflection that we explore here. We have reasons to think that it is possible to assist pupils in their learning by offering them the development of thought that integrates the conceptual discoveries in the history of the theories of vision from Empedocles (five centuries B.C.) to Alhazen (11th Century A.D). From that perspective, the history of science can become an expository tool for science and serve as a teaching guide. In this paper, we will present an analysis of the cognitive impact of a teaching–learning sequence of the optical mechanism of vision built in reference to the history of theories of vision.

Proposition of an Elementary Explanation of Vision

Vision may be considered as a cerebral interpretation of the effect of the light on the retina. Figure 1 gives a general idea of the mechanism of vision as it could be taught at an elementary level (children 10–15 years old). In this diagram, two spaces can be distinguished: the physical one (in front of the eye), and the psycho-physiological one (from the retina to the cortex). In this paper we wish to consider the physical space that includes an ordinary object lit in an ordinary way.

In the physical space, vision can be explained in this way: In order to see an object lit in an ordinary way, it is necessary for the light coming from this object to penetrate the eye of the observer. An observer can see an object if light coming into his/her eye is neither too strong nor too dim. To understand this explanation, one must assume that ordinary objects lit in an ordinary way reflect the light that they receive. However, the entry of light into the eye is only one of the conditions for vision to

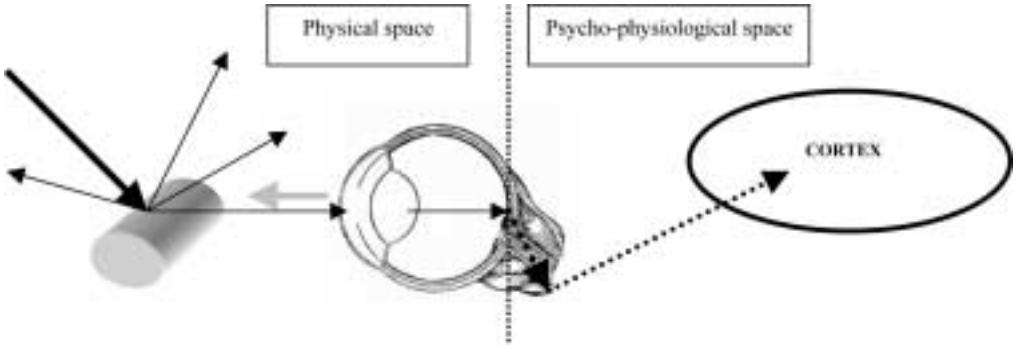

Figure 1. Mechanism of vision from physical and psycho-physiological points of view. The plain arrows represent light (incident and diffused) while dotted arrows figure nervous signal propagation into visual system. The grey arrow represents the direction of vision

occur. Actually, the direction from which looking takes place (representing the observer's intention) is another condition that seems important to students and therefore cannot be neglected in our model of vision.

Children's Understanding of Vision and Historical Development

We wanted to focus on the way a sample of 227 students aged 12–13 spontaneously explain vision (before any kind of training about the matter). From Figure 2 we asked them to answer the following question: "Explain the mechanism of vision, that is to say the way we see objects around us. You can use the illustration if you want". Our purpose was first to detect the "direction" favoured by the pupils to explain vision, and second to identify the nature of the link between the eye and the object seen.

The great majority of the students (204 out of 227, 90%) answer the question by filling out the proposed illustration with arrows. Figure 3 shows illustrations for which arrows were added.

Moreover, 14 students (out of 227) explain vision with the emission of something from the eyes, without the help of a drawing. In total, 196 pupils out of 227 (86% of those interviewed) explain vision with the help of an Eye → Object component, while 31 pupils out of 227 (14% those interviewed) favour an Object → Eye direction. If we pay attention to the vocabulary used by the students in their answers we realise that light is only rarely the protagonist of their explanations (see Table 1). When it is called "sight", "look", "vision" (71% of the answers), the arrow Eye → Object indicates an entity of a more psychological nature than physical. It sends us back to the "grey tinted" arrow of Figure 1. Therefore it seems legitimate to us. Our teaching–learning sequence aims at completing an explanation of the mechanism of vision that favours the Eye → Object "direction" that we consider insufficient but most often not erroneous.

Children's understanding of phenomena associated with light has attracted a lot of research in different countries, and our study only confirms a strong trend of reasoning already updated (Osborne & Black, 1993). As a general rule, it is rare to appreciate that normally lighted objects reflect the light that they receive (Guesne, 1984). Light is identified as its primary source or as the bright area sometimes visible on the surface of the object, not as the invisible entity that spreads from normally lighted objects (Anderson & Karrqvist, 1983; Galili, 1996). However, the phenomenon of diffusion and the penetration of the eye by light are the basic principles of the model

Figure 2. Illustration proposed to the pupils as a potential support for their explanation of vision

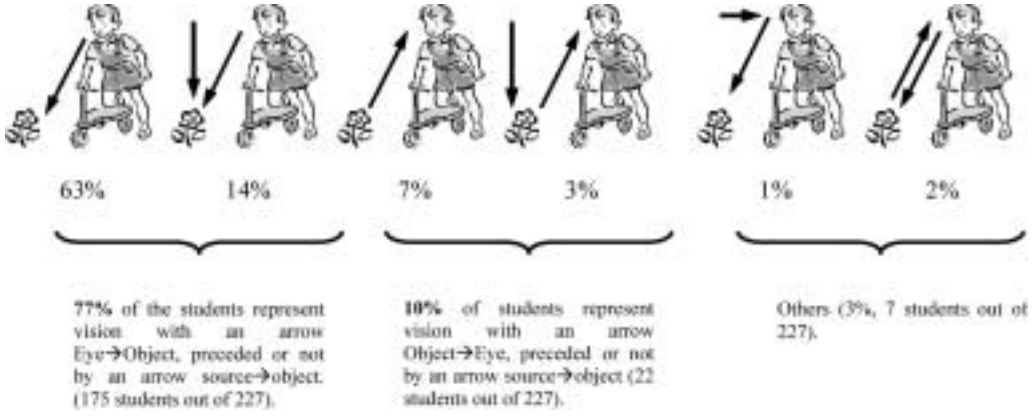

Figure 3. Synthesis of the results obtained for Question 2. These results only concern the answers of pupils having drawn arrows on the illustration; that is, 204 pupils out of the 227 interviewed (90% of the total number)

of vision that we have just put forward. We can therefore expect the assimilation of this model to be very difficult for the students. Moreover, most of them think that the penetration of the eye by light comes necessarily with the disturbance provoked by dazzle, a particular situation that makes vision difficult, indeed even impossible (Guesne, 1984).

