A little knowledge is a dangerous thing: understanding of rectilinear propagation vs. diffraction of light

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Theoretical framework and rationale for the study

Previous studies (Guesne, 1984, Kaminski, 1989, Osborne & al., 1993, de Hosson, 2004) have shown that most children and adults don't have a clear representation of the propagation of light and encounter difficulties to explain how an object lit by a *secondary* source of light is viewed. It also appears than understanding how light fills the space between a source and an object can be a difficulty for many of them (Driver, Guesne & Tiberghien, 1985, Ravanis et al., 2013, Chu & Treagust, 2013). Most of these studies involve experimentations in a wide space (for example a room lit by a lamp or sunlight) and diffusion of light by a surface (usually a wall or an object).

The present study aims to identify the participants' representations of light and its propagation from a *primary source* through the closed space of a black box and in the absence of multiple diffusion and reflection. The elements of explanation then involve two distinct notions: that light propagates in a straight line; and the necessity for the light to reach the eye in order to be seen.

Our experimental device draws on an experience of W. Kaminski and C. de Hosson and uses a small closed black box (Blanquet, 2010; Fig. 1) separated in two compartments by an intermediate partition pierced with a ∅7 mm single hole. At one end, a bulb (primary source of light) is inserted into a hole drilled in the middle of the box; three observation holes are drilled at the opposite end.

When the box is closed, it is possible to see light through the middle hole, thanks to its alignment with the bulb and the hole in the partition; and through that hole only, since the other two are not aligned with the source and middle hole and since the phenomena of multiple diffusion and reflection on the walls are negligible, the inside of the box being black.

Fig. 1. Example of a black box (top removed and without bulb) used to present the experiment to the participants in the study.

This study aims to document, by a cross-age study, the evolution of the representations of what happens inside the box by primary school pupils, future primary school teachers and physics students entering university.

Method

Data collection Procedure: The black box is shown to the participants with the light off, the top removed and the partition in place. A questionary with a cross-sectional diagram of the box and allocated space to write their explanation is provided (see Results section bellow). They are asked to indicate through which hole(s) they think they might see the light of the bulb, once the box is closed and the bulb lit. They are then invited to draw a diagram (with elucidation of its signification if needed) of what they think will happen in the box and to write explanatory sentences. After retrieving the questionnaires, they have the possibility to observe the phenomen and find that they only can see the light of the bulb through the middle hole.

Participants: This study was first carried out as part of a European PEERS exchange programm between a Romanian and a French university, involving primary school pupils (n=841), undergraduate students in Education Sciences in Romania, aiming for a career as primary teachers (n=132) and French students in first year of a Master dedicated to future primary school teachers (n=236).

It was then expanded to middle school (n=25) and high school (n=57) pupils and students entering their first year of physics study at university (L1 = 330; L1 physics n=256, INSA engineering school, n=74) or preparing a technical diploma in physical measurements at university (DUT, n=218, first year=135/ second year=83) (1834 participants overall including 433 Romanian, fig. 2). 200 pupils and students at French middle school (11 to 15 y.o.) and high school (15 to 18 y.o.) levels will complete the study (in progress).

Level	6-7 y.o. (CP/K1)	7-8 y.o. (CE1/K2)	8-9 y.o. (CE2/K3)	9-10 y.o. (CM1/K4)	10-11 y.o. (CM2/K5)	13-14 y.o. (4^{e}/K8)	15-16 y.o. (6e/K10)	Univ. L1	Univ. DUT	Prim. Teach
Girls	56	75	98	119	54	15	39	89	43	331
Boys	57	72	124	117	65	10	14	235	169	36
No Answ.	2	0	0	0	0	0	0	6	6	1
Total	115	147	222	236	119	25	53	330	218	368

Table 2.: Repartition of participants in the study by level and sex

Analysis of data: It was possible to distribute the participants' drawings among five wide categories, C1 to C5, in which 90% of the answers fall (Fig. 3).

