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Beyond a Dichotomic Approach, The Case of Colour Phenomena

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This research documents the aims and the impact of a teaching experiment concerning colour phenomena. This teaching experiment is designed in order to make students consider not only the spectral composition of light but also its intensity, and to consider the absorption of light by a pigment as relative, instead of as total or zero. Eight teaching interviews conducted with third-year university students were recorded, transcribed and coded. Their analysis suggests that two 'anchoring cognitive reactions' were likely to facilitate students' learning in a forthcoming sequence on this theme. It also makes it possible to evaluate the importance of a strong obstacle, that is the interpretation of absorption/transmission curves, or the multiplicative aspect of subtractive synthesis. Finally, the students' comments about their feelings at the end of the interview introduce a brief discussion about the benefits and/or frustration in terms of intellectual satisfaction.

Keywords: *Physics education; Design research; Conceptual Development; Colour; Absorption; Dichotomic approach*

Introduction

It is commonly advocated that, in order to teach concepts, we need to provide students with a simplified access to the real world. This process may pose little danger for an appropriate learning of physics if the descriptive models and statements chosen remain reasonably consistent with the observable facts. But this is not always the case and some 'teaching rituals' (Viennot, 2006) are sometimes based on prototypical statements that contradict what can daily be observed by students. 'Black objects do not reflect any light' is one of these inadequate statements that can be found in some teaching materials within the context of the learning of light

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sources.[1] This statement contradicts the fact that the impact of a red laser beam remains visible whatever the colour of the surface on which the light is sent might be. Indeed, asserting that 'black objects do not reflect any light' is based on an oversimplified view of the real world involving an 'all or nothing' reasoning process and does not include the fact that light should be considered in a quantitative way. Such an oversimplified view of light phenomena can be observed in teaching rituals concerning colour vision. The classical rules of additive mixing provide for instance the outcome of two beams of coloured lights superimposed on a white screen (e.g. 'with red plus green, you get yellow') correspondingly, the outcome of sending a coloured light beam on a filter or a pigment may be given by a rule of subtractive mixing such as 'with red plus yellow, you get red'. But such a reduced stating of the rules does not permit a proper interpretation of what students can observe in daily life. This is not only for practical reasons (for instance, an omnipresent ambient light) but also because of the need to consider both the composition of the light sent and its intensity. In this research, we present the impact of a teaching pathway designed to stress the process of colour vision, a pathway that takes into account the intensity of light. Following, in particular, the work of de Hosson and Kaminski (2007), our intention is to lead students from an 'all or nothing' way of reasoning to another involving 'more or less' terms, in order to make the visibility of the impact of a laser beam on any coloured surface intelligible. Our main research question is focused on the concept of absorption in the context of colour phenomena, a concept that has proved to be very difficult. Findings by Chauvet (1996) in particular indicate that absorption is not spontaneously mentioned by art students when explaining the colour of pigments illuminated by various lights (first-year university students after the French baccalaureat). In our investigation, the focus is on the *multiplicative* aspect of what is somewhat improperly named *subtractive* synthesis. To our knowledge, there is very little research available on this theme.

Rationale

We seek to know to what extent students with the usual background concerning colour can benefit from a teaching pathway designed to stress the role of both light intensity and spectral composition. The focus is on the multiplicative aspect of subtractive synthesis, which is related to the idea of a greater or lesser absorption.

The subtractive colour synthesis is traditionally explained following what we have called an 'all or nothing' approach. As an example, the ritual statement: 'when a blue object is illuminated with red light it appears black ... '[2] contradicts everyday life observation because it simply does not fit with the sound consequences of the physical model of transmission/absorption by red, blue and green pigments (or filters). Considering the following absorption curves (Figure 1) and specifically the foot of the each curve which reaches the wavelength value of a red laser beam (633 nm), we figure that a very low value of percentage of diffuse transmission may result in a perceptible effect. In other words, the attention paid to the feet of the curves indicates that a blue or green pigment can diffuse red light depending on the

