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Maurines, Laurence

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This particular study is part of a research programme on the difficulties encountered by students when learning about wave phenomena in a three-dimensional medium in the absence or presence of obstacles. It focuses on how students reason in situations in which wave optics needs to be used: diffraction of light by an aperture, imaging in the presence of diffraction, and coherent illumination imaging. Paper and pencil questionnaires were designed and two hundred French students (aged 19 to 23) were questioned after lessons on wave optics. Tendencies towards geometrical reasoning are shown to recur. Students reason at a macroscopic level, following the rays of the incident light, instead of reasoning at an elementary waves level in using the phase concept and the Huygens-Fresnel principle. Consequently, for them, the image of a point source located at infinity is behind the image focus plane of the lens when diffraction has to be considered. Moreover, it is not possible to have the image of the source and of an illuminated diaphragm behind one lens: these images cannot exist simultaneously or are merged. Some remarks are made on the way waves are taught in France and some pedagogical implications are discussed.

1. INTRODUCTION

From a constructivist point of view of learning, the knowledge that is to be taught and the students' ways of thinking have to be analysed before deciding course content and designing pedagogical units. This is why for nearly forty years, numerous studies have analysed pupils' and students' ideas in many areas in physics. This particular study is part of a research programme aimed at facilitating a discussion of the learning and the teaching of waves (mechanical waves, sound, and light) at the upper secondary level and university level and at helping in the development of innovative pedagogical units. It focuses on situations in which wave optics, more precisely scalar wave optics, has to be used. This area of physics has become a subject of great importance since the development of the laser. Practical applications of the wave model of optical imaging exist in many fields, in particular in those of television and photographic enhancement and microscope improvement, to list only a very few (Hecht, 1987).

Optics is a domain of physics which involves many different models. Sometimes it is easy to choose the model to be used; sometimes not. So this is a useful area in which to help students have a better understanding of modelling. This means that students are expected to know the concepts and laws on which each model is based and to be able to choose the model that has to be used in a given situation. This also means that students should know that some models can explain more situations than others and that models are intellectual constructs which explain or predict phenomena but are not the phenomena themselves. So, when students have to learn wave optics, for them it is not a question of changing systematically from a mode of reasoning based on geometrical optics to another mode of reasoning based on wave optics; it is instead a question of using these two ways of thinking in appropriate situations. We can account for the conceptual evolution of a student's way of thinking with the model of conceptual profile proposed by Mortimer (1995) and inspired by the notion of epistemological profile advanced by Bachelard (1975) for the history of a scientific concept. The two profiles present different zones corresponding to the different ways of conceiving a scientific concept, each successive zone having a more explanatory power than its antecedents. They also include a zone corresponding to pre-scientific ways of thinking strongly rooted in common-sense reasoning. According to this model of conceptual change, learning science means changing or modifying a conceptual profile and becoming conscious of the different zones of the profile.

We shall focus here on three wave situations: diffraction by a small aperture, imaging in the presence of diffraction, and imaging of transparent objects illuminated by coherent light. Diffraction and optical imaging are taught at different levels of scientific education in France. Diffraction by an aperture is introduced qualitatively for the first time in upper secondary school (grade 12) and studied quantitatively with scalar wave optics in the second year of undergraduate studies in physics. The formation of images by lenses is part of the programs of lower and upper secondary school (grades 9, 11, and 12) and of the first year of undergraduate studies. The defects in images caused by diffraction are introduced qualitatively in grade 12 and studied quantitatively in the second year of undergraduate studies in physics. Coherent light imaging is generally taught in the third year of undergraduate studies in physics. It is only at this level that the wave model of optical imaging is studied thoroughly. Prior to this, optical imaging is studied with geometrical optics except when teaching the defects in images caused by diffraction Consequently, it is fair to consider the ways in which students understand the wave situations we investigate and the explanations they develop. Do they base their reasoning on wave optics as they should do, or on geometrical optics, or on something else?

In the studies presented here, conducted among students who had lessons on wave optics, we are not concerned with studying the "spontaneous reasoning" that exists before learning about such or such physical phenomenon. We highlight the difficulties encountered by students in mastering the principles and concepts of the wave-geometrical model by analysing how students reason post-instruction. We are interested in the differences between students' reasoning and scientific reasoning and in the general ways of reasoning that teachers can observe in their classes; we are not interested in the reasoning of a given student. We focus on students' errors even if students' answers may be partially right, especially since the students had lessons on wave optics. However, we obtain information on some components of the students' knowledge which can be considered as correct under certain circumstances. These components can be emphasised in teaching in order to help students to construct new ideas. As often occurs in this type of study, it is first of all a question of tracking students' errors; then we must try to understand what aspects of these errors are due to teaching and what can be attributed to pre-existing ways of thinking acquired before the lesson.

The research on the knowledge and ways of reasoning used by pupils and students is not unified (di Sessa, 2006). In fact, there are many orientations and theories of conceptual change and many ways of analysing students' thinking. When we started our research programme on three dimensional wave phenomena in 1994, we chose to analyse the conceptual difficulties encountered by students because there was no such study and because waves were known to be a difficult topic to teach. Since some studies have revealed that students who have correct ideas of science and modelling also have a better mastery of models, it seemed worthwhile to explore the question of the role of this 'meta knowledge' on the understanding of wave optics, especially since optics involves different models. It could be the next stage of this research programme.

Another question that is discussed in the research on the students' knowledge concerns its epistemic structure: is this knowledge coherent or is it only in pieces? Following Minstrell (1992) and di Sessa (2003, 2006), we defend the idea that both features appear, depending on the point of view we are considering. It is possible to indicate cognitive constructs, more or less dependent on their context. When comparing the answers and explanations given in different situations by students, their knowledge seems to be in pieces and without consistency, especially before the lesson. Indeed, students can first use different cognitive patterns in situations that are explained the same way by physics; second, students are sensitive to the way the situations and questions are presented; third, students do not necessarily seek coherence, especially since they are not conscious of their ways of thinking. But, it is possible to emphasise that the students' answers are the local manifestation of typified tendencies of reasoning that are encountered throughout these situations. Moreover, we demonstrate that the typified tendencies we indicated in the wave situations investigated appear in other situations dealing with waves, and more generally in other domains of physics. Following Peterfalvi (1997), we maintain that these transversal tendencies are the true obstacles to learning. Errors correspond to the ways these tendencies are revealed in a given situation. Thus, we have attempted to provide a coherent and synthetic description of the answers given, and more specifically of the errors made, by students by organising them according to a small number of characteristics. Like the models used in other fields, the model of the students' reasoning that we advance is not a simple description of students' answers. It also includes interpretive elements introduced by the researcher that assume how students think: Its strength is intended to be more than a catalogue of unconnected "pieces of knowledge" consisted of a list of errors. It gives meaning and coherence to the answers given by students to various questions in a large variety of situations concerning waves. We realize that a given student's reasoning will not necessarily conform completely to the model we advance. We hypothesise that the tendencies we have isolated for students' to reason in a particular ways– even if these tendencies have not been observed in the majority of students – may occasionally appear in the reasoning of any given student. It is also possible that the student's reasoning relies on other characteristics which we have not focused on, in particular the 'piecemeal' application of correct scientific reasoning.

When we started our research programme on wave phenomena in a three dimensional medium in the absence or presence of obstacles in 1994, situations requiring the use of wave optics were even less explored by science education researchers than others. It is still the case that most studies relating to light concern situations in which the geometrical model of light can be used. In particular, studies can be found on vision, on the formation of shadows and of images made by a lens or a mirror (Fawaz and Viennot 1986; Feher and Rice 1987; Goldberg and Mc Dermott 1987; Kaminsky 1989; Galili 1996). With the exception of our work in this domain, only a few studies on light concern situations in which the scalar wave model of light (Ambrose et al 1999; Colin and Viennot 1999, 2001; Romdhane and Maurines 2003, 2005; Romdhane 2007) or the electromagnetic model (Wosilait et al 1999) are necessary. Other studies relating to waves deal with the propagation along one direction of visible mechanical signals (1992; Wittmann 1999) and of sound (Linder and Erickson 1989; 1993, 1997, 2003; Wittman 2003). The particular study presented here, thoroughly published in French only (1997, 1999, 2000), is still supplementary of these studies since the situations explored and the questions asked are different. Moreover, it presents a part of the analysis of the physics content which we conducted during our research programme on the difficulties encountered by students when learning waves. This content analysis (see the overview of our research programme, 2001a) gave us the framework to compare the students' answers with. It led us to clarify some confused points and to give a new look into the physics of waves. Finally, the approach we chose in examining the difficulties encountered by students is still original since it consists in looking for a model of students' reasoning valid in a large variety of situations concerning wave phenomena (mechanical waves, sound, and light).

The research questions we chose to explore were determined by the analysis of four related topics: the physics used in the situations investigated, the history of optics, the textbooks used by students, and the difficulties encountered by students in the field of optics and waves previously put forth by science education researchers. This analysis was begun before carrying out the enquiries among the students, continued when questioning students in taking into account their answers, and later refined. For the sake of brevity, we will not present here the results of the analysis of the history of optics (for details, see the overview of our research programme, 2001a). We will only emphasise how the light situations investigated are explained using the scalar wave model, which we called the wave-geometrical model. Indeed, this will be useful when we present the problems we have explored, as well as in our analysis of students' answers and discussion of the pedagogical approaches used in textbooks.

We will delineate the main trends of reasoning used by students and show that some of them are close to the spontaneous ways of reasoning we presented in our first studies on mechanical signals among students who had not had class instruction on waves (1992, 1993). Thus, some ways of reasoning are revealed to be highly resistant to change: encountered before lessons on waves, they adapt to new situations and can be found at a high level of teaching, even among teachers. We will also confront our results to those published by other science education researchers on the conceptions on waves and show that the model of students' reasoning we advance can account for them.