Yet, historically, blindness caused by light seems to be the basis of a first optical theory of vision. From the fifth century B.C. and for more than 15 centuries, the scientists interested in vision based their ideas on the "direction" of sight. Following the Pythagoricians, some stood behind the idea of emanating from the eye (extramission) whereas others, inspired by the atomist theories, maintained the idea of the eye receiving something coming from the object (intromission). It was not until the 11th century that Ibn al-Haytham (Alhazen) defined light as and independent and invisible

Table 1. Vocabulary used by the students to explain vision (with or without the use of the illustration)

Vocabulary	*n*	Percentage	Vocabulary	*n*	Percentage
Sight	113	50	Image	15	7
Look	25	11	Flower (or object)	3	1
Vision	22	10	Shape, appearance, something	4	2
Eye or the eyes	17	7	Colour	4	2
Ray	4	2	Light, sign, signal	5	2
Something	5	2			
Others	10	4			
Total direction eye → object	$N = 196$	86	Total direction object → eye	$N = 31$	14
Total			$N = 227$ (100)		

agent transmitter of sight. Far from being embraced by medieval philosophers, this explanation was commonly accepted by the scientific community only five centuries later with the advent of Keplerian optics (Lindberg, 1976; Park, 1997; Ronchi, 1956).

History of Science in Science Education: An integrated approach

Over the past decades, investigators have pleaded for the incorporation of the history of science in science education. In France, a great effort has to be made by putting forward teaching–learning sequences that are historically oriented. Recently, the National Curricula for secondary schools (pupils 10–14 years old) made strong recommendations for science teachers to implement the history and philosophy of science (HPS) in their courses, but, in concrete terms, the available materials are still inadequate.

Pleading for a Science Education Based on History of Science

Worldwide research shows that HPS possesses a great potential for an improvement of the learning process, especially within the constructivist perspective (Matthews, 1994; Monk & Osborne, 1997). HPS provides students with a more comprehensive view of science and allows them to be more actively involved in the learning of science. Thus, a pupil's view of the nature of science may change when some learning materials are historically situated (Driver, Leach, Millar, & Scott, 1996; Solomon, 1994). In particular, an appreciation of the creative role played by the great scientists of the past can be an antidote to the excessive determinism of many pupils (Irwin, 2000). Moreover, it as been shown that HPS aims at developing a knowledge of science that gives students and teachers the key to learn *about* science and not only *of* science (Justi & Gilbert, 2000). Besides, the obvious role played by thought experiment in the history of science (Kuhn, 1977), and more specifically in the history of optics, oriented our pedagogical strategy towards a non-experimental sequence.

Furthermore, HPS uncovers the scientific process and provides the teacher with the difficulties people had in establishing the knowledge, including controversies, instead of focusing solely on final products. HPS also gives turning-points that can inspire the teachers with particular pedagogical strategy. Thus, it can be used as an organising principle for the curriculum (Jung, 1994; Matthews, 1994):

> Knowledge of the historical development of a discipline can assist teachers in anticipating and understanding difficulties that contemporary students have with learning subjects. The history can also suggest questions and experiments that promote appropriate conceptual change in students […]. Knowledge of the slow and difficult path traversed in the historical development of particular sciences can assist teachers planning the organization of a program, the choice of experiment and activities, and their responses to classroom questions. (Matthews, 1994, p. 51)

Decades ago, Piaget and Garcia described both the psychogenesis of individual learning and the development of scientific thought as following parallel paths

(Piaget & Garcia, 1989). Afterwards, such parallelism was examined and discussed (Nussbaum, 1989). It has been evidenced that there are important differences between student's thinking and the historical products of science (Carey, 1985). Although, even if epistemological and cultural contexts are different and incomparable (Nersessian, 1989; Saltiel & Viennot, 1984), knowing what difficulties were faced in the building up of knowledge, the epistemological obstacles involved, may constitute an essential aid to understanding students' difficulties (Sanmarti & Izquierdo, 1995). Furthermore, students' conceptions often have common features with some ideas in the past. Consequently, it opens the way to a possible identification of the student to the scientist in the past which can be helpful to learners:

> It is comforting to perceive that others have thought in a similar manner—that to hold such thoughts is not to be guilty of mere stupidity. For after all, highly respected and intelligent men of the past have though in very similar way. (Monk & Osborn, 1997, p. 413)

A lot of materials have been produced by researchers that put HPS into teaching–learning sequences. The introduction of HPS in optics teaching has also been implemented. Galili and Hazan developed an experimental course in geometrical optics that incorporated historical ideas regarding the understanding of light and vision. This course was based on an investigation that established parallelism between some historical ideas and development and the scheme of student's alternative knowledge with respect to vision (Galili, 1996; Galili & Hazan, 2000). Using an "historico-investigative method", Kipnis blends optics with elements of its history and suggestions on performing investigative experiments. Dealing with a repeating historical discovery, his book shows to a teacher how to present optical concepts to students in the process of their discovery and make students participate in it (Kipnis, 1993).

Presentation of the "Dialogue on the Way Vision Operates"

Our purpose was to organise an optics sequence based on historical grounds (an integrated approach), which appears quite different from introducing history into a science sequence (an add-on approach). In that perspective, we favoured the use of an original drama we (author) developed (see Appendix). Indeed, drama is meant to be a very powerful teaching strategy for enhancing meaningful learning in science. More specifically, using drama as a supporting learning strategy can provide a better understanding of the nature of science (Boujaoude, Sowwan, & Abd-el-Khalick, 2005). Drama can be used to portray the dynamic of the science whereas most of the textbooks present science as a final product ignoring its developmental nature. Thus, drama is the way we worked on to portray the dynamic of a piece of the history of optics.