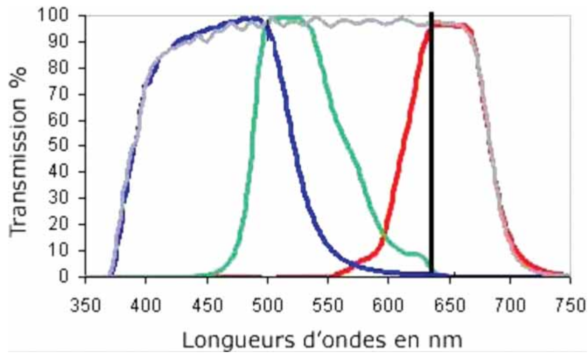


Figure 1. Absorption curves of primary blue (*left*), green (*middle*) and red (*right*) filters. Horizontally: wavelength. The sum of the three transmission factors is shown (*in light grey*). A 633 nm laser beam (*black vertical line*) is transmitted (*resp.* diffusively reflected) with a certain percentage by both blue and green filters (*resp.* pigments). According to the intensity of this beam, visible effects (red impact) can be seen on blue and green coloured surfaces.

intensity of the incident flux: 1% of 'a lot of' incident light provides a non-negligible amount of diffused light. This multiplicative aspect of colour subtractive synthesis has led us to reconsider traditional approaches of the teaching of 'colour and vision', taking into account a more appropriate view with respect to both everyday life phenomena and physics.

Our investigation is set in the framework of *didactical engineering* (Artigue, 1994), where some hypotheses on the expected teaching learning processes can be tested through the confrontation of an *a priori* and an *a posteriori* analysis. In this perspective, the design of a teaching sequence is explicitly organized on the basis of certain expectations ('hypotheses') concerning a given set of variables, of why they are relevant, and of how they are supposed to clench certain targeted intellectual processes. The *a posteriori* analysis compares what is observed and what was expected as regards the impact of these variables. But the term '*a priori*' should not be misunderstood. '*A priori*' expectations do not stem from nothing. They are usually the result of a confrontation between previously known common ideas or typical students' reactions and the targeted comprehension. They usually involve what one assumes is logical intellectual functioning on the students' part, albeit on erroneous premises. In our case, little in research literature concerned the topic addressed. Therefore, we had to work out our primary expectations. In order to refine the *a priori* analysis, we chose to conduct a preliminary investigation using the *teaching experiment* method (Komorek & Duit 2004) which involves a learning pathway that takes the form of a discussion that is orientated towards conceptual acquisition, a discussion that is strongly structured and guided, and allows students to expose their initial thoughts and their reactions to various questions and requests. Consequently, we do not consider that such a 'teaching experiment' *directly* provides the pattern for a possible sequence. Rather, we propose this intellectual pathway to students in order to obtain a preliminary access to some aspects of their common reactions. We consider that the results of this investigation should inform the design of a forthcoming sequence – a design which ought to take into particular account many variables related to the context. In particular, these results could provide reasons for the choice of an appropriate audience.

The teaching goals at stake are not *a priori* very simple. Beyond the objective of fostering conceptual acquisition, we have in mind a second perspective: seeing how an exigent approach may, or may not, foster students' 'intellectual satisfaction' (Viennot, 2006), despite non-negligible obstacles. This might be defined as 'a feeling linked to the impression of having understood a complex topic to a certain extent, one that can be identified quite clearly, this being accomplished with a good quality/cost ratio' (Mathé & Viennot, 2009). In this respect, the choice of the audience is quite critical. Note that we do not consider here a kind of motivation that would be necessary for students to engage in physics, but a feeling that should be a product of learning, be it on very ordinary topics.

This second perspective is not, in this study, supported with a strong experimental set-up, given that we will collect only some clues in this respect. But we think it is important to concentrate our investigation along this line of concern, in order to justify the relatively high level of intellectual ambition that it demands from students.