We begin by presenting some remarks on the wave and geometrical models of light and the questions investigated. Then, we describe the methodology used in the enquiries before presenting and discussing some results. Finally, we make a few remarks on the way waves are taught in France and show some of their pedagogical implications.

2. FRAMEWORK

2.1 Some remarks on the wave and geometrical models of light

As we have already noticed, optics is an area which involves different models. For the sake of brevity, we cannot present here all the models which can be used in the situations investigated. We will focus on the two models that are taught in undergraduate studies: the classical geometrical model that we refer to here simply as the geometrical model; the wave geometrical model, based on the Huygens-Fresnel principle, whose name we abbreviate here as the wave model. Details on the modern geometrical model, the spectral model based on the Fourier transform, and the electromagnetic model can be found in (1999, 2000, 2001a). Moreover, for the same reasons of brevity, we cannot present all the situations investigated. Details on the spatial filtering experiment called the central dark ground method and the properties of rays and point sources in wave and geometrical models can be found in (1999, 2000, 2001a, 2002).

Let us first examine how these two models explain what is observed on a screen placed behind an aperture lit by a parallel beam of light that is parallel to the optical axis. When the luminous spot observed on the screen has the same size as the aperture, the rectilinear propagation law of geometrical optics is sufficient to explain the form of the spot. When this is not the case, diffraction by the aperture is said to occur, that is to say *'any deviation of light rays from rectilinear paths which cannot be interpreted as reflection or refraction'* (Sommerfeld 1967, p.179). In this situation where the size of the opening is not large enough compared to the wavelength of the light[i], it is necessary to use a wave model of light. In the scalar wave model used when the point of observation is far away from the aperture[ii], a light wave is characterised by a scalar field described by a function of space and time. For example, in the case of the propagation along one direction of a plane monochromatic wave, the field can be described by a sinus function of x and t: $y(x, t) = a \sin(\omega t - kx)$. In order to explain why the spot observed on a screen placed behind the aperture is not similar to the aperture, we must first decompose the aperture into infinity of fictitious sources (Huygens sources) and consider that they have a constant phase relationship since the incident light is a plane wave (the Huygens sources are coherent). Then, we have to consider that the waves emitted by the Huygens sources form a single resultant wave. The wave surface of the resultant wave is the envelope of the wave surfaces of Huygens waves (Huygens principle) and its rays, that is to say the direction of energy propagation, are perpendicular to this wave surface. In order to determine the distribution irradiance on the screen, we have to use the amplitude superposition principle derived from the field superposition principle: the amplitude[iii] of the resultant wave is the sum of the amplitudes of all the Huygens waves. As the Huygens waves interfere constructively and destructively, it is possible to have bright and dark fringes surrounding a central spot. The smaller the width of the aperture, the wider the bright central spot will be because the difference of phase of the waves emitted by the Huygens sources placed on the edges of the aperture is even less when the aperture is small.

So in a situation where diffraction cannot be neglected, two levels have to be considered: the level of the elementary Huygens waves and the level of the resultant wave, which we have called the macroscopic level, for lack of a term commonly used. Figure 1 shows the two types of drawings relating to each of these levels[iv]. In a situation that involves propagation, it is sufficient to use the rectilinear propagation law of geometrical optics and consider only the macroscopic level. What has been said can be generalised for other types of waves.

Figure 1 about here

Let us examine now how each model, the geometrical model and the wave model, explains the formation of the image of an object placed in front of a lens. Following Goodman (1972), the term image as we use it refers to the distribution of light intensity, which looks like the object and which can be observed under certain conditions on a second plane called the conjugate plane of the plane where the object is located. The properties of this image (position, shape, distribution of light intensity) can be explained by the geometrical model of light in geometrical situations, that is to say when the object can be considered as a source of incoherent light (extended primary source of light or object lit by such a source of light) and when the image of a point is a point. The wave model has to be used in wave situations, that is to say when the image of a point is not a point[v] or when the object can be considered as a coherent source of light (point source emitting a monochromatic light or laser, object lit by such sources). In geometrical situations, the wave model led to the same results as the geometrical model but took much longer to apply!

When the image of a point object can be considered as a point, the optical device is said to be stigmatic. This image is the stigmatic or geometrical image of the point object. In that case, all the rays of light issued from the point object and passing through the lens obey the laws of the geometrical optics. The emergent rays are rectilinear and converge at the same point, the stigmatic image. The position of this image can be obtained by taking the intersection of two rays issued from the point object. When the point object is far away from the lens, *ad infinitum*, the beam of light emitted by this point is parallel and its image appears in the focal plane of the lens. When the point object is nearer, the beam is no longer parallel and its image is no longer in the focal plane of the lens.

In wave optics (Goodman, 1972), the wave behind the lens is considered as the superposition of the waves emitted by the coherent Huygens sources of the emerging wave surface. It is possible to demonstrate that the best reproduction of the object, 'its image', may be found on the plane predicted by the geometrical optics, the conjugate plane of the plane where the object is located. On this plane, the wave amplitude distribution corresponds to that given by the Fraunhofer diffraction of the incident wave by the lens. It is equal to the Fourier transform of the wave amplitude distribution on the emerging wave surface. When the diffraction by the lens can be neglected[vi], the wave amplitude on the conjugate plane is non-zero only at a point coinciding with the geometrical image of the point object. When the diffraction by the lens has to be considered, the wave amplitude is non-zero on a small area surrounding the geometrical image. This bright spot is the spread image of the point object and its shape depends on the shape of the aperture limiting the emergent wave.

Consequently, geometrical optics is sufficient to explain where and how the image of a primary point source exists when diffraction is neglected. Wave optics is necessary when diffraction has to be considered. As in the case of the propagation of light through an aperture, two levels are considered in the wave-geometrical model and only one in the geometrical model. Figure 2 presents the types of diagrams used in each model[vii].

Figure 2 about here

Finally, let us examine how the image of an extended object is obtained in each model. In geometrical optics, the position and the shape of the image of an extended object are obtained by decomposing the object into incoherent point objects and in taking their images. The image irradiance is obtained by applying the energy conservation law and adding together the intensity of the waves emitted by all the incoherent point objects (photometry). In wave optics, the image of an extended object (primary or secondary source) is also the superposition of the images of all the point objects. But in that case, the image of a point object is obtained by the wave method mentioned above, and the point objects may be coherent or incoherent. This depends on the nature of the light emitted by the object, when the object is a primary source, or on the nature of the light illuminating the object, when this object is a secondary source. In order to obtain the irradiance distribution of the image of the extended object, wave amplitudes have to be added up in the case of coherent illumination; otherwise, in the case of incoherent illumination, wave intensities must be added up. What has been said also applies to transparent objects, whether they are objects which change the wave amplitude (for instance a diaphragm) or objects which change the wave phase (for instance, a very thin specimen observed through a microscope).

In both types of illumination, there is not only the image of the illuminated object behind the lens but also the image of the light source. These two images are not at the same place along the optical axis: in order to take a picture of the image of the illuminated object (for example, in the case of an object observed with a microscope), it is necessary to focus the camera on the conjugate plane and not the focal plane. The shape of the image of the source depends on the nature of the illuminated object (diffracting or not) and is explained by wave optics in the first case and by geometrical optics in the second case. It must also be noted that the nature of the light illuminating an extended object, and consequently the nature of the model giving its image, depends on the size of the source of light[viii]. If this source can be considered as a point, the light is coherent.

The image of an extended object lit by incoherent light and the image obtained with coherent light can be regarded at first approximation as identical. In fact, the type of illumination affects the quality of the image and this influence is very complex (Goodman, 1972)[ix]. On the other hand, the properties of the images are different in spatial filtering situations, that is to say when little masks are placed in the back focal plane of the lens. For example, when a small stop is placed at the image focus of the lens, the shape of the image observed beyond it is changed when the illumination is coherent and when diffraction[x] is considered. When the illumination is incoherent, the shape of the extended object is not changed[xi]. Only the light intensity decreases slightly. For details on the explanation of these experiments, and on the properties of rays and point sources in both situations, see 1999, 2000, 2001a, 2002.

In conclusion, we must remember that geometrical optics can be used only in the case of incoherent illumination and scalar wave optics must be applied in the case of coherent illumination[xii] or when diffraction has to be considered.

2.2 Questions explored

Our research on mechanical waves propagating along one direction (a bump on a rope or a sound in the air, 1986, 1992, and 1993) has shown that students' reasoning consisted of following a travelling shape considered as a whole and as a material object. The question which next presented itself was to examine how students reasoned in the case of three dimensional phenomena and whether they also focused on a travelling shape considered as a whole. We decided to explore this question in particular in situations where the Huygens-Fresnel principle had to be used (1997, 1999). Indeed, since the application of this principle must consider a wave as the result of the composition of an infinite number of elementary waves, it seemed to be incompatible with the kind of reasoning that we supposed students would use. So we first examined how students described and explained what happens to light when it passes through a 'small' aperture and how they visually formulated their ideas in drawings.

Second, as we actually pointed out that students do not use the Huygens-Fresnel principle in diffraction situations but tend to consider the aperture as a whole and follow the rays of the incident light through the aperture, we wanted to explore the consequences of such reasoning. So we started a second study on imaging in the presence of diffraction (1999, 2000). As the rays of the light propagating behind an aperture illuminated by a parallel beam are no more parallel when diffraction must be considered, we examined whether, for students, a point source is imaged when diffraction must be considered and where this image is when it exists.

We found that the kind of reasoning which consists in following the rays of the incident light through the aperture was also inconsistent with the existence of the image of a transparent extended object illuminated by a coherent light because it supposes the consideration of Huygens sources. As a result, we examined whether or not students think that the diaphragm illuminated by a parallel beam has an image, where they assume this image is, and how it appears when it does exist. As this type of reasoning also seems inconsistent with the existence of several images along the optical axis, we presented students with a device where two images – a primary source and the illuminated diaphragm - could also be observed behind a lens.