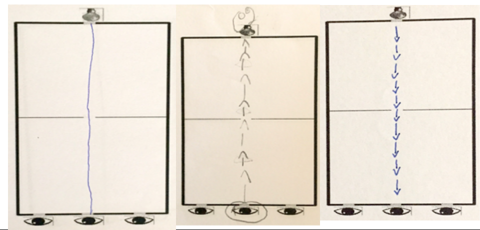
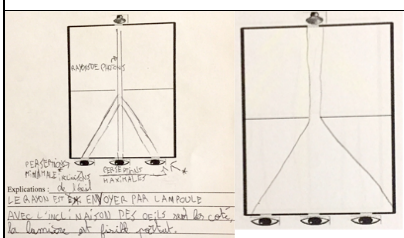
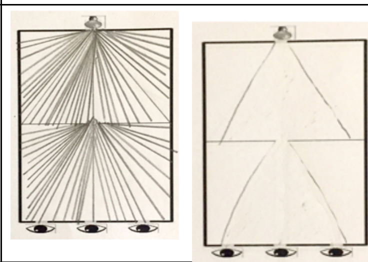
Category C1: only the middle hole is surrounded and the box remains empty 	 Category C2: a line (either thin or thick) connects the bulb to the central eye, with or without arrow(s)
 Cat. C4: a line, thin or thick connects the bulb to the hole in the partition from which three or more lines depart, or a "funnel" to the three eyes, with or without arrow (s)	 Category C3: several lines come out of the bulb or the entire compartment is lit and a single line (thin or thick) connects the hole in the partition to the central eye
	 Category C5: several lines come out of the bulb; or the entire compartment is lit and then, from the hole in the partition, leave two or more lines to the three eyes, with or without arrow(s)

Fig.3. Description of C1-C5 Categories and examples of drawings for each category.

The presence of arrows in one or two compartiments and their direction (bulb to eye or eye to bulb) as well as the written participants' explanations in relation with their drawing (such as justifications related to rectilinear propagation of light, diffraction, dispersion, etc.) were also coded but codage will not be detailed here due to length constraints.

Results

Counter-intuitively enough, in both countries, the percentage of correct answers *decreases* in a similar way as primary school school children grow up (fig.4), to become a small minority among students at university (11% in Romania and 16 to 27% in France). At K6-K9 levels, rectilinear propagation of light and model of light rays are explicitly taught in France: it may explain the high score (100%) of the K8-participants (n=25) in the study.

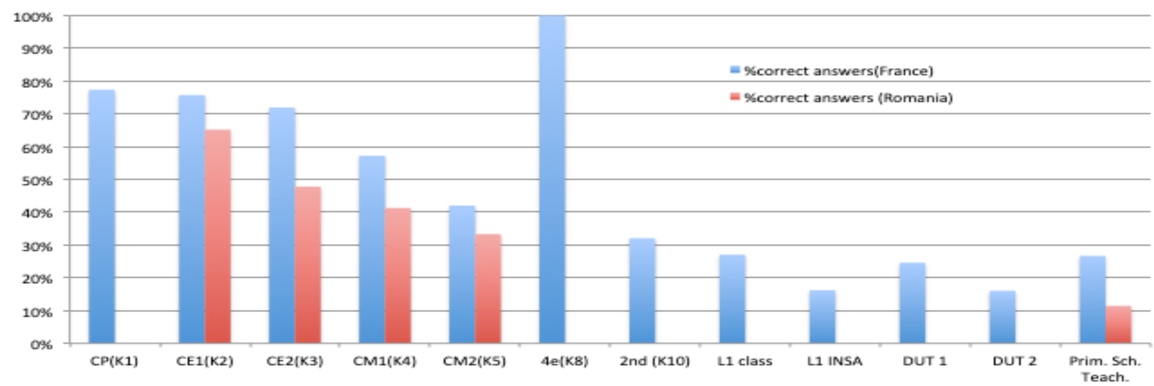


Figure 4: Evolution of corrects answers (C1+C2+C3) according to the age of participants in France (blue) and Romania (red)