Research Method

The Interviews

The interviewees were eight prospective physics and chemistry teachers beginning their third year at a university (Université Paris Diderot-Paris 7, France). In their two first years, they took and graduated in the same academic physics subjects (geometrical and ondulatory optics, Newtonian mechanics, fluids statics and electromagnetism), as all physics students begin to be professionally specialized from the third year. Thus, these students can be considered as very likely to have been taught colour phenomena in a ritual way, both in secondary school and in the framework of the teaching of optics in their first year at university. By 'a ritual way', we mean that all of the students were taught the spectral composition of light, with the prototypical example of the rainbow, as well as the basic rules of additive and subtractive colour mixing. Each of these rules is most commonly illustrated with three overlapping coloured circles, apparently in an algorithmic register. These circles are often represented on a white background (Viennot et al., 2004) which, in the case of additive colour mixing, is not appropriate. Indeed, 'no light' should correspond to a black background. This is typical of a 'ritual' teaching of colour phenomena, namely, the role of light is not stressed.

The learning pathway proposed to the interviewees can be described as follows: the student is first reminded of the rule of additive mixing of lights (e.g. red + green → yellow) in a context where it works, that is, in a black room and with light beams of similar intensities. A setting of coloured shadows with three lamps (Chauvet, 1996; Olivieri, Torosantucci, & Vicentini, 1988) is shown to demonstrate, with simple equipment, all the basic rules of additive and subtractive mixing, and the student is invited to predict the outcome of various changes in this setting (Figure 2). These changes are only on the register of the presence/absence (phase *P*/*A*) of a given coloured beam.

The device shown in Figure 2 makes it possible to evidence the visual response due to beams of lights that impact on a white screen and diffusely reflect towards the observer. Blocking off one or several coloured beams, thanks to the tetrahedron placed in front of the screen, results in various colours on different areas of this screen. These colours can be predicted by the classical rules: each part of the screen is illuminated by one, two or three coloured beams. There is a direct correspondence between what is seen and what is predicted by the rules. In particular, when the three beams reach a given zone, this part of the screen is (quasi-)white. Moreover, the students are provided with a reminder of the rules (appendix), so that – probably – they do not feel they are being evaluated. This also avoids any lapses in memory. We observed that none of the students said that it was the first time they were addressing this topic. Most of them commented on their lack of specific recollections. This at least confirms that they had previously been taught this topic.

The next phase of the interviews is critical. It is labelled *M*/*L*, in order to designate a 'more or less' approach, to indicate that the intensity of the incident light is considered an important parameter. The light source is now a laser pointer, and what is to be predicted and justified (*M*/*L1*), then observed and discussed (*M*/*L2*), is the effect of this beam on various areas of a sheet of paper, printed with the six basic pigments of the graphics palette of a computer (red, green, blue, yellow, cyan and magenta), plus black. The experiment is carried out in a very dim ambient light.

Once the experiment is performed, it is possible to observe a bright red impact on the areas of the sheet which are, respectively, white, red, magenta and yellow. By contrast, the impact is still red but less bright on the areas of the sheet which are, respectively, black, green, blue and cyan. In each group, the brightness is similar

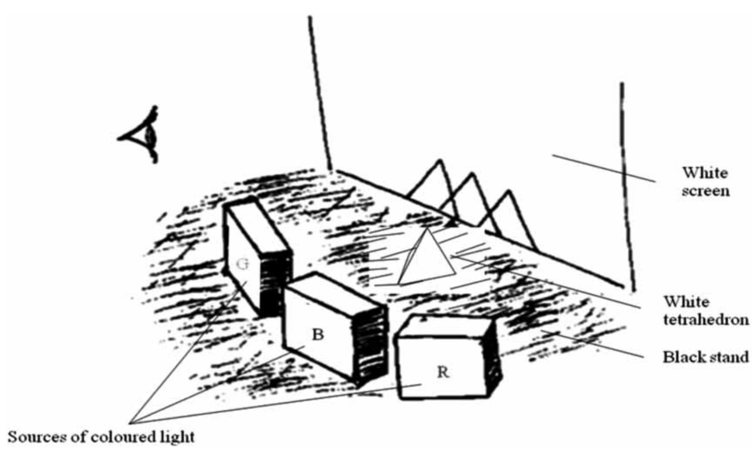


Figure 2. Coloured shadows: the setting used to remind interviewees of the classical rules of colour phenomena (Chauvet, 1996).

across the different pigments, low for the latter group, high for the former. The intellectual path we intend to facilitate should lead the student to realize that, surprising as it may be, the outcome of this experiment can be explained provided the concept of partial absorption is used. To this end, it is necessary to consider that there is a brighter impact on the pigments that are classically declared not to absorb a red light – in fact they absorb a small proportion of the incident red light; and there is a dim impact on the pigments that are classically said to absorb the red light – but in fact absorb only a high proportion of such a light (Figure 1).