3. METHODS AND SAMPLES

The above-mentioned problems were explored with a set of paper and pencil questionnaires describing experimental situations that are usually presented to students in classes on wave optics. The questions were unusual in the sense that students were not asked to do algebraic or numerical calculations. They were asked to explain what happens to light, whether or not an image exists, and where and what it looks like. They were also invited to justify their answers and to formulate their ideas visually in a diagram describing the experimental situation.

Our choice to analyse only the qualitative aspect of the students' reasoning might be considered as surprising: physics models are complex in the sense that one fact can rarely be directly interpreted with only one variable. This is all the more true in the case of wave optics where one fact cannot be explained by a simple relation between the physical quantities of the model. However, the choice we derived is based on several reasons. First, we make two hypotheses concerning learning in physics: on the one hand, the two dissimilar levels of models and facts must be differentiated, in particular with respect to the language used in teaching; on the other hand, it is helpful to emphasise the different ways in which a model can be expressed. Following Duval (1995), we consider that students should be able to move from the algebraic register of a model to the graphic register or the register of natural language. Second, we consider that different qualitative ways of reasoning exist. We are interested here by two of them: one is based on the mathematical formalism of the model and consists in using it qualitatively in order to predict and explain the facts; the other is not based on the mathematical formalism but on spontaneous patterns of thought. Our presentation of the physics models in the previous section may be considered as a qualitative interpretation of the mathematical framework. Following Duval (1995), students could be expected to advance such qualitative explanations of the situations encountered in teaching. Third, much research suggests that open qualitative questions can clearly bring to the fore the type of difficulty that the usual quantitative exercises avoid or hide. Moreover, they also reveal that the way students use the laws and principles they have learned may be guided by the construction of an erroneous qualitative representation of the situation.

A total of 220 French students (aged 19 to 23) were questioned. 80 students were just beginning their first year of university and the instruction they received on optics was still at the secondary school level. They had been introduced to the formation of images formed by a lens and the geometrical model of light, diffraction through an aperture, and the wave model of light. Some of these students followed an optional lesson in which they approached optical instruments consisting of several lenses (microscope and telescope). In the lesson on the diffraction of light by an aperture, students should have only learned that the diffraction phenomenon characterises waves and that the size of the diffraction pattern depends on the size of the aperture, the wave-length of the wave, and the distance between the screen and the aperture[xiii]. Experiments were done not only with lasers but also with spectral sources, filters and condensers. In the optional lesson on optical imaging, they should have been introduced to the existence of several images along the optical axis: the intermediate image of the object given by the first lens, the final image of the object given by the two lenses of the instrument, and the image of the aperture limiting the first lens formed by the second lens, which is on the plane where the eye has to be placed. Moreover, they should have learned that the quality of the image of a point depends on the diffraction caused by the aperture of the objective. These students only answered the question on diffraction by an aperture.

140 students had physics classes at the university level and were set all the questions. Thirty were in classes training them to enter Engineering High Schools (second year of university) and had classes on wave optics during the year they were questioned. The others were in classes training them to teach physics and chemistry at the secondary level (fourth year of

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university). They received lessons on wave optics when they were in their second and/or third year of university studies: it depends on the university where they graduated in science and on the specialisation they chose (physics or chemistry). The analysis of the programs followed by these two sub-groups reveals that all these students should have been introduced to geometrical optics and the images produced by compound instruments during their first year of university. All of them should have also approached the diffraction caused by an aperture and optical imaging in the presence of diffraction. At this level, diffraction caused by an aperture is explained by the Huygens-Fresnel principle. Particular attention is given to the Fraunhofer diffraction (observed when the aperture is lit by a parallel beam and when the point of observation is far from the aperture) and to the diffraction that alters the formation of images. A look at the textbooks written for the secondary year of scientific studies reveals that students could have approached the central dark ground method.

Since our work aims at improving the teaching of waves, we chose a way of analysing students' answers that seemed to be the most appropriate for teachers to use in their classes because it links students' errors to a small number of typified tendencies of reasoning we suppose students use throughout the situations investigated. This approach resembles to the method proposed by Minstrell (1992) and Peterfalvi (1997). The students' answers, comments, and drawings were processed in three steps. They were first analysed sub-group by sub-group, questionnaire-by-questionnaire and question-by-question. Representative categories of explanatory patterns or strategies employed by students in addressing a particular situation were identified, taking into account what was said and drawn and looking for regularities. Our prior analyses of physics content and of research on conceptions about waves lead us to group these categories (the 'facets of knowledge and reasoning' as they are called by Minstrell) around the same explanatory model (the clusters or 'schemes' of knowledge and reasoning). The schemes of knowledge correspond to the same idea or physical mechanism, underpinning all the facets affiliated with that scheme. They are less dependent on the context, and hence, possess a more inclusive meaning than facets. Free from the constraint of mutual consistency, schemes may coexist and complement each other in a variety of associations. It must be noted that the *'the facets' form although formulated by researchers, was mainly determined by the students (their wording, elements of their drawing) in making sense of a particular situation, whereas a scheme was formulated and determined solely by the researcher, reflecting his/her intention to generalise and see a common rational in a number of "formally" different patterns of knowledge or behaviour...'* (Galili and Hazan, 2000). At the next step, we compared the schemes supposed to be used by students in various wave situations and grouped them into four ways of thinking which are supposed to be used in all light situations. Two of these ways of reasoning concern the physical explanation underpinning the students' answers and are derived from our prior analysis of the physics content and of the research on conceptions about waves. They can be interpreted as two aspects of the object-notion based reasoning put forward in our first research on waves. Another way of reasoning is linked to the number of variables taken into account by students, and yet another one to the more or less abstract nature of the concepts on which students' reasoning is based. They are two other points of view on students' reasoning. As the study presented here is part of our research programme, only one way of reasoning is really developed: the geometrical reasoning which is one aspect of an object-notion based reasoning. The others are encountered in other situations and regarding other questions[xiv]. Since the students' thinking depends on the situation and the question proposed, we choose to call them 'trends of reasoning' and prefer to qualify the facets and schemes by reasoning only.

Because the students who received instruction at secondary school level and the students taught at university level gave nearly similar answers to the question on the diffraction by an aperture, no distinction has been made between them. Moreover, since the answers given by the different sub-groups questioned on optical imaging were so close, we finally grouped them. Whereas the heterogeneity of the population could have been a problem, it appears an advantage here. Indeed, it let us suppose that the ongoing difficulties originate in pre-existing tendencies of

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reasoning that are already in place before receiving instruction. Moreover, the analysis of textbooks used by students led us to conclude that traditional teaching tends to strengthen these tendencies.

At this stage of our research, we sought to pinpoint the difficulties encountered by students and propose a preliminary interpretation. The strength of our work lies in its ability to give meaning and coherence to the results obtained in a large number of situations (Vanderberghe 2006).

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For the sake of brevity, we present only the main results here. The texts of the questionnaires appear in the appendices. Figures showing typical students' diagrams and comments are given throughout the presentation of results.

4. RESULTS

4.1 Students and the diffraction of light through a small aperture

113 students were asked to describe, explain and draw what happens to a laser beam when it passes through a "small" aperture (for details on the questionnaire, see appendix 1). They mainly produce two types of diffraction diagrams (table 1), **both concerning only the macroscopic level.**

Table 1 about here

The diagrams called 'Deviation diagrams' emphasise the bending and spreading of the light beam when it passes through the aperture. Answers 1 and 2 in Figure 3 are examples of such an answer: the incident beam is represented by two rays located on the edges of the aperture which change direction as they pass through it. In the type of diagram called a 'division diagram', the incident beam is not represented by two rays but by one ray only. This ray is divided into two or more rays when it passes through the aperture (answers 3&4 in Figure 4) so that the aperture seems to act as a new source of light, especially when more than two rays are drawn behind the aperture. This type of diagram also concerns the macroscopic level and not the elementary waves level because only a single source is drawn instead of an infinite number. The type of diagram called (D+d) combines the two previous types of diagrams and seems to emphasise that diffraction occurs only at the edges of the aperture, which is incorrect. Only 41% of the students drew interference fringes on the screen. These fringes do not seem to result from the superposition of waves emitted by different point sources: some students presented a diagram on which only one source seems to be considered (answer 4 in Figure 3).

Figure 3 about here

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Most of the 76 comments given with the diffraction diagrams describe what happens at a **macroscopic level**. They usually included everyday words: *'the beam is spreading '; 'rays are bending', 'divided'*. Words having a precise meaning in optics are used incorrectly (20%). The light is said to be *'reflected'* or *'refracted'* to be *'diffused'* or *'dispersed'*. Whereas the explanation of diffraction is based on the words 'source' and 'interference', the former word appears in only a few comments (11%), most of the time meaning 'a single new source of light'. and not 'an infinity of sources on the incident wave surface'. The latter word appears in still fewer comments (3%). 16% of the comments point out the action of the edges of the aperture. The outer rays of the beam are deflected by the edges as if it were a reflection (words showing a contact action such as 'contact', 'obstacle', and 'knock' are used). These comments resemble a geometrical explanation. This is also the case for the comparison some students make: the bending or spreading of the light is compared to that produced by lenses: *'when passing through the aperture, light diffuses the way it does at the cinema'*. Moreover the outer rays are the only ones to be deflected, as if they were attracted by the edges.

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4.2. Students and optical imaging

A questionnaire dealing with the prototypical device used in filtering experiments was designed and distributed to a total of 84 students (appendix 2). The first question concerned the image of the point source when a diaphragm is placed in front of the lens. The second question dealt with the image of the diaphragm and the third one with the image of the diaphragm when a small stop was placed in the back focal plane of the lens. Two types of diaphragm were proposed: diffraction had to be neglected for the first one and considered for the second one. For the sake of brevity, we will not examine here the case of the non diffracting diaphragm and the third question dealing with the filtering experiment (see 1999c, 2000, 2002).