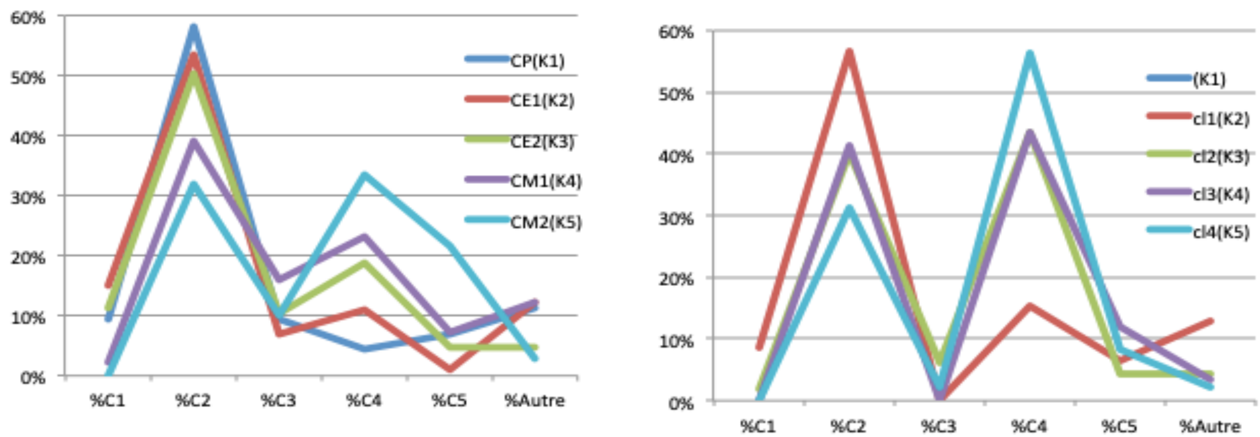


Fig. 5. Evolution of categories according to the age of French (left) and Romanian (right) primary school children.

Drawings and explanations involving vision seem to be favored by younger students, while older ones try to associate it with arguments about the propagation of light. While categories C1 and C3 are common among French children, they are very rare amongst Romanian children. The number of C4-type representations increases more rapidly among Romanian pupils than among French pupils, unlike the C5-type representations (Fig. 5).

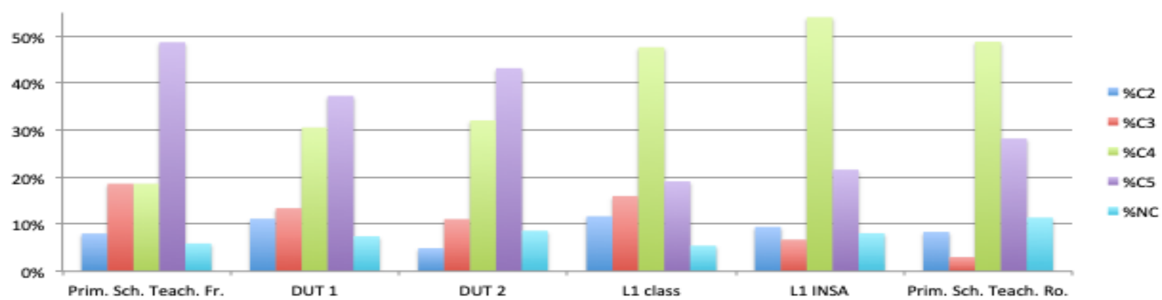


Fig 6: Repartition of the different categories among adults (C1= 0%)

Percentage of correct drawings among adults varies between 11% (Romanian future primary school teachers) and 27% (Fig. 6.). Comparaison with their written explanations reveals an excellent concordance. The rare false positive are caused by participants belonging to C3 & C5 categories and using vision process argument (e.g. “I see the light from the side”).