Our drama was built thanks to a rational reconstruction (Koyré, 1973) from elements of the history of vision until the 11th century. This reconstruction was made for an educational purpose from original books of Aristotle, Lucrecius, Plato, Empedocles, and Alhazen. As we knew learners' difficulties and conceptions about vision, we tried to establish a conceptual route that should be used as a cognitive

pathway for the students (see Table 2). In this research, we make the hypothesis that this conceptual route, which starts from the controversy over the "direction" of vision, enables the learners to assimilate an explanation of the mechanism of vision in accordance with the one presented earlier (see Figure 1). The fact that they agree to take this path could benefit from the opportunity given to them to relate to those representing extra or intromissionist ideas. Indeed, from the "direction" point of view, students' ideas about vision are very similar to the ones developed by the Ancients in reference to the historical controversy over the "direction" of sight and the process that brings Alhazen (1989) to propose a new explanation of vision in the *Kitab al manazir* (*Book of Optics*).

Table 2. Presentation of the drama step by step

Steps of the drama reading	Explanation of the steps' content
A → B: Controversy surrounding the direction of sight	Simplicio and Salviati are gathered on Sagredo's initiative. The latter would like to understand how vision is made. Simplicio maintains that vision operates in an eye → object direction. As for Sagredo, he quotes the Greek atomist scientists and evokes an object → eye direction. Salviati does not give any answers but qualifies vision as of a "passion"
Unity in the functioning of the five senses	Salviati calls on Aristotle's authority and gives three examples (hearing, smell, taste) associating every organ with its *stimulus* for all senses. Simplicio and Sagredo admit that the sense of sights operates on the mode of passion (reasoning by analogy). The question of the identification of the *stimulus* of sight follows
B → C: The phenomenon of blindness caused by light	Salviati evokes a situation in which one is blinded by light
C → D: Quantitative treatment of sight and analogy with hearing	The idea that the eye is sensitive to light destabilises Sagredo and Simplicio, who concludes that the entrance of a very strong light into the eye prevents one's vision. Salviati prepares the conceptual change that will enable Simplicio and Sagredo to accept the fact that light going into the eye does not necessarily come with a disturbance. He reasons by making an analogy with hearing to get the others to accept the link between "the entry of moderate light" and "vision". Sagredo seems receptive to Salviati's theory, Simplicio rejects it, arguing that objects we see do not send out light
D → E: Diffusion and model of vision	Salviati asks Simplicio and Sagredo to follow him in his reasoning, inspired by the theory of Alhazen in which "a very intense light" blinds the observer and "a quantity of light which is neither too strong nor too dim" is linked with vision. Moreover, Sagredo comes to the conclusion that the fact that one can see implies that lighted objects continuously send back the light that they receive

Note: Letters A, B, C, D and E appear in the *corpus* of the drama.

The "Dialogue on the Way that Vision Operates" (author) is a conversation between three characters discussing explanations of sight. The characters are named the same as the characters from the *Dialogue Concerning the Two Chief World Systems* of Galileo (1967) and their role is quite identical. Our text is essentially an argumentative one.

Salviati is the knowledgeable one. Using a method mainly based on evocation, he orchestrates the debate. Salviati has a very precise idea of the intellectual path he wants the others to take. Each question he asks, each thinking experiment he suggests, leads them to a new step in the reasoning. Simplicio is fiercely attached to extramissionist ideas, he is the one whose ideas need to evolve; he is here to cause trouble to Salviati. As for Sagredo, he does not have a clear-cut opinion, he seems open to Salviati's ideas and, at the same time, he listens to Simplicio's arguments. He plays the part of a curious character who seeks to understand the one who has theories he is not familiar with while putting his own knowledge to the test. Sagredo's function is to support Salviati's speech and restrain Simplicio's aggressiveness. His interventions and questions support Salviati, they allow the debate to move forward.

Our drama aims at supporting a step by step learning process (Table 2). Starting from a supposed debate between students, first, we wish to encourage the emergence of a consensus about the "direction" of vision; in other words, lead the majority to accept the object → eye direction. Concerning this point, we see as essential the idea of unity of functioning of the five senses presented by Aristotle. In the *De Anima,* he places vision within the larger context of the operation of the soul and writes: "Sensations are meant to be moved, to suffer […] every sense is driven by its own sensitive organ" (Aristotle, 2000, 439a).

Supposing that most students are convinced by Aristotle's words and accept an intromissionist functioning modality, we then have to bring them to identify the agent responsible for vision. This next step is actually very complex. First it requires that students carry out a conceptual change since they have to build a conceptual object the nature of which may clash with the one that is generally given. Second, we need to clarify the paradox mentioned earlier: for the students, the fact that light penetrates the eye dazzles the observer. As we mentioned earlier, the issue of light blinding the observer leads Alhazen to declare that "vision will occur only as a result of something coming from the visible object to the eye […]. What comes from the object to the eye is nothing but the form of the light and colour" (1989, book 1, chapter 6, p. 78)—this marked the beginning of optics, "the science of light". According to Alhazen, if a strong light disturbs the eye and hurts it, it is because it is a property of sight to be affected by light. And to come to the conclusion that light is the stimulus of the sense of sight, he thinks of light not *only* as a conceptual entity, but *also* in terms of the quantity that the objects (luminous by nature or by diffusion) send out to the eye:

> The effect produced by the light in the eye is of nature of pain. But while some pains are such that they disturb the organ suffering the pain and perturb the soul, others, being mild, are bearable and neither disturb the organ suffering the pain nor perturb the soul.

> Pains of this description are not felt and their subject does not judge them as pains on account of their mildness. The proof that the effect of light in the eye is of nature of pain is that strong light disturbs the eye and hurts it. Now the effects of light in the eye are all the same kind and they vary only by more or less. But owing to the mild effect on the eye of weak and moderate lights they are not felt as pain. (Alhazen, 1989, book 1, chapter 6, p. 84).

So, for Alhazen, the eye feels the lighting and this sensation depends on the quantity of light that penetrates the eye. The eye sees the object when there is neither too much nor too little light coming from the object. Therefore, it is with a quantitative treatment that Alhazen manages to define light as the stimulus of sight. And it is the same treatment that we offer our students: to reason in terms of "quantity" of light, and no longer in terms of "light" only.

Our dialogue meets the requirements of an "educational reconstruction" that closely links analysis of science, content's structure, analysis of the educational significance of that content, research on teaching and learning processes, and development of pilot instruction (Duit, 2000). It fits with the students' reasoning about vision, it takes into account epistemological and historical considerations, and it favours students' interaction. Finally, each stage of the reflection is based on the elements that we think are key ideas of the understanding of the optical mechanism of vision; that is:

- The five senses work with the same principle: a specific organ is sensitive to a *stimulus* coming from outside.
- A light that is too strong "hurts the eyes".
- Ordinarily lighted objects send out the light that they receive.
- The light sent out by normally lighted objects penetrates the eye of the observer.