4.2.1. ***Image of a point source when diffraction has to be considered***

Only half of the students (56%, N=84) gave a correct answer: the point source is imaged. Moreover, only half of these students correctly positioned the image of the point source (53%, N=47). The others did not specify the position (23%, N=47) or placed it behind the focal plane of the second lens (24%, N=47). The comments and diagrams tell us that these students do not use wave optics the same way as the students who placed this image correctly do. Indeed, instead of using the Huygens-Fresnel principle and decomposing the diaphragm in Huygens sources, they follow the rays of the light emitted by the source and draw rays diverging behind the diaphragm. So, instead of drawing a diagram like the first diagram in Figure 4, they drew diagrams like the second one and gave the following explanation: *'The image of the hole can be observed. The place of the image when the diaphragm diffracts is* <u>*different*</u> *from when it does not diffract* <u>*because rays after diffraction do not have the same propagation direction*</u>'.

42% of the students (N=84) gave an incorrect answer: the point source is not imaged. After evaluating the justifications given by these students, it seems that:

- for many students (63%, N=35), an image is the stigmatic image of the geometrical optics. Part of them (43%, N=35) refer only to what is observed on the screen: '*there is diffraction, a* <u>*diffraction pattern*</u> *is observed and an image of the hole T can no longer to be seen*', '*the* *image of T cannot be observed because rays do not converge towards the same point behind the lens L_2'* (comments given with the diagram 3 in Figure 4). The others (20%, N=35) also refer to concepts and models, and specify that only geometrical optics can explain images: *'rays are diffracted; they are going in random directions, geometrical optics laws cannot be applied'*.

- for the other students (20%, N=35), what is seen is not the image of the point source but the image of the diffracting diaphragm : *'the source of light for L_2 is a secondary source, that is to say D_2. One overlooks that there is a primary source (T) and then D_2 is the new source of light for L_2'*; *'the split D_2 acts as a new source ("loss of the memory" of the existence of T) '* (comment given with diagram 4 in Figure 4).

Figure 4 about here

4.2.2. ***Image of a diaphragm illuminated by a coherent light when diffraction has to be considered***

Only 58% of the students (N=84) gave a correct answer: the diaphragm is imaged. The other students did not answer (15%) or answered that the diaphragm is not imaged (27%). In that case, we once again encounter the ideas that an image is the stigmatic image of geometrical optics and that only geometrical optics can explain images. The diaphragm has no image when diffraction is considered because *'rays are going in all directions'*, *'this is a diffraction phenomenon which does not obey geometrical laws'*.

Only 27% of the students who said that the diaphragm was imaged (N= 49) gave a correct position to the image of the diaphragm: it is in the conjugate plane of the object plane. The others do not specify the position of the image (28%, N=49) or place it in the focal plane of the lens (45%, N=49). The comments and diagrams point out that these students followed the rays of the incident light and did not decompose the diaphragm into Huygens sources. For them, the image of the diaphragm is merged with the centre of the diffraction pattern: *'Image of D_2 : geometrical* *image through L_2, that is to say in the focal image plane F'_2. This image of D_2 will be in the centre of the pattern diffraction'*.

Since the students did not always clearly answer the question on the shape of the image of the diaphragm, another questionnaire (appendix 3) that focused only on this problem was distributed to 17 other students. Only 23% of them correctly answered that the shape of the image of the diaphragm is a circular image. The majority of students (71%, N=17) described and drew the image of the diaphragm as if it was a diffraction pattern or a diffraction spot: *'It is a bright spot surrounded by dark and bright rings: it is the diffracted image of the diaphragm'*. Only a few students used a ray diagram to construct the image of the diaphragm. There is always only a single ray going from a point of the diaphragm to the screen (answers1 and 2 in Figure 5). What is seen on the screen looks like the projection of the diffraction pattern on it: *'D', image of D, is in fact the projection of concentric circles caused by diffraction in D through the lens L_2. There will be a succession of dark and bright fringes'*.

Figure 5 about here

5. DISCUSSION

5.1. Model of the students' reasoning

Let us first explain that the 'map' presented in Figure 6 emphasises the links between the facets of reasoning derived from the students' answers, the categories in which we group them (the schemes of reasoning), and the trends of reasoning we advance to account for the students' difficulties. This map has been constructed by comparing the students' answers to the characteristics of the concepts and models used in wave and geometrical situations that our analysis of the physics of waves put forward. Thus the analysis of the physics content appears to be the fundamental element which gives reliability to this map. In order to help the understanding of this map, we assign symbols to the facets, schemes and trends of reasoning and refer to these symbols when explaining below how we analyse students' reasoning. The first facet accounts for the answers given by students in the diffraction situation only, the others for the answers produced in the wave imaging situation; the second and third ones also concern the diffraction situation. Facet F2 may be considered to be correct in the diffraction situation and to be wrong in wave imaging situations. Facets F3, F4i and F5i may be considered to be partially right. Facets F1d and F6i to F9i correspond to wrong answers. Let us also specify that this particular study of our research programme allows us to track one of these particular trends of reasoning- the geometrical reasoning- because it is focused only on specific situations and also because the questions do not explored all aspects of the situations we explored.

Figure 6 about here

In the wave situations investigated, students tend to reason on the basis of concepts similar to those of geometrical optics. Indeed, they do not reason at an elementary waves level by using the phase concept and applying the Huygens-Fresnel principle, that is to say in decomposing an aperture into Huygens source and in applying the amplitude superposition principle. Instead, they **reason at the macroscopic level,** using the energy concept and following rays issued from the source: this constitutes scheme S1 on the map. Consequently:

- when passing through a "small" aperture, the rays of the incident wave seem to be reflected or refracted by the edges of the aperture (8% of the 83 students who gave diffraction drawings): this is facet F1d for the diffraction situation.

- when passing through a “small” aperture, the rays of the incident wave are deviated (33% of the 83 students who gave diffraction drawings). This is facet F2 which appears in the diffraction situation and the imaging situations. Students do not know that a reasoning which consists in following the incident rays of light is inappropriate when looking at the position of the image of the source: facet F2 may be considered to be correct in the diffraction situation and to be wrong in wave imaging situations.

- the aperture is not decomposed but considered as only one source of light (23% of the 83 students who gave diffraction drawings). This is facet F3 which appears in the diffraction situation and the imaging situations.

- the image of a point source *ad infinitum* is placed behind the back focal plane of the lens when there is diffraction (31% of the 36 students who answered that the image exists and gave its position) : this is facet F4i for the imaging situation.

- the image of a following diaphragm is merged with the image of the source in the focal plane of the lens (60% of the 37 students who answered that the image of the diaphragm exists and gave its position): this is facet F5i.

Moreover, many students tend to think that **there is no image in wave situations** and that the concept of image belongs to geometrical optics only (scheme S2). Consequently a point source is not imaged when diffraction has to be considered (42%, N=84): this is facet F6i.

These schemes of reasoning are typical of what we have called a trend towards **"geometrical reasoning".** This trend of reasoning is referred to as O1 on the map[xv]. This type of reasoning is close to the trend observed by other science education researchers:

- in wave situations such as the diffraction by an aperture, Ambrose et al. (1999) noticed that *'students drew straight lines to show the path of light through the centre of the slit and attributed diffraction to some sort of interaction between the incident light and the edges...'*: this is facet F2.
- in the case of interferences with the double-slit device, students did not use the wave superposition principle and the concept of phase but an intensity superposition principle: the pattern observed on the screen seems to be the superposition or the juxtaposition of two patterns formed by each slit (Ambrose and al. 1999). The same result was obtained by Romdhane and Maurines (2003) for a device that consisted of three holes. Moreover, a tendency to consider that the modulation of intensity occurs when the incident wave goes through the interference device is also revealed in the case of thin plates (Romdhane, 2007).

It is possible to account for these types of answers by adding two other facets dealing with interference situation and linked to the scheme S1.

- Colin (2001) remarked that the diagram relating to the diffraction pattern observed in the back focal plane of a lens seemed to be understood by students as the deviation of the incident wave: '*these students seem to forget or misunderstand the phenomenon of diffraction, and so too, consider the lines they have drawn as rays of geometrical optics that go straight on through the holes to an image on the screen or that are "deviated" by the holes as refracted rays at the interface of two media*': this is facet F2.
- in the results obtained by Colin (1999, 2001) we also notice a tendency to confuse the image of a diffracting diaphragm with the image of the point source and to consider that there is no image in a wave situation such as the interferences formed by the double-slit device. The first answer corresponds to facet F5i, and the second one to scheme S2 and another facet not included on the map dealing with imaging in the presence of interferences.

In the questionnaire on optical imaging in wave situations, the same tendency to consider an image as a whole - like the trend pointed out by many researchers in geometrical situations - emerges (Fawaz and Viennot 1986 ; Feher and Rice 1987 ; Goldberg and Mc Dermott 1987 ; Kaminsky 1989 ; Galili 1996). **The image seems to be the object, which is travelling** and changing when something happens on the path of light: this is scheme S3. First, students draw the same type of drawings in wave situations as in geometrical situations: only a single ray coming from an object point contributes to the construction of the corresponding image point (facet F7i). Moreover, when there is diffraction somewhere in an optical system, the following images have kept the 'memory' of this diffraction so that they look like the diffraction pattern observed in the back focal plane of the lens (71%, N=17): this is facet F8i.