At this stage, the interviewer is supposed to be rather directive and to introduce the absorption/transmission curves of three filters (Figure 1), red, blue and green (*M/L3*). The goal is to help students understand, in particular, the role of the feet of the curves which 'reach' the value of the wave length (633 nm) of the laser beam. This essential conceptual knot is introduced via a discussion about the passing bands of three wide band filters (by and large: a third of the spectrum of white light), analogous to the red, green and blue pigments used in our experiment. The students' attention is, in a somewhat directive manner, called to the 'feet' of the curves. The conceptual target is to reconcile what the students have seen with the laser beam, on the one hand, and the classical rules on the other hand: 1% of an intense red light, that was diffused thanks to a 'foot' of the transmission curve of a green pigment, was enough to see a red impact on a green area.

The final step (*M/L4*) consisted in asking students for their global evaluation of the teaching interview, their feeling at the end. Students were asked to formulate their level of satisfaction, to be rated from 1 (poor) to 5 (very high), or to express it in a sentence should they prefer to.

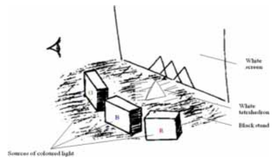
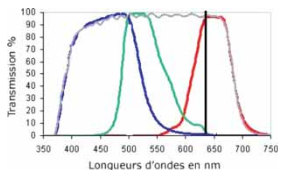
Table 1 outlines the main steps in the design of these interviews.

We referred to these interviews as 'strongly structured and guided'. In the first phases (*P/A*, *M/L1* and *M/L2)*, the structure was mainly provided by two successive experiments with contrasted outcomes. The interviewer's input was mainly aimed at better understanding what the students meant. Thus

> Int 31: What did you learn about black?
> Jo 32: I learned that it was a lack of light.
> Int 33: Well, but an object, what does it do to light?
> Jo 34: Err . . . a black objet?
> Int 35: Yes, if you illuminate this object, what will it do to the light?
> Jo 36: Err . . . It will absorb the light.
> Int 37: Is that what you have learnt or are you thinking this up now, with this experiment?
> Jo 38: It is what I have learnt.
> Int 40: It is coming to your mind?
> Jo 41: Err . . . No.
> Int 42: No?
> Jo 43: Err . . . This is what comes to my mind when I think about it, but . . . .

At certain stages in these interviews, the interviewer's comments may, however, be less neutral. This was the case, for instance, when the discussion concerned the localization of the impact of the red beam on a red zone (*M/L1*). Thus, in the following

Table 1. Main steps in the teaching interviews.

Phase	Our conceptual targets and questions	Material setting	Main aspects of the discussion (planned and/or expected)
P/A	Students are reminded of the classical rules First observation of their reactions		The students appropriate the classical rules, predictions on this basis, observation, discussion, recapitulation Table of rules left to students
M/L1	Intense coloured light on pigments: Do students transfer the classical rules or not if yes how?	A red laser pointer A sheet of black paper with six coloured areas: red, blue, green, yellow, magenta and cyan	Predictions with arguments: Impact visible or not, if so, description of the impact, with arguments
M/L2	Performing the experiment: how do they react. . .do they use M/L approach?		Strong destabilization expected
M/L3	Understand multiplicative aspect of absorption? Explain the difference between experiments used in the *P/A* phase and *M/L* phase?		Important input on behalf of the interviewer to help students comprehend the meaning of the curves
M/L4	Global evaluation of the design		Expressing feelings

excerpt, the interviewer asks the reason why such an impact could be localized, a strategy which finally failed to bring the brightness into the discussion:

Int 180: Will I see the impact?
Sa 181: Err . . . no, err, yes, it is not exactly the same red, but yes.
Int 182: Yes or no? Can you tell me where light is impacting?
Sa 183: Yes
Int 184: How will you know, given that it is red on red?
Sa 185: Yes, . . . , no, . . . , it is not possible.
Int 186: Do you refer to your experience? It is red, but is the impact visible or not?
Sa 187: I would say yes!
Int 188: Given your experience?
Sa 189: Yes
Int 190: OK, you can say that.
Sa 191: Yes, yes.