	2nde (K10)	DUT 1 (K13)	DUT 2 (K13)	L1 class (K13)	INSA (K13)	Prim. Sch. Teach. (K16)
Usable written Explanations	52	134	83	266	74	239
correct answers	17	30	14	72	12	57
correct answers without false expl.	17	28	14	59	12	56
% correct answers without false expl.	*33%*	*21%*	*17%*	*22%*	*16%*	*23%*
Usable Drawings	35	134	81	256	74	236
% Good answers (C2+C3)	*32%*	*25%*	*16%*	*27%*	*16%*	*27%*
Type of argument used in correct answers						
explicite rectilinear propagation	59%	71%	50%	64%	17%	27%
vision process	35%	4%	7%	22%	0%	16%
negligible diffraction and light rays	0%	14%	29%	14%	75%	0%
other explanations or no clear explanation	6%	11%	14%	0%	8%	57%
Type of argument used in incorrect answers						
diffraction argument	0%	43%	62%	60%	87%	8%
"Propagation of light everywhere" expl.	31%	25%	14%	5%	5%	9%
"Diffusion of light everywhere" expl.	0%	6%	1%	4%	2%	27%
Vision process	9%	7%	6%	8%	0%	23%
"different intensity of light" expl.	11%	0%	6%	0%	0%	9%
"Reflection of light" expl.	0%	4%	3%	3%	0%	5%
Other explanation	14%	7%	7%	10%	6%	7%
Not clear or no justification	34%	9%	0%	9%	0%	12%

Table 7. Proportion of correct written answers among French K10 and students and repartition of their explanations

Unlike K8 students, French K10 students fail to predict what they will observe; percentages are close to those of adults. The K10 curriculum includes the notions of wave, total reflection and refraction, diffusion, spectrum of light. All High school students receive this teaching. Incorrect explanations at K10 level and among all K13 and K16 students participating in the study include references to such notions. All K13 participants come from the K12 scientific section and were taught about diffraction and to identify situations where it is relevant to take it into account, interferences, spectral analysis and did an experimental work to observe the influence of the size of an hole on the diffraction pattern. Athough none of K10 and 6% of K16 students mobilize explicitly diffraction as an argument, 37 to 85% of K13 students mobilize diffraction in their explanation. In the best case (INSA, students selected on their academic results) less than 13% conclude it is negligible in the considered situation.

Analysis and limits

77% of the youngest pupils (K1) achieve correct predictions. This high percentage of success doesn't necessarily imply a correct representation of the path of light (e.g. only the light coming out of the hole can allow me to see the bulb and it only happens in the middle hole), since the sole projection of the gaze towards the light source also provides the correct answer through to the use of eye-based reasoning (e.g. my eye can see the light through the middle hole because there is no obstacle between my eye and the bulb). The counter-intuitive evolution of pupils' correct answers according to their age could thus be related to the conflict aroused by the search for coherence between different explanatory systems. As their written answers are very poor (or inexistant), a complementary study including interviews should be performed to elucidate their reasoning in this situation. Previous studies on their understanding of light and vision have already shown nevertheless the large diversity of their representations (De Hosson, 2004).

Contrarywise, 77 to 89% of adults fail to predict what they will observe and trace broken or discontinuous lines between the light bulb and the hole through which they look in the box; they rarely use the ray model in a relevant way (3 to 15%). Their explanations suggest a misuse of concepts learned at school, especially the concept of diffraction. Students who studied it at highschool the year before the passation of questionnaire are more impacted (43 to 87%) than future primary school teachers with K10 level in physics (6%), and students with the highest academic results fail the most (INSA). It is nevertheless difficult to evaluate which proportion of K15 "propagation/diffusion of light everywhere" explanations may also refer to a diffraction phenomenon without formulation of the concept, in the absence of interviews of these students.

Conclusion, implications and perspectives

These results question the effectiveness of geometric optics teaching at school, the understanding of more sophisticated models by students and a probable interference between them. They also suggest some tracks for educational action. It is now consensual to rely on students' initial conceptions - erroneous or not - to build the expected knowledge of school curricula. Yet, the representations found in most adults do not appear at a significant level (20 %) before 8-9 y.o. Investigative approaches on the notions of gaze and of rectilinear propagation of light, based on the proposed box problem and starting with 8-9 y.o. children might thus avoid the permanent installation of erroneous conceptions, which unfortunately appear to be robust up to adulthood. The introduction of the diffraction phenomenon in the scientific section of High school seems to yield a very partial understanding and even to lead a large number of students to use it in an abusive manner, without taking into consideration the diameter of the considered holes. The proposed experiment could also serve as a support for working with more advanced students on the concept of the validity domain of a theory and the choice of the model to be considered according to the data of the problem at university level, this research is in progress.

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