In fact, in these situations where the extended object is a transparent object lit by a primary source, students seem to follow something issued from the source which moves along the optical device and can change. This trend of reasoning is close to the reasoning pointed out in our first research on the propagation of mechanical signals along one direction (1992, 1993) and in our second research on the propagation of waves in a three dimensional medium (1997, 2003). Indeed, students follow the visible shape which is propagating on a rope, or the sound signal which is propagating in air or in a material medium, or the wave surfaces they draw to represent waves propagating in a three dimensional medium. They consider them as a whole and, when something occurs during the propagation, they change them in the same way as material objects are changed. Moreover, questions focused on the propagation velocity (1992, 1993, 1997) indicate that students explain the motion of mechanical signals by using a spontaneous mechanics close to that advanced by Viennot (1996) for material objects. Linder and Erickson (1989) put forth the same mechanistic reasoning in the case of sound. More recently, Wittmann et al (1999, 2003) obtained the same results for the propagation of a bump on a string and a sound signal. This is why we introduce the same notion here as the one proposed in our previous research, the notion of a travelling supply. Everything happens as if a supply of light was given to the optical device by the source, moves along the optical axis and can change during the propagation (this constitutes trend O2). We found two ways of reasoning: the supply can keep the mark of its origin so that the image of the source is observed (facet F4i), or the supply cannot keep the mark of its origin so that the image of the last obstacle encountered is only observed (facet F9i).

If the tendency towards object-notion based reasoning is also encountered for other waves and situations (trend O) and in other physical fields (electricity, mechanics, and thermodynamics: see the overview of Viennot 1996), the tendency to reason on the basis of geometrical concepts concerns only three-dimensional waves. In fact, geometrical reasoning is a way of adapting mechanistic reasoning to new situations. In the situations investigated here, mechanistic reasoning is revealed in two ways: some students do not reason on the basis of a travelling supply (they decompose the aperture that is imaged into points and place correctly its image) but use geometrical reasoning (the image of the aperture is not changed in a spatial filtering experiment such the central dark ground method as if the illumination and the points of the aperture were incoherent, see 1999, 2000, 2002); other students reason on the basis of a travelling supply (they do not decompose the aperture into points and draw only a single ray from a point source to a point image[xvi]).

In conclusion, we shall note two points concerning the two other trends of reasoning which we do not develop here. Concerning the number of variables which have to be taken into account, several studies have revealed that students tend to reduce their number (e.g. Viennot, 1996). This appears in two ways. On the one hand, the physical quantities are not differentiated by students – for example, the notion of supply accounts for a reasoning in which force, speed, and energy are confused. On the other hand, students reason on the basis of one variable at a time. Here, another way of simplifying how models can be used is revealed: this concerns the trend to link the image concept to the geometrical situations and the geometrical model only. Similar tendencies to link a concept and a law to a particular situation have been pointed out by Hirn and Viennot (2000) in her research on the ways teachers have taken into account the evolution of the optics program in grade 8 in France. Concerning the nature of concepts on which the students' reasoning is based, several studies indicate that students focus on visual signs, more generally on perceptible signs, so that a concept seems to be considered as a concrete notion. Here, there is almost no distance between the facts and the physical explanation consisting in following the incident rays of light. This is undoubtedly a manifestation of the trend put forth by many researchers that students considers model and facts to be identical.

The ways optics is taught in France do not help students to overcome their difficulties. In fact:

- where the tendency to reason at a macroscopic level is concerned, an aperture is often considered as a whole and said to act as a source of light when diffraction has to be considered. Only in quantitative explanations using the Huygens-Fresnel principle is the aperture decomposed into Huygens sources.

- when we look at the tendency to consider that optical imaging and diffraction are two exclusive phenomena, some approaches encountered in lessons where these two phenomena are joined (defects in images) raise questions. In the textbooks relating to waves and diffraction used in the first two university years, the diffraction pattern observed in the focal plane of a lens is rarely said to correspond to the spread image of the point source. In the textbooks relating to geometrical optics, the distortion of an image caused by diffraction is not always mentioned; very often a point seems to be imaged only if all the rays issuing from this point and emerging from the lens focus at a single point. Moreover, in both types of textbook, the concept of rays only seems to be valid in geometrical situations because its definition is based on experiments showing narrow rectilinear light beams by diffusion. Since a geometrical image is obtained using rays, how can students understand that images exist when light is diffracted?

- concerning the tendency to merge the images of several different objects, most of the time the point of interest is only in the image of the source. Even if this question is approached with a compound instrument in grade 12, only teaching at a higher level deals with this problem. In geometrical optics, this is in connection with the aperture and field stops of an optical system and even in this case, the diaphragm is presented rather as limiting the light beam instead of as an object, which is imaged. In physical optics and in spatial filtering situations the diaphragm is presented in this way.

6. CONCLUSION

The geometrical model of students' reasoning advanced here gives meaning and coherence to students' answers obtained not only from the enquiries presented here but also found in others which we have carried on. Moreover, it joined the observations and the conclusions of other science education researchers. An analysis of the books used by students and the results obtained in the fields of common reasoning in physics suggest us that the trends towards a geometrical reasoning is a way to the object-notion based reasoning to fit to wave situations and that the common reasoning is hardly put into question with the methods of teaching waves today, in France at least.

The research on optical imaging has been carried out and broadened to include incoherent illumination situations. Indeed, some questions were worthy of further exploration, in particular those relating to the number of images observed behind the last lens of an optical system and the conditions for an object to be imaged. We have investigated the effect of different factors: the existence or lack of a material support for the optical object, the type of light emerging from the secondary source of light (diffracted or not), the kind of illumination (coherent or not), the presence of another primary source or of another transparent object. The interested reader should consult (2001b) where these points are developed.

We have now to examine the limits of our work. At this stage of the research, we were interested in testing our hypothesis derived from our previous studies that students tend to reason at a macroscopic level in wave situations. We were not interested in analysing how the students' ways of reasoning change with teaching and consequently we have not designed the enquiries in order to answer this question. However, some indications on this evolution have been obtained. We found that most of the students who had lessons at the university level for the first time gave the same answers as the students who had not. These resemblances are not really surprising: constructing a qualitative reasoning on the basis of a model like the wave model is a difficult enterprise because of the wave formalism and of the wave concepts themselves ; the questions we elaborated are qualitative and suppose to master a qualitative reasoning to whom students are certainly too rarely trained. Our research on the propagation of mechanical signals put forward that the trend to reason on the basis of a travelling supply is less resistant to teaching than the trend to consider the signal shape as a whole. Indeed, the former way of reasoning is less encountered after the first level of university teaching and the latter after the second one only. This lets us assume that differences about the diffraction situation could appear after the teaching of the third year of university in physics. As we did not know exactly what physics material was presented to students of the fourth year of university who want to be teachers, it would be worthwhile to collect such information and to plan investigations on optical imaging before they graduate in science because differences should appear according to their initial specialisation and the lessons on waves they had. As the results in the domain of problem solving show that qualitative physics reasoning is mainly done by experts and not by novices, it would be fruitful to examine how students cope with questions concerning the relation between the formal components of the model and the facts. Asking them to comment modelling explanations or experimental results should allow us to put forward more differences between them.

At the end of this paper, we are left with a crucial but not a new question: what do we want students to understand? How can we help them to overcome their difficulties?

Let us first note that studies conducted by Wosilait et al (1999) have proven that tutorials designed to supplement standard calculus-based courses which take into account the students' difficulties are effective in helping them construct and apply a basic model for light. We subscribe to the progression they chose and the methods they proposed, and agree with nearly all their pedagogical proposals. Their work suggests introducing the concept of differences in path length and the principle of superposition of amplitudes with a two-source interference in water, and extends this basic model first to interference given by the double-slit device[xvii], then to multiple-slit interference and finally to diffraction by a slit. They highlight the role of qualitative questions and a strategy that elicits personal ideas (sometimes even by using the wave model in a wrong way) before confronting these subjective ideas with real world phenomena, photographs, or graphs of the intensity of interference and diffraction patterns. They emphasise the importance of visual representation by suggesting that students make an analogy between light interference and interference in water and proposing the use of diagrams of sinusoidal curves in order to determinate maxima and minima in an interference pattern, or diagrams showing rays and differences in path length.

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Let us now conclude by stressing four other points. In order to help students not to reason at a macroscopic level and to consider the wave as a travelling object, the macroscopic wave should also be reconstructed from the elementary waves level by applying the Huygens principle qualitatively[xviii]. This can be done early for the wave emerging from an aperture. This approach should allow students to connect the level on which the current teaching focuses (the elementary waves level) and the level on which common reasoning focuses (the macroscopic level). Of course, it is not a question of examining how the energy is propagated in any situation because this question would require a vectorial model. It is possible to mention the two levels and construct the resultant wave surfaces and the rays in a far field (they are perpendicular to the envelope of the wave surfaces of the Huygens sources distributed on the aperture). Such diagrams can be found in Hecht (1997). In order to help students not to reserve the wave model for wave situations, a geometrical situation (propagation through an aperture or imaging) has to be studied, applying both models. Even if this approach is useless in practice, it is worth using because it emphasises the difference between reality and a model and, as a result, the abstract nature of models. In order to help students not to think that diffraction and optical imaging are two exclusive phenomena, it would be worthwhile to define an image as an irradiance distribution when referring to the phenomena and not as the crossing point of two rays in reference to the formalism of a geometrical model. This should help them to understand that a point blurred by diffraction is also an image. In order to help students to consider that different images can exist in an optical system, they could be set experiments and questions such as those presented in the enquiry on optical imaging. This could be done early in secondary teaching with geometrical situations (incoherent illumination and no diffraction). Experiments presenting several objects standing in a line in front of a lens (one lamp and two slides on which vertical or horizontal lines are drawn, two lamps, or one lamp and a slide) could be proposed (see 2001b). This would prepare students for lessons on compound instruments and situations used in coherent optical imaging.

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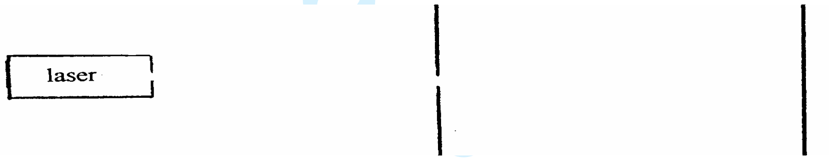
light, *Physics Education Research: A supplement to the American Journal of Physics,* vol. 67, n°7, pp. S5-S15.