Int 192: But well, tell me how I will see red on a red background. I need a contrast. Will it be a contrast of colour?
Sa 193: Yes, because it is not exactly the same red.
Int 194: If it were exactly the same red . . . look, look at that (*red beam impacting on the white wall*). The colour is rather close.
Sa 195: Yes but the laser light is not, err, no, I don't know.

The interviewer's role changes considerably when he addresses the subject of the absorption/reflection curves (*M/L3*). Here, given that the students are not familiar with this tool, the interviewer's style becomes much more declarative and directive, despite the dialogic structure of some parts of the discussion:

Int 345: We are going to see how absorption with filters (or pigments) works. Look, here are some curves, with what are called 'passing bands', for the red filter, the green filter and the blue filter//. Passing bands//This does not mean that some light is generated by the filter. In fact it is a passing band because (*the sheet is turned upside down*) the rest of the incident light is absorbed. 100% absorption there *(showing*) for red light. 100% absorption there for red light and there (*the foot of the 'red' curve*), much less. Green (*filter or pigment*) that transmits or sends back red light. Here is the curve. There (*spectral zone*) all the light is absorbed, there (another *spectral zone*) all the light is absorbed. Now, what's up with my laser beam? 633 nm. What can I say given . . .

Sa 346: Err, it is the wavelength.
Int 347: It's the wavelength. What happens to this light when it impacts on this filter?
Sa 348: It is absorbed.
Int 349: Completely?
Sa 350: Almost completely.
Int 351: Almost . . . where does it happen?
Sa 352: Err, here.
Int 353: Yes, yes and what does that mean 'almost'?
Sa 354: Very very little.
Int 355: Yes, it is quantified there (*showing*).
Sa 356: Yeah, OK.
Int 357: It is quantified . . .
Sa 358: . . . with percents.

The idea of multiplication is not expected to stem from the document alone. What will be observed after this intervention is the acceptability and usability of such a notion with a given experiment. We do not claim that this is the best possible way to stage the introduction of rates of absorption or of reflection symbolized by curves. This introduction is only what may be done in this context, in order to begin to document students' reactions in this respect. This is a typical case of how a teaching experiment may differ from a research-based sequence.

Processing and Analysing the Interviews

The interview transcripts were submitted to a thematic content analysis, each category being defined by a theme that can be identified in the students' comments (Table 2). The data are processed using two types of categories. Some originate in our *a priori* analysis and others emerge from the transcripts (Strauss & Corbin,

Table 2. Main thematic categories used in the analysis of the interviews

Theme	Code
Colour of the predicted or observed impact	Red, blue, green, magenta, yellow, cyan and black
Call on daily experience	Exp
Use of classical rules (dichotomic, that is 'all or nothing')	*R*
Impact visible/invisible	Loc/NoLoc
Impact localized, thanks to contrast of colour even if the localization is implicit	Loc ≠
Impact explicitly localized, thanks to contrast of brightness	LocB
Impact more or less bright (in French: plus ou moins intense, lumineux)	B↑
Two groups of pigments are identified, one with strong absorption of red light, one with low absorption of red light	2G
More or less absorption	+/−A
More or less intensity	+/−I
More or less light	+/−L
Multiplicative effect of absorption	X
Importance of the power of the source	P
Presence of ambient light	Amb

1990). We pinpoint and count the occurrence of each category. This process was conducted independently by the two authors and the final classification emerged after a discussion between them. Concerning the students' doubts and feelings, their comments will be extensively cited.

Results

The impact of the didactic intervention was measured through the analysis of the recordings and scripts of the eight interviews. All students' interventions are quoted using the first two letters of his/her first name (student's pseudo) and the number of his/her comment in the progress of the interview.