A Teaching–Learning Sequence based on the Dialogue

We shall now focus on the way students who have never been taught optics responded to our teaching–learning sequence. We hoped to show that its use can constitute a means of efficiently assisting the learning of the optical mechanism of vision. Our intention was to offer the students a learning situation based on the drama and to follow their cognitive process step by step.

Methodological Approach

Our sequence relies on the pedagogical model for incorporating HPS described and implemented by Monk and Osborne:

> The elicitation of a prediction is a key feature of this model. […]. For our model, the phenomena that are presented to students in the first place must have been the subject of some historical theorizing by earlier scientists that can be set alongside the students' own ideas. (1997, p. 414)

Whereas the Monk and Osborne teaching process is divided into six phases, in our own teaching–learning sequence Phases 3–5 are gathered together as no empirical tests are proposed here (Table 3).

Table 3. Presentation of our own teaching–learning sequence in regard to the Monk and Osborne teaching process for incorporating HPS in science education

	Monk and Osborne's teaching process	Our teaching–learning sequence
Phase 1	Presentation of phenomenon	Presentation of phenomenon
Phase 2	Elicitation of children's ideas	Elicitation of children's ideas
Phase 3	Historical study	Historical study based on the use of a drama that includes an historical conceptual change
Phase 4	Devising test	
Phase 5	The scientific idea and empirical tests	
Phase 6	Review and evaluation	Review and evaluation

The six phases should last 1 h. Concerning our investigation method, it leans on the teaching–learning sequences research has recently developed and detailed in a special issue of *International Journal of Science Education*:

> A teaching learning sequence is both an interventional research activity and a product, like a traditional curriculum unit package, which includes well-searched teaching-learning activities empirically adapted to the students' reasoning. At times, teaching guidelines covering expected student reactions are also included. (Méheut & Psillos, 2004, p. 516)

More specifically, our purpose was to empirically validate local hypotheses concerning the learning process and the teaching effect. This is the reason why our teaching–learning material (the drama) was developed in parallel with an appropriated *scenario* that includes a planned teaching. This *scenario* predicts and theoretically justifies in detail the teaching–learning process as it is expected (see Table 4). As the one described by Lijnse and Klaassen, it relates the interaction of teaching and learning activities:

> We may consider the *scenario* to be a hypothetical domain-specific didactical theory that can be tested and revised […]. In the try out of the teaching sequence, the *scenario* functions as a detailed research instrument that guides our observations and interpretations of the teaching–learning process. (2004, p. 540)

We chose to experiment our teaching tool during interviews conducted with six pairs of students aged 12–13 in order to study the teaching and learning process in communities of learners. The way the interviews are conducted is presented as a planned teaching based on a supervised reading of the drama (our *scenario*). It relies on the progression presented in Tables 3 and 4. For each and every one of our questions or interventions, we indicate the probable reactions or the supposed effects. We also give some elements of the supposed cognitive process underlying. These predicted associations (question/reaction/cognitive process underlying) constitute the assumptions that we wish to put to the test of experimentation.

From that perspective, the research we present is close to a "teaching experiment", which has proven to be a valuable research method to investigate teaching and learning processes (Duit, 2000; Duit, Roth, Komorek, & Wilbers, 1998). Here

Table 4. *Scenario* of the teaching–learning sequences based on the supervised reading of the *Dialogue*

Local stages	Planned teaching	Supposed children reactions	Cognitive process
Stage 1: Elicitation of children ideas (Phase 2)	"Would you explain by writing or drawing how do we see the surrounding objects?"	The children draw and write	Awareness of spontaneous ideas about vision
		They disagree on the direction of vision	Socio-cognitive conflict
Stage 2: Unity in the functioning of the five senses (Phase 3)	"Please now read the beginning of the drama from A to B. What do you think about Simplicio and Sagredo's ideas?"	The children relate to one of the characters of the drama	Identification
	"Do you agree with Salviati when he asserts that all senses operate the same way? Why?"	The children accept the idea that the sensation is explained by the action of an external agent on a specific organ. They wonder about the nature of what penetrates the eye	Analogy reasoning
Stage 3: The phenomenon of blindness	"Read the drama from B to C and answer to the question asked by Salviati"	The children admit that light has an effect on the eye	Empirical reasoning that associates blindness with light (not to much light)
Stage 4: Diffusion and quantitative treatment of light (out of reading)	Teacher interrupts the reading of the text to discuss the subject of light being sent out by normally lighted objects: "Do you think you could be dazzled by an object? Does an object continuously sent out light?"	For the children, the light stays on the object when it is not strong enough to bounce. There is a threshold under which a lighted object does not send light anymore. This threshold fit the case in which their are not blinded by the object	Awareness of spontaneous ideas about diffusion : discontinuous reasoning empirically justified
Stage 5: Quantitative treatment of sight and analogy with hearing	"Please now read from C to D. Do you think vision and hearing operate the same way?"	The children agree with the analogy with the sense of hearing	Analogy reasoning for treating light in a quantitative way
		Some of them should realise that sound and light operate the same way : even if we feel no pain, sound can enter into the ear	Cognitive conflict
		Some of them should change their mind and explain that the eye may receive light even if no sensation is felt	Conceptual change

Table 4. *(Continued)*

Local stages	Planned teaching	Supposed children reactions	Cognitive process
Stage 6: Diffusion and model of vision	"Please now read from D to E. What do you think about the way vision operates? Compare with your first answer"	The children should admit that an object that is lighted sends out part of the light that it receives At the same time they may realise that the light sent out from the lighted object goes into the eyes and that is what makes this object visible	Conceptual change: continuous reasoning rationally justified Awareness of the conceptual change

Note: This table relies on the progression presented in Table 3 but only Phases 2–5 of this progression are detailed.

we play the part of both the interviewer (who tries to understand students' views and reactions and to control teaching effect) and a teacher (who tries to make the learners build a new explanation of vision). This method appears to be well suited for the first steps of designing teaching and learning sequences that can later serve as a basis for teaching in real classroom situations. In that case, the planned teaching presented Table 4 should be considered as a guideline and thus be used by any science teacher.