Correspondence

APPENDIX 1
Text of the questionnaire on diffraction through a small aperture

Consider the following experiment:

laser which is emitting a very narrow beam of light — screen with a very small hole — screen

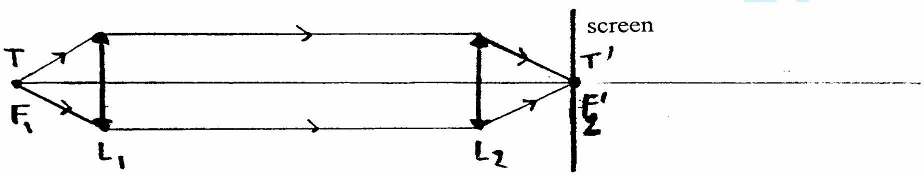


Questions : Explain what happens to the light. Draw it above and explain in some detail what you are doing.

APPENDIX 2
Text of the questionnaire on the formation of optical images in wave situations

A hole is illuminated with a yellow light source and a condenser (not represented). The image of T is made on a screen E with two lenses L_1 and L_2 with 10 cm of focal length. The hole T is in the focal plane of the lens L_1 (F_1 is the object focus of this lens) and the screen is in the image focal plane of the lens L_2 (F'_2 is the image focus of this lens).

reference situation



A screen with a hole pierced in it is put between the two lenses. The hole D_1 is large enough for light not to be considered as diffracted, the hole D_2 is too small and light is considered as diffracted.

figure 1 : no diffraction

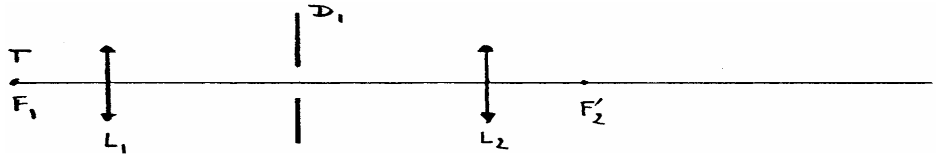
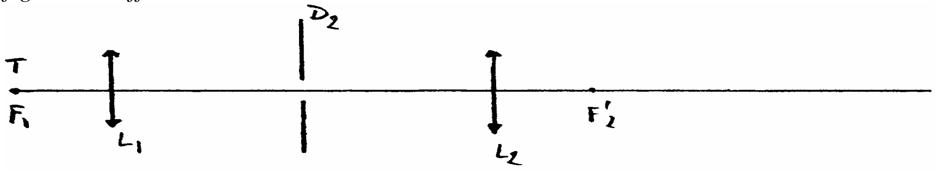


figure 2 : diffraction



Questions

1) Can the image of the source hole T be observed?

a) with D_1 :If not, why not? If it can, why? Is it in the same place and of the same shape as in the reference situation? If so, why, if not, why not?

b) with D_2 : If not, why not ? If so, why? Is it in the same place and of the same shape as in the reference situation? If so, why, if not, why not?

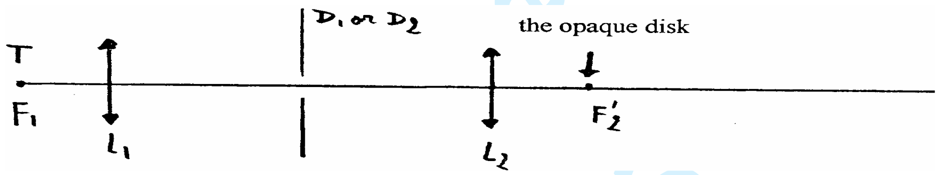
2) Is it possible to observe the image of the holes D_1 and D_2 placed between the lenses?

a) case of D_1 : If not, why not ? If so, why? Place the image on figure 1

b) case of D_2 : If not, why not? If so, why? Place the image on figure 2

3) For the first question, if you have answered that the image of the source hole T can be observed, answer the following questions:

The image of T obtained with D_1 is totally covered by a little opaque disk. The same disk is put on the image of T obtained with D_2.



a) Can the image of the hole D_1 be observed?

If not, why? If yes, why? Is it the same as the one obtained without the opaque disk? yes, no, why?

b) Can the image of the hole D_2 be observed?

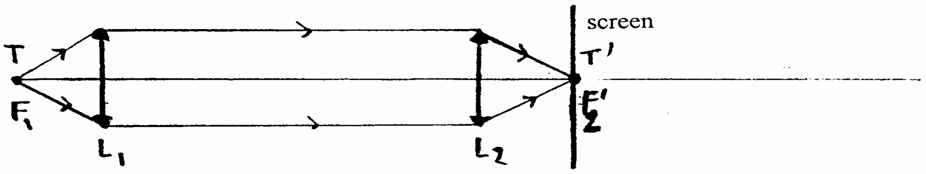
If not, why not? If yes, why? Is it the same as the one obtained without the opaque disk? yes, no, why?

APPENDIX 3

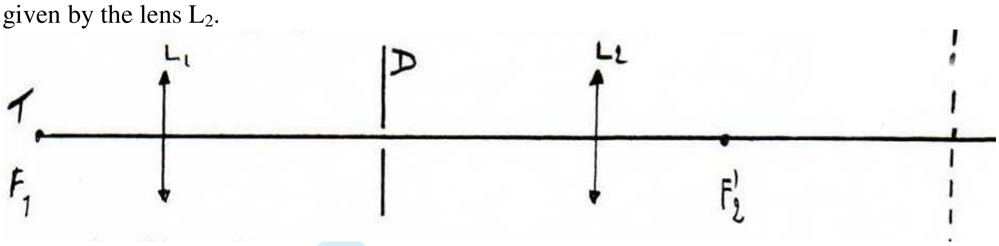
Text of the questionnaire on the shape of the image of a diaphragm when diffraction has to be considered

Reference situation

T is a hole lit by a source of yellow light and a condenser which are not drawn. T' is the image of T formed by the two lenses L_1 and L_2 with the same focal length. T is small enough so that the beam of light between the two lenses is parallel to the optical axis.



A circular diaphragm D is now placed between the two lenses. The diameter of D is small enough so that the diffraction of light cannot be neglected. D' is the image of the diaphragm D given by the lens L_2.



Question: Is the image of the diaphragm D a circular spot? If yes, why? If not, why not? what is its shape ?

A small stop is placed on the back focus of the lens L_2.

Question: Does the image of the diaphragm still exist? If so, why, how does it appear? If not, why not?

NOTES

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[i] Diffraction of visible light can be observed by the naked eye through apertures of a tenth of a millimetre or less. This is why this is not a phenomenon often observed in everyday life. As the wavelengths of the visible light lie between 400 and 800nμ., many textbooks make an error when they write that the diffraction of light occurs through apertures of the same size as the wavelength of the light. This error, also made by students (see Maurines, 1997 and Ambrose et al, 1999), indicates a tendency toward an object-notion based reasoning which consists of following the wave considered as a whole through the aperture.

[ii] When the point of observation is near the obstacle, another model has to be used, the electromagnetic model. It is based on two vectors, the electric field and the magnetic field, and on Maxwell equations (Born and Wolf, 1980).

[iii] Here, the amplitude is the complex amplitude of the function describing the field of the wave.

[iv] These diagrams are based on rays. There is also another type of diagrams based on wave surfaces. See (1997, 1999).

[v] We will consider here that the lens is corrected for the geometrical and chromatic aberrations. The position and the shape of an image with geometrical aberrations can be explained at first approximation by geometrical optics. For the irradiance distribution, it is necessary to use wave optics (Born and Wolf, 1980).

[vi] The size of the diffraction spot depends on the wavelength of the light, on the diameter of the lens and its focal length, and on the positions of the object, the lens and the image. As the lens always has a finite diameter, diffraction cannot never be removed. It can be neglected in the usual observations but must be considered in the case of devices with high magnification (microscope, and telescope). It also depends on the desired precision: an image could look like a point when observed with the eyes and to be surrounded with diffraction rings when observed with a magnifying lens.

[vii] When the lens is corrected for the geometrical and chromatic aberrations, the quality of the image is only limited by the diffraction caused by the finite size of the lens. In that case, the wave surface of the emergent wave is spherical (Goodman, 1972). This is why we draw Huygens sources on an arc of circle centred on the image focus of the lens on the second diagram of Figure 2.

[viii] More precisely, it depends on the width of coherence of the light wave in the plane where the illuminated object is (Born and Wolf, 1980).

[ix] The two types of images have the same general shape but not the same details (Goodman, 1972). For example, the coherent image of the edge of an aperture has sharper edges than the incoherent image but shows oscillations of the

light intensity. The resolution of the details is complex because the distribution irradiance depends on the distribution of the phase of the object in case of coherent illumination. The incoherent image is not necessarily better than the coherent image. For example, the resolution of the images of two point objects obtained with coherent illumination can be the same as with incoherent illumination but can also be better or worse.

[x] In the experiment discussed here, two types of diffraction occur: the diffraction by the illuminated object and the diffraction by the lens. In order to simplify the explanation, we only consider the diffraction by the illuminated object.

[xi] That does not mean that it is impossible to change an image in case of incoherent illumination (Goodman, 1972).

[xii] Coherent optical imaging is a quite recent field of physics and this is certainly why its teaching raises discussion. Thus, there are discussions of the way to present situations to students where diffraction and interference are observed in the presence of lenses. In his first publication, Colin (1999, 2001) suggests the use of the two models, geometrical optics and wave optics, in the same prototypical situation involving an object illuminated by a plane wave, a lens and a screen. He proposes to use geometrical optics in order to explain the existence of the image of the illuminated object and wave optics in order to explain the existence of the diffracting pattern. Moreover, he suggests ascribing a different meaning to the "rays" drawn from a point source: in the first case, they are a path for energy; in the second case, a path for phase propagation. Our analysis of the physical content and the results of our enquiries lead us to think that this approach raises more difficulties than it resolves. In a later publication (2002), this point of view has been given up. The accent is only put on the fact that the rays to be considered depend on the point of observation.