P/A Phase

This part of the interview was devoted to reminding the students of the classical rules about colour mixing, in a context of change by the presence/absence (*P/A*) of the beams.

Placed in this context, the students seem to be rapidly at ease. Table 3 displays the time it took them to successfully use these tables in relation to what they saw. This time includes checking that a colour obtained with two beams can be predicted with the corresponding rule of additive mixing as well as by considering the effect of a filter absorbing the third colour (here blocked by the tetrahedron) on white light.

No particular difficulty was encountered, even with students who had very little school memories in this domain. We do not claim that in such a short span of time

Table 3. Time spent with students in *P*/*A* phase

Students' pseudos	Time spent in *P*/*A* phase
Jo	9 min, 25 s
Ju	12 min, 54 s
Me	15 min, 01 s
Mu	12 min, 49 s
Op	11 min, 30 s
Sa	14 min, 03 s
Tia	12 min, 05 s
Thi	13 min, 34 s

the students had reached a sound comprehension of colour phenomena, especially of what concerns absorption. Our objective was limited to putting them in a reasonably comfortable situation when using, with our help, the classical rules summed up in the reminder they had at their disposal (appendix).

M/*L Phase*

The second phase (*M*/*L*) was divided into several parts. We sum up the main results successively hereafter.

M/*L1: Predicting the Outcomes of Partial Absorption of a Laser Beam.*

In this first part, it was observed (Table 4) that, concerning the pigments commonly described as 'absorbing red light' (black, blue, green, and cyan), a majority of students (six out of eight) predicted that the impact of the laser beam would not be visible on the background ('NoLoc' in Table 2) for at least three of these four areas. Therefore, these students behave as if they were applying the classical rules. They were all very explicit in this regard ('*R*' in Table 2) for at least three of these colours.

However, one of these students expressed a doubt concerning the impact on the black zone:

> Ju 83: Can we see . . . ? Can we guess the red colour on a black background . . . ? . . . but I don't know.

Another student who also expressed a doubt concerning black chose to answer that the impact would be faintly visible and also expressed a doubt concerning blue, this time relying on his experience:

> Thi 96: In principle, I can't see anything. But does that black really absorb everything? I don't know!
> Thi 98: We will see a little something (*with black*) but it will be less sharp than . . .
> Thi 122: I am aware that when the laser beam is directed onto the sheet *(with blue pigment)*, we will see something, because I have already played around with a laser.

Table 4. Outline of the students' predictions and comments concerning the impact of a laser beam on various coloured areas of a sheet of paper. See codes in Table 2.

Student	Black	Blue	Green	Cyan[a]	Red[a]	Magenta	Yellow
Jo	Black	Mixing then blue	Green	Cyan	Red B↑	Magenta, then red	Red
	NoLoc	NoLoc	NoLoc	NoLoc	LocB	Loc ≠	Loc ≠
	R	*R*	*R*	*R*		*R*	*R*
Ju	Black	Blue	Green	Cyan	Red B↑	Red B↑ then magenta	Magenta
	Loc?	NoLoc	NoLoc	NoLoc	LocB	Loc ≠	Loc ≠
		R	*R*	*R*			
Me	Black	Blue then?	'same as for blue'	Cyan	Red	Red	Yellow Loc
	NoLoc, then?	NoLoc, then?	NoLoc	Loc	Loc	Loc ≠	then red
	R	*R*	*R*	*R*		*R*	Loc ≠ *R*
Mu	Black	Blue	Green	Cyan	? then red	-Amb.: magenta Loc	-Amb: yellow, Loc
	NoLoc	NoLoc	NoLoc	NoLoc	NoLoc	-noAmb.: Red Loc ≠	- noAmb: Red Loc ≠
	R	*R*	*R*	*R*	*R*	*R*	*R*
Op	Black	Blue	Green	Cyan	Red	Red	Red
	NoLoc	NoLoc	NoLoc	NoLoc	Loc	Loc	Loc
	R	*R*	*R*	*R*	*R*	*R*	*R*
Sa	? then	? then					
	Red	Red	Red	Red	Red	Red	Red
	Exp.	Exp	Exp	Exp.	Exp. then	Exp.	Exp.
	Loc ≠	Loc ≠ 'despite' *R*	'despite' *R*	Loc ≠	? NoLoc	Loc ≠	Loc
Tia	Black	Blue	Green	Cyan	Red	Magenta?	Magenta?
	NoLoc	NoLoc	NoLoc	NoLoc	NoLoc	Loc	Loc
Thi	Black?	Blue	Green	Cyan	-Amb: Red B↑	Red B↑	Red
		NoLoc (*R*)					
	Loc	Then: Loc	NoLoc	NoLoc		LocB	Loc
	R	Exp	*R*	*R*	LocB *R*	*R*	