A Place for Argumentation

Following the presentation of a problematic phenomenon (stage 1: "how do we see the surrounding objects?") we think that plural viewpoints will emerge. Hence, this stage provides opportunities for students to be actively involved in a dialogic activity where a process of argumentation can be enhanced. In such manner, and mostly in a classroom context, knowledge can be co-constructed by the group:

> The group interaction enables the emergence of an understanding whose whole is more than the sum of the individual contribution. (Newton, Driver, & Osborne, 1999, p. 554)

From the 1990s onwards, there has been a considerable amount of research devoted to the role of argumentation in science teaching and learning. Investigators point to the view that argumentation has a role not only in developing a better understanding of the epistemic basis of science, but also in achieving a better conceptual understanding of science itself (Grace & Ratcliff, 2002; Newton et al., 1999; Osborne, 2005). Moreover, discourse-based activities generate great satisfaction for the students engaged in communication process while learning science (Nolen, 2003). Recent approaches explored the knowledge construction by students dealing with argumentative operation (Jimenez, Reigosa Castro, & Diaz de Bustamante, 2003). In doing so, they gave typical features of the arguments and justifications offered by the learners to their peers while involved in problem-solving, and proposed a framework for the quality of argument (Osborne, Erduran, Simon, & Monk, 2001; Osborne, 2005).

In the field of optics education, Erduran, Osborne, and Simon developed materials that could be used for supporting argumentation in the classroom. Presenting competitive theories of vision to students 12–13 years old (light travels from the eye onto object versus light reflects off objects into our eye), the authors analyse students discussions and abilities to use provided pieces of evidence in order to decide whether the evidence presented support the competitive theories. More specifically, they examine the explicit oppositions in children discourse and establish a five-level analytical framework for assessing the quality of argumentation. This enhances that most arguments belong to a level (Level 2) where argumentation consists of claims with either data, warrants or backings but does not contain any rebuttals (Erduran, Osborne, & Simon, 2005).

However, introducing argumentation into the classroom requires that science teachers be convinced that argumentation is an essential component for the learning

science. In addition, teachers must be offered practical pedagogical tool to implement argumentation in the classroom (Mortimer & Scott, 2003). From that perspective, our teaching–learning sequence can be considered as a guidance for supporting argumentation in the field of optics. Beginning with a question dealing with theory of vision, it opens the way for a discussion in the classroom based on an opposition in students discourse.

Following this sequence and the conceptual change underlying it, we hope that the students adopt a cognitive process in which their reasoning is no more referring to the principle of "all or nothing" ("light penetrates the eye", "I'm blinded; light doesn't come into the eye anymore", "I can see"), but it becomes a more complex reasoning expressed in terms of "too much", "enough", or "not enough" light: so one has to associate the feeling of blindness with "too much" light, vision with "enough", and the absence of vision with "not enough" light coming into the eye of observer.

Interview Analysis

All interviews were tape-recorded and transcribed for analysis. Each one of them was planned to last 1 h. The transcriptions allows us to compare learners' reactions with the ones we anticipated (Table 5). Doing so, we hope to bring out the elements that will allow us to assess the educational impact of this teaching-learning situation.

Stage 1: Controversy over the "direction" of vision

Five students (out of 12 questioned) explain vision with the sending of "something" from the eye designated with the terms "vision", "look", or a "radar". Three students say that the eye receives an "image" or a "thing" from the object. Light is spontaneously evoked only by one student. The latter has quite a satisfying interpretation of vision: "vision is the light which comes in the eyes". His explanation is nonetheless dismissed by a classmate; according to her, if light penetrates the eyes, one is blinded by it. Etienne and Julie (Binomial 5) do not argue over the direction of sight (they both consider it to be the object $\rightarrow$ eye direction), but over the nature of the entity that goes from the object to penetrate the eye. For Etienne it is light, but for Julie it is an image. In three binomials (out of the six interviewed for our research) the students express contradictory opinions.

Stage 2: Unity in the functioning of the five senses

We ask them to read the beginning of the Dialogue, from "I have invited you here today …" to "… smells in our nose". Following this first reading sequence, some students stress the fact that they recognise their ideas (and their disagreement) in those evoked by the protagonists of the conversation.

Our goal here is to bring the pupils to accept the fact that the sense of sight operates on a same pattern as all the other senses: the sense organ is stimulated by an

Table 5. Student's reactions step by step

Local stage	The students' reactions (N = 12)	Effective cognitive process
Stage 1: Controversy surrounding the direction of sight	Five students explain vision eye → object	When it happens, debate leads to argumentation
	Five student explain vision object → eye Two students do not give any explanation [*Three binomials express contradictory ideas*] [*One student explains that light is the stimulus of sight*]	
Stage 2: Unity in the functioning of the five senses	11 students explain vision object → eye	Identification proves to be efficient
	One student explains vision eye → object [*Two students explain that light is the stimulus of sight*]	Analogy reasoning is an operational process
Stage 3: The phenomenon of blindness caused by light	12 students (every one of them) explain vision in a object → eye direction [*Two students explain that light is the stimulus of sight*]	Everyday life observation becomes an efficient reasoning tool
Stage 4: Diffusion and quantitative treatment of light (out of reading)	Eight students explain that in the case of a normal vision, the light "remains" on the objects	When it happens, debate leads to argumentation.
	Four students explain that lighted objects continuously send back the light they receive	
Stage 5: Quantitative treatment of light and analogy with hearing	12 students (every one of them) explain vision in a object → eye direction [*Nine students admit that the light is the stimulus of sight and that normally lighted objects send back the light that they receive …*]	Analogy reasoning is an operational process that leads to a continuous reasoning (Stage 6, Table 4)
Stage 6: Diffusion and model of vision	12 students (every one of them) explain vision in a object → eye direction 12 students admit that light is the *stimulus* of sight [*Nine students admit that normally lighted objects send back the light that they receive*]	Conceptual change seems to occur thanks to a quantitative treatment of light

external agent. We ask them if they agree with Salviati when he asserts that all senses operate in the same way. All the students acknowledge the logical aspect of the Aristotelian argumentation and the explicit comparison with the other senses turns out to be convincing. Among the five students who had first expressed the idea of an eye → object direction, four admit that they might have made a mistake. This is the case of Océane (Binomial 3): "I think I might be wrong. It must probably work like sound. There's a thing that goes into the eye".