[xiii] It has to be noticed that the physics program of the grade 12 invited teachers to introduce the history of optics in their classes. So, they could have chosen to present students with the Huygens principle like some authors of textbooks do.

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[xiv] For more details, see the overview of our research programme (2001).

[xv] Another scheme of reasoning is linked to this trend toward a geometrical reasoning: it consists in considering incoherent point sources and indisguinshable rays so that the image of a diaphragm is not changed in a filtering experiment: Details can be found in (1999, 2000, 2001a, 2002).

[xvi] This tendency to reason on the basis of a travelling supply also leads students to answer that the centre of the image of a 'diffracting' diaphragm is missing when a small stop is placed on the path of light, just as the centre of the image of an object is missing when a small mask is placed on the lens.

[xvii] As students have difficulties to differentiate between interference and diffraction, we should rather use an interference device which is not based on diffraction for the analogy between interference in water and light interference. We prefer to use first a device such as the Meslin lenses and then the double-slit.

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[xviii] There are also discussions on the method to use in teaching. For instance, Colin (2002) does not agree with the use of drawings based on the Huygens principle. In fact, it seems to us that the two types of drawings, those based on wave surfaces and those based on "rays", must be used. Each type of diagram has its advantages and disadvantages (see 1997, 2000) but it seems to us that the first type of drawings emphasises the existence of two levels more easily than the second one. However, we must remember that it is impossible to know the phase and the amplitude of a wave in both diagrams

Geometrical reasoning in wave situations: the case of light diffraction and coherent illumination optical imaging

FIGURES

Figure 1: the two levels and the two types of diagrams in a wave model

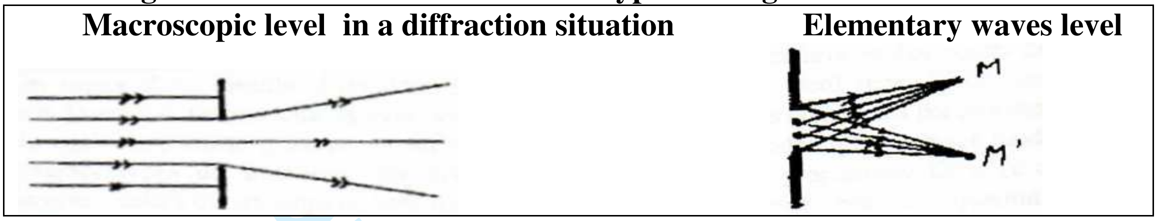


Figure 2: two models for explaining the image of a point located at infinity

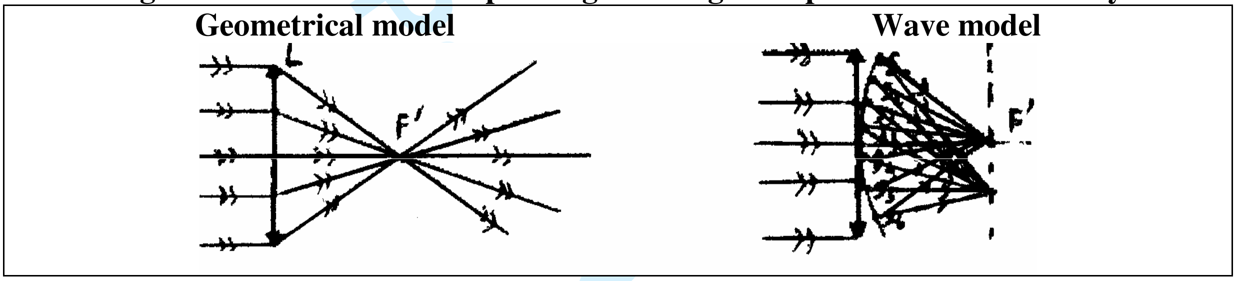


Figure 3: typical answers explaining what happens to a laser beam when passing through a small aperture

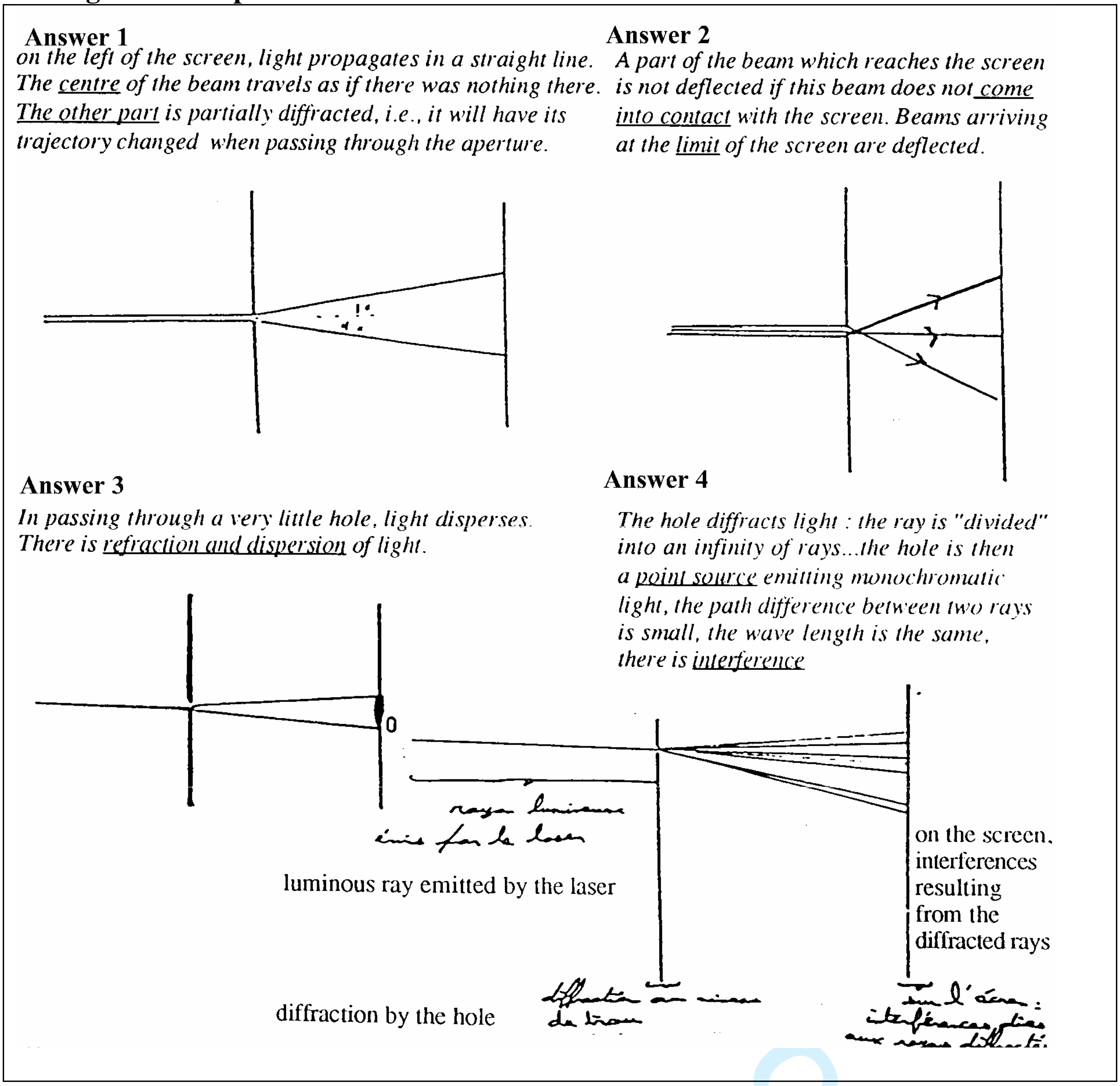
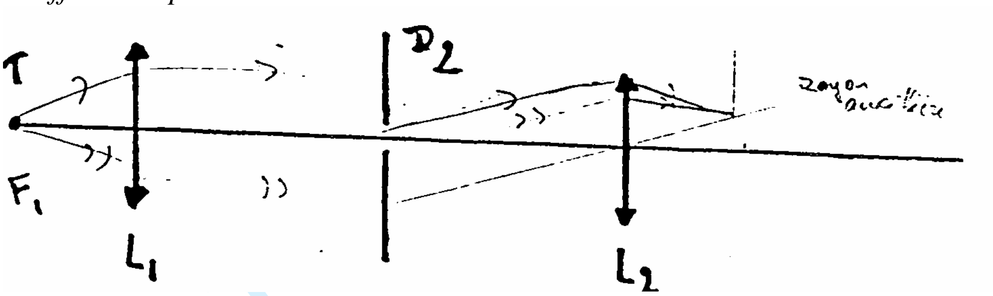
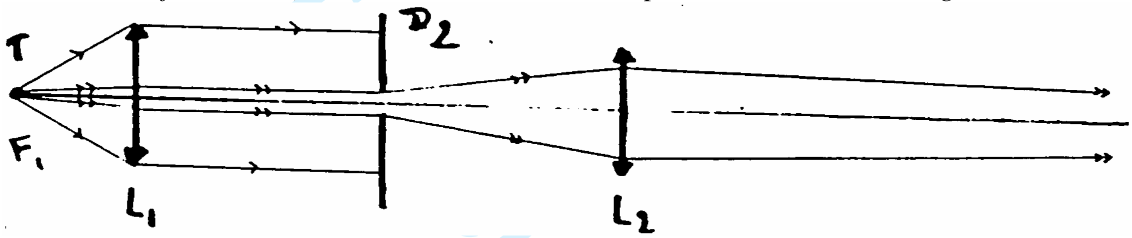