[a]These two colours are inverted in the table with respect to the order of the questions in the interview.

Finally, one student kept saying, throughout this part of the interview, that, given her 'experience', she was expecting a red spot on each of the coloured – and black as well – parts of the paper. In two cases (blue and green), she added 'despite the rule'.

The responses are more diversified as regards the second group of pigments, red, magenta and yellow.

The first allusions to the 'brightness' of what is seen (Jo, Ju and Thi) happened in the case of a red paper illuminated by the (red) laser beam, that is, interestingly, in a case when the classical rules predicted no absorption. Indeed, the problem which arose then was that of localizing – or not – a red spot on a red background. Among the five students who did not call on a contrast of 'brightness', three predicted a localized impact without providing any justification (Me, Op), or simply mentioning 'her experience' (Sa), and the others (Tia, Mu) predicted that the impact would not be localized, as stated in this comment:

Tia 80–2: We will see the impact (. . .), but we will not localise it.

In the cases with magenta and yellow pigments, students used complex ways of reasoning involving the idea of colour mixing. This was sometimes done in a naïve way, possibly as with paints (Chauvet, 1996):

Ju 128: (*with yellow*) Err . . . , stupidly enough, I don't know if it's correct, but me, when I am told 'red plus yellow', I see the result as a kind of orange colour.
Jo 128–132: (*with magenta*) "I think the colour we will see will be different from magenta and red. (. . .) I think blue. (. . .). Err//It's a way of reasoning a little like//an additive mixing of colours.

By contrast, a student had an expert way of reasoning (involving the common rules and the ambient light):

Mu 134: Magenta, that's red and blue, therefore (. . .) it emits only red and blue.
Int 135: Then, I send some red light on it.
Mu136: Therefore, it sends it back, but it also sends back some blue, err . . .
Int 137: It also sends back some blue . . . . Can it send back a colour that was not received?
Mu 138: No, but it receives white ambient light, so, it will send back . . .
Int139: Due to white light?
Mu140: Yes.

One student (Sa), already cited, kept to the same type of reasoning throughout the interview, e.g. it is my experience (*that the impact will be red*). Thanks to her experience, she had no hesitation concerning the colour of the impact, but was unable to predict whether the red spot would be visible on a red background. On the other hand, she could not rely on any other tool to reason about the proposed situations:

Op 144: But I don't feel at ease with 'absorbing'.

M/L2. Putting Predictions to the Test

In the second part of this phase (*M/L2*), students were invited to put their predictions to the test. Beyond the often unpredicted colour of the impact – red – what emerged clearly for *all* of the students (Table 5) was the idea of the 'brightness' of an impact zone. The surface brightness is different for two groups of pigments. The first group comprises the pigments that classically are said to absorb red lights: black, blue, green and cyan. The second group of cases corresponds to the 'non red-absorbing' pigments (red, magenta and yellow).

Table 5. Main characteristics of students' reactions when presented with the impacts of a laser beam on various pigments (phases *M/L2, M/L3*, see codes in Table 2)

Student	Acknowledging the existence of two groups of pigments 2G	Mentioning more or less 'brightness' (B↑) to describe the impacts	Mentioning more or less absorption (±A), intensity (±I) light (±L)			The multiplicative role of a passing band very clearly acknowledged X	Low intensity of the sources: seen as condition for the classical rules to apply with pigments