All the students having changed their minds about the direction of sight seem convinced with the validity of Salviati's reasoning, but find themselves faced with the difficulty of identifying the entity that penetrates the eye. So, for Florestan "it would be logical for all the senses to function the same way, but what's the thing that goes into the eye?" Annabelle (Binomial 1) asks a similar question: "I think something goes into the eye, but what? It must be something that we don't know about yet."

After the second stage of the interview, 11 students (out of 12) seem to be convinced that vision of an object is the result of an external agent's action on the eye, coming from this object. The beginning of the Dialogue confirmed the explanations of the students who had made the assumption that vision worked with the object → eye direction, and it convinced almost everyone else of it. The analysis of this second stage of the interview allows us to think that the theory in which all senses operate in accordance with a modality based on "passion" leads the students to consider vision in the object → eye direction. And even though the identification of the *stimulus* remains very difficult, it fascinates all of them.

Stage 3: The phenomenon of blindness caused by light

The second phase of the interview ends with the question about the nature of the entity that comes from the object into the eye. We ask the students to read Salviati's line from "… we have the sensation of taste …" until "… for 10 seconds?", and to answer the question asked by Salviati. All the students answer that staring at the sun is unbearable and dangerous. Some associate the fact that we are blinded with the entry of sunlight in the eye. For Kevin (Binomial 6), it is impossible to stare at the sun because in that case "light comes into our eyes". On the other hand, in three binomials the reasons put forward explicitly take into account the excess of light that goes into the eye. Thomas (Binomial 3) speaks of a "surplus of light on the retina". These answers show the beginning of a quantitative reasoning.

Stage 4: Does the light "stay" on the normally lighted object?

We then asked them if they think they can be blinded by an object and to describe what happens in this case. We intended to check out the subjective existence of a threshold from which light would "stay "on the object that is observed. This would mean that diffusion is not perceived as a phenomenon associated with lighting. To

the question "Do you think you could be dazzled by an object?" most of the students reply that it is possible, provided that the object is either a mirror or very strongly lit. According to Alexis, we are blinded because the light "bounces" on the objects and hurts the eyes. This is also Camille's opinion; according to her, "the light comes on the objects, rebounds and attacks the eye". As we expected, the majority of the students link the entry of light in the eye with the sensation of dazzle. They realise that objects send out light when they are blinded by these objects. In that case the light is so "strong" that it rebounds on the objects. In other words, for some students there is a point from which light is not sent out by objects and this point is determined by sensorial perception only (the fact that they are not blinded anymore). Eight students (out of 12 interviewed) say that the moment when the blindness stops coincides with the moment that the light "stays" on the object. Kevin and Florestan (Binomial 6) are among this group of students:

Teacher:	Do you think we can be blinded by something else than the sun/by an object for instance? Could you be blinded by this pen here?
Florestan:	If the light is very strong it can be reflected // It's reflected on the pen and it goes in the eyes and we are blinded
Teacher:	And when do we stop being blinded?
Florestan:	When the light is not reflected anymore.
Kevin:	It stays on the objects.

For these students, the moment when the blindness stops coincides with the one when the light does not go into the eyes anymore. And that moment coincides with the one when objects do not send out light anymore. Four students support the opposite opinion. For them, objects continuously send out the light that they receive and we just do not realise it. So, for Charles (Binomial 2), "The light always moves back but we don't realise that, it's as if it didn't move back; it's very weak". At that moment in the interview, we could not really know whether Charles made the connection between vision and the entry of light in the eye.

After this fourth phase, two students (Etienne and Thomas) give an interpretation of vision that meets our expectations. Two other students (Camille and Charles) say that lighted objects send back the light they receive without linking this phenomenon to a sensation of disturbance or blindness, but we do not know whether these students associate the fact that we see objects with the light that these objects send out into the eye of the observer. The other eight (i.e., the great majority) admit that objects send out light only when the light is strong enough to "rebound". In that case it penetrates the eye of the observer, who is therefore blinded by it. So for these students, the entry of light in the eye is a restrictive factor for the sense of sight.

Stage 5: Quantitative treatment of light and analogy with hearing

We invite the students to move on with the reading of the text from "what a strange idea!" up until "… allows us to hear". We wish to measure the effects of an analogy with the mechanism of hearing. The second phase of the interview enabled us to see

that students seemed to have difficulties with the parallel between the senses of sight and hearing. Some of them stressed the fact that it was hard for them to find an equivalent of sound for the sense of sight. In this new phase of the interview, Kevin and Florestan (Binomial 6) seem sensitive to the analogy proposed by Salviati even if they have some doubts about it:

Kevin:	Well it seems, it seems what we said before is not right.
Teacher:	What do you mean?
Kevin:	Well, objects always send out light, and that's what makes it possible to see them.
Teacher:	And so we're not dazzled?
Florestan:	No, it's a question of quantity // quantity
Teacher:	Explain that to me.
Florestan:	Well, vision // vision is when light goes in the eyes, but not too much. It's the happy medium.
Kevin:	But, you know, what's weird is that we don't realise it, whereas we can hear sounds. But we can't see light.

The analogy with the sense of hearing brings Kevin and Florestan to propose a correct explanation of the mechanism of vision in which light is considered in a quantitative manner: "It's a question of quantity", Florestan states. For the two students, it seems that the entry of light into the eye is no longer considered as the cause of a disturbance but as the cause of vision. Kevin reconsiders his previous assertion—"objects do not send light"—to eventually say that "objects always send light" and "that's what enables us to see". He realises that this "weird" interpretation requires a certain effort of imagination: "we don't realise it", as sound is not comparable with light—"we can hear sound, but we don't see light". The *light* that is referred to here is neither the primary source nor the bright, lighted area; that is to say, the "light that can be seen". In turn, Kevin affirms that *light* is an invisible entity. After this reading sequence, Kevin, Florestan, and Charles develop a new conception of light and vision, clashing with their initial representations. It is the same for Alexis (Binomial 4):

> It's not the same as what we said before. In fact, it always penetrates the eyes when we see things. It's just that there is less of it. And so, we don't feel it.