Figure 4: examples of students' answers on the image of a point source when there is diffraction

Answer1 *Yes, there is diffraction but there is not only one image point because there is a diffraction point*

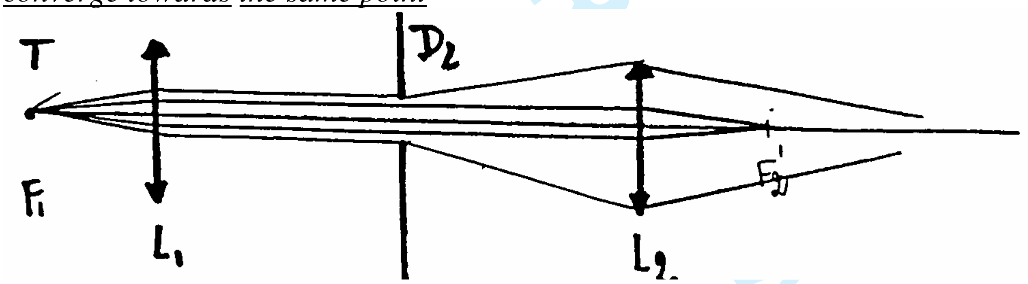


Answer 2 *Yes, the image of T can be observed but* *<u>not at the same place</u>* *(the screen has to be moved further on). T' will have the same shape but not the same brightness.*



Answer 3

no, the image of T cannot be observed because rays emerging from the lens L_2 <u>do not converge towards</u> <u>the same point</u>



Answer4 *the hole D2 is acting as <u>a new source</u> ("loss of the memory of the existence of T)*

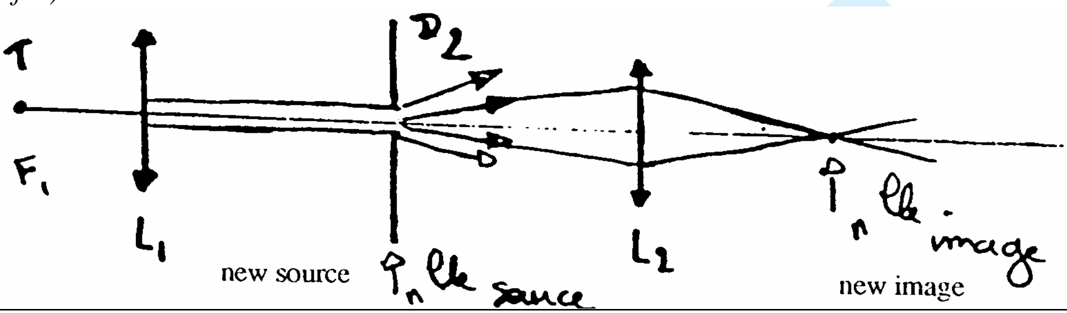
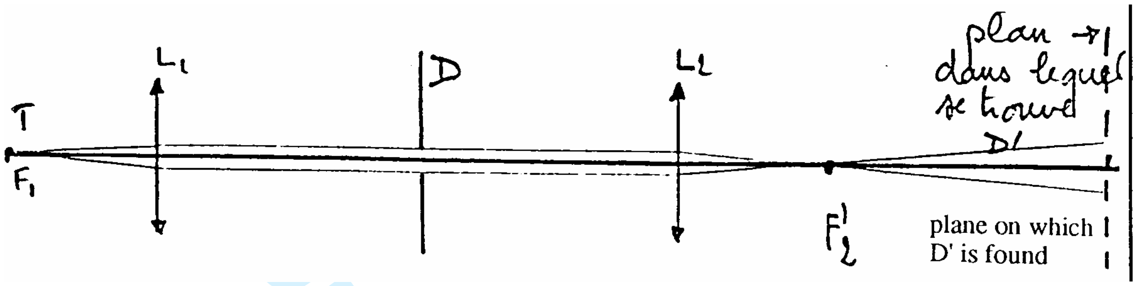
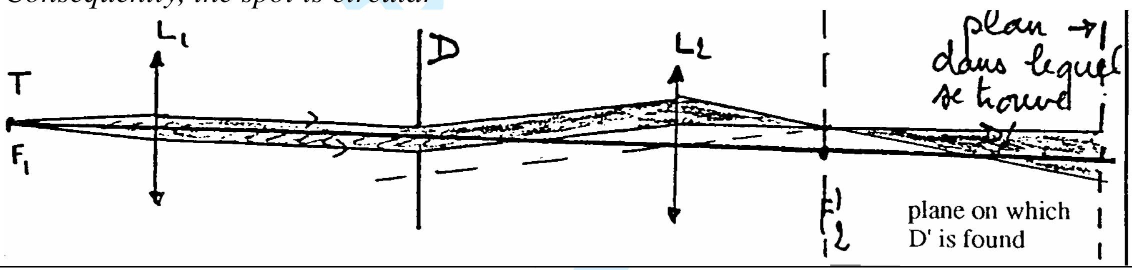


Figure 5: examples of students' answers on the shape of the image of a diffracting diaphragm illuminated by a parallel beam.

Answer 1 : *we have a circular spot : image of the hole. Outside, light is slightly diffused by diffraction but as we are not in the focal plane, the diffraction image is blurred.*



Answer 2 *the plane is at a greater distance from L_2 than the focal length. Consequently, the spot is circular*



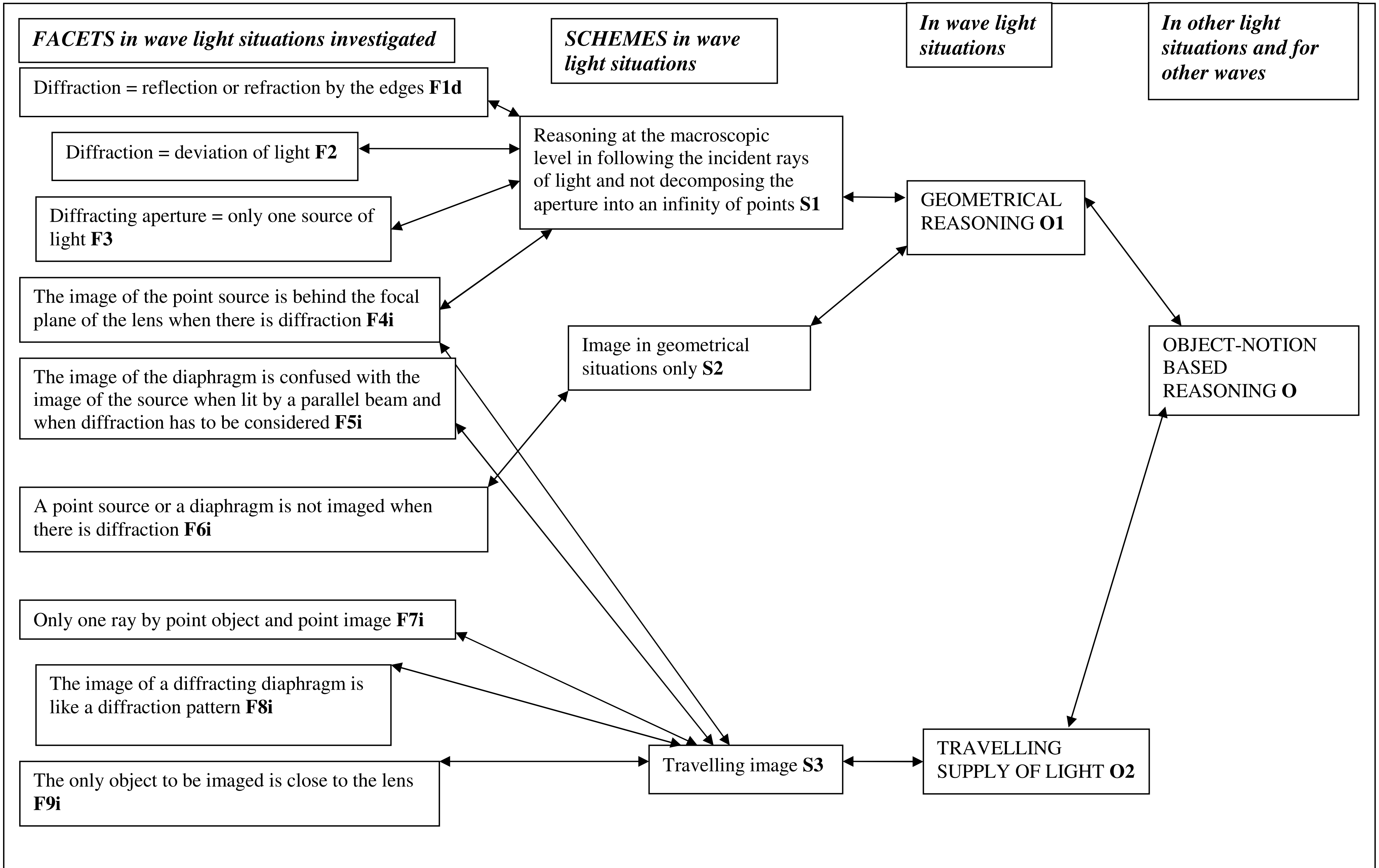


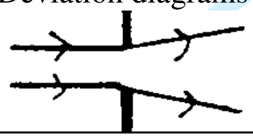
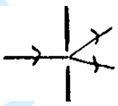
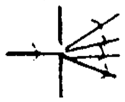
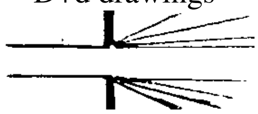
Figure 6: facets, schemes and trends of reasoning used by students in wave situations

Geometrical reasoning in wave situations: the case of light diffraction and coherent illumination optical imaging

TABLE

Table 1: types of diagrams

(percentages calculated based on the number of students giving a diffraction diagram : N =83)

Deviation diagrams	Division diagrams	D+d drawings	interference fringes drawn on the screen
	 		
33%	19% 40%	8%	41%