Again, the analogy with the sense of hearing lead Pierre and Alexis to treat light in a quantitative way in order to build a model of vision that would be rationally acceptable. It is an identical reasoning that enables Océane (Binomial 3) to agree with her classmate.

> Well, he's right, we can't feel the light but it still penetrates the eye. It's just that there mustn't be too much light if we want to see. It's a question of quantity.

Following this fifth stage of the interview, nine students (out of the 12 affected by our experimentation) acknowledge the fact that light is the *stimulus* of the sense of sight. The analogy with the sense of hearing seems to bring them to think of light in a quantitative way. Diffusion of light therefore becomes a phenomenon associated with lighting and not a consequence of the great quantity of light that hits the

object. The majority of the students question the idea of a point under which light would not be sent out by the objects and blind the observer. This blindness and the penetration of the eye by light become facts, the association of which is no longer exclusive.

Stage 6: Diffusion and model of vision

The interviews continue with a last reading phase. We ask the students to read the text until the end (from "if I have understood …" up to "… I find your theory very convincing"). We then ask them what they think of Salviati's reasoning. All the students who, prior to that reading phase, had explained vision the right way see their opinions confirmed by Salviati's words, and that fills them with enthusiasm. As the reading comes to an end, all the students seem to admit that seeing an object requires that the object sends out light into the eyes of the observer. This sixth stage may appear to be more direct than the ones before as the model of vision is presented by Salviati in the text. However, it is important to us to remember that the explanation of Salviati is actually a support for confirmation for 9 out of 12 students questioned. Moreover, we must point out the fact that it is not given immediately, but it is the end of a cognitive path that all the students have taken. It has enabled them to become involved in research processes, to formulate assumptions illustrated by a certain number of thinking experiments.

What did the Children Think about the Dialogue …?

After each interview, we wanted to have the students' feedback on the proposed teaching sequence. Many of them spontaneously mention the historical dimension of the Dialogue and, according to them, there are a lot of benefits linked to this dimension. The history as we staged it in our text enables the pupils to have access to how people saw things in the past. That is what most of them seem to appreciate—like Julie (Binomial 5), "It's interesting to talk about people, what they did and what they thought before", or Kevin, "it's funny to see that we said the same thing they did". The interest in the theories of scientists of the past is also stressed by Océane (Binomial 3):

> I enjoyed it. This is history of science and it's good because you can become aware of what people thought before. Moreover, what I said earlier [The eye sends a vision] was like the beginning of the text so I think it's reassuring to see that some people had the same idea.

The argumentation developed by Océane shows that the fact that students are given the opportunity to relate to the characters of the text has some positive effects. On the one hand, the fact that they can link their ideas to the ones of their elders seems to help the students make the significance of their mistake less alarming; and, on the other hand, it develops their answers when they are correct. This is the case for Etienne (Binomial 5)

> I knew that the theories of the beginning were not good and it feels good to contradict a scientist and be right.

Thanks to the fact that students can relate to scientists of the past, the history of science becomes an effective tool of enhancement and also a learning tool, as identified by Morgane (Binomial 2): "In fact, comparing the way we understand things to the way they did before, it can help us later if we have the same problem as them". Because she witnesses the thought processes leading to the elaboration of an optical explanation of vision, the historical perspective becomes a learning tool for some students, a means to understand how knowledge is built up. Aside from the motivations linked to the history of science itself, the reasons stated mostly concern a possible identification process from their ideas to the ones developed by the characters of the text. But what seems essential to us is that the characters are recognised as supporters of theories that have existed. In other words, the Dialogue does not seem to be perceived as an inventory of imaginary theories with no historical credibility, but as the believable staging of a controversy that could have really taken place in the past. The fact that the names of certain scientists are mentioned contributes to the fact that this text is identified as a historical support by the students.

Conclusion

Thanks to the reconstruction of the history of theories of vision, we have pointed out the different ideas that would constitute the key steps of our teaching sequence: One must first consider the five senses according to a common modality of functioning based on "passion", accept that light affects the eyes, and break, with a thought experiment, the exclusive link that associates the feeling of dazzle with the fact that light penetrates the eye. This last step is conditioned by a quantitative treatment of light. These steps therefore constitute the framework of our text and the stages on which we have built the scenario of our interviews. Following the analysis, we noticed that the same ideas enabled the students to question their original representations and progressively replace them with a satisfying explanation of the mechanism of vision. Consequently, in the limited field of the optical mechanism of vision, it seems conceivable to adapt and not transpose a historical progression to an individual process of knowledge acquisition.

This look back on the history of the theories of vision gives us the opportunity to reflect on the question of supposed analogies between the historical development of ideas and the individual process of assimilating scientific knowledge. In his essay on optics, Alhazen relies on a situation of dazzle to convince the reader that light has an effect on the eye. This empirical acknowledgement leads him to formulate the idea that vision is the result of light penetrating the eyes. The evocation of a situation of being dazzled by light leads the majority of the students to think that the entry of light in the eye prevents vision. What appears to be a historical condition of the development of ideas in optics constitutes a major obstacle to the students' understanding of the mechanism of vision. Focusing on the students' reasoning enables us

to realise the effort of abstraction made by Alhazen. A few years ago, in an identical context, Thomas Kuhn the philosopher wrote:

> Part of what I know about how to question dead scientists has been learned by examining Piaget's interrogations of living children. (Kuhn, 1977, p. 21)

If the historical analysis gives an idea of the level of difficulty of a teaching matter, science education enables us to propose a particular reading of the history of theories of vision and contemplate a conceptual path from a specific point of view. The ideas that have stood out come directly from the history of science, and we organised them in reference to the difficulties that the students face. It was done in order to help a learning process that favours the understanding of a rather abstract explanation. Of course the controversy over the "direction" of sight exists among the students and in the history of science. We took advantage of this parallel to create a teaching–learning sequence that is based on the fact that students predictably relate to scientists who have their place in history. Furthermore, this teaching–learning sequence makes students become aware of their own cognitive process. Indeed, some of them were able to clearly analyse the elements that helped them to change their spontaneous ideas.

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Appendix. Dialogue on the way vision operates

Sagredo: **[A]** I have invited you here today so that we might talk about the way vision is made and functions.

Simplicio: I fear, my dear friend, that our discussion may be difficult as I do believe that Salviati and I have conflicting opinions concerning this subject. It is my belief that the reasons of vision lie in the eye. As numerous ancient scholars have suggested, I believe that to see an object, the eye must send something towards this object. Thus, I imagine that we can see the objects around us thanks to this ability we have to emit something which, coming out from the eyes, goes in the direction of the objects to be seen.

Sagredo: It seems to me that all the Greeks did not reason that way. Is it not true that Lucretius and others before him explained the vision of an object through the entrance into the eye of an image of that object?

Salviati: First and foremost, I am very glad to talk to you about Lucretius. The beauty of his texts moves me every time I read them. And if you should not share his opinion, I nonetheless hope that you will be able to appreciate the greatness of his poetry.

Sagredo: Do not keep us waiting any longer.

Salviati: Listen to me then: "Among all objects, there are some which we call shams: they are sorts of light membranes which have detached from the surface of the bodies and which flutter about in the air in all directions. They are shadows or images sent out by objects. Besides, many of them can be seen emitting their elements, like smoke coming from green wood or heat from fire, or even the shells that cicadas abandon in the summer. Another example could be the yellow, red or green veils which, stretching above the audience in vast theatres, lit by torches or daylight, colour the stage with their reflections."

Simplicio: This theory seems absurd to me: how can you explain that exhalations detached from immense objects, such as mountains, can penetrate our eye which, on the contrary, is extremely small?

Salviati: I would like to remind you that by presenting Lucretius's ideas to you, I have done nothing but answer Sagredo's request. I never told you that I shared his ideas. Indeed they present some inconsistencies. Nevertheless, they seem to me to be closer to my personal theory than yours.

Sagredo: Then you think that if we see, it is because objects send out images of themselves into our eyes?

Salviati: That is not what I am saying. Nevertheless, this theory teaches me that vision is the result of an action onto the eye. And what seems to me to be interesting here is that vision is regarded as a passion, that is as the reception into the eye of something coming from outside.

Sagredo: Do not all our senses function on this principle?

Salviati: That is a crucial point you are bringing forward, Sagredo. If Aristotle is to be believed, it seems that the five senses all function in the same way. They are the result of an external action (stimulus) on a specific organ called the sensory organ. Each organ finds itself affected by specific impressions coming from objects. Thus, we can hear because we receive sound in our ear, we can feel because we receive…

Simplicio: …smells in our nose…**[B]**

Salviati: …We have the sensation of taste because our mouth receives flavours, and so on. And as my objective is to convince you that vision is a passion, inasmuch as it is the result of an action onto the eye, I have here an argument which no doubt will convince you more than any other. Please allow me to first ask you a question: Do you think you can stare at the Sun for ten seconds? **[C]**

Simplicio: What a strange idea!

Sagredo: Of course not, that would be much too painful, and it would damage one's sight.

Salviati: Precisely. And do you know why?

Sagredo: No doubt because the light coming from the Sun is too strong.

Salviati: Exactly. You admit then that too strong a light provokes painful effects on the eye, and that, therefore, the eye is sensitive to a light that is too strong. You cannot think that there is something which goes from the eye toward the object because, in this situation, there would be no reason to suffer in front of a particular object rather than in front of another. If one is dazzled while looking at the Sun, it is undoubtedly as a result of the strong light entering the eye.

Sagredo: I agree with you altogether, dear Salviati, but do not forget that we are trying to understand the manner in which we see, not the manner in which we do not see. Whereas the situation you describe, that of being dazzled, is totally different from vision.

Simplicio: You are wandering from the point, Salviati. Sagredo is right, the entrance of light into the eye prevents one from seeing.

Salviati: Allow me to correct you, Simplicio. You say: "the entrance of light into the eye prevents one from seeing", and I say, the entrance of a very strong light into the eye prevents one from seeing. Can you mark the difference?

Simplicio: Certainly. However, I cannot see the point you are trying to make. Are we not here to talk about the way vision is made? Come straight to the point, I beg you.

Salviati: Unfortunately, I cannot convince you straight out of the validity of my theory. I will need some circumlocutions. You will notice that whenever you are dazzled, the unpleasant sensation lasts for a certain time, preventing you, among other things, from reading for a while. Thus, a strong light does not only affect the eye but also the sight. Exactly the way too loud a sound hurts our eardrum whereas a moderate sound reaching our ear allows us to hear. **[D]**.

Sagredo: If I have understood your comparison, dear Salviati, a moderate light would allow us to see.

Simplicio: But this is absurd! When we look at the world around us, we see objects which do not emit any light towards us. If it were the case, we would be perpetually dazzled!

Salviati: Calm down please, Simplicio, and try to follow my way of reasoning. Is it not true that to see an object which does not emit light by itself, it is necessary to light it?

Sagredo: Indeed, nobody would ever imagine to think that it is possible to see in the dark.

Simplicio: Only cats are capable of that.

Salviati: Let us leave cats alone for a while, if you do not mind. They certainly do not see better in the dark than you or I. So, to see an object, it has to be lit. The less an object is lit up, the less visible it is, and the more it is lit up, the more visible it is. If however, it is too lit up, sight is impaired and the vision of this object turns out to be impossible. Do you not think that this phenomenon is similar to the one we have already mentioned, that of being dazzled when we look at the Sun?

Sagredo: Certainly. An object lit by a very intense light behaves exactly like the Sun. It reflects into the eye too strong a light, and this light hurts the eyes. That is what happens for instance when one looks at snow on a sunny day.

Salviati: Well! Now you take the light into account! Imagine now that this lighting progressively diminishes. The fact that you see this object implies that it is still lit, doesn't it? And the fact that you see it perfectly and that you manage to make out its smallest details, means that you are not hindered by the entrance into your eye of too strong a light. In that case then, what has changed is not the entrance of light into the eye, but its quantity. In other words, the eye feels the sensation of light, and this sensation depends on the quantity of light which penetrates the eye. A man can see when the quantity of light emanating from objects and penetrating his eye is neither too strong, nor too dim. This theory was developed by a very famous arabic scientist called Alhazen.

Simplicio: Does that mean that all the objects surrounding us continually emit light into our eyes, even though we have no evidence of that?

Sagredo: You believe there is no evidence? Is the mere fact that you see these objects not the evidence that light is sent?

Salviati: I see, dear Sagredo, that you seem to be convinced. Simplicio, what do you think?

Simplicio: I must admit that I find your theory very convincing. **[E]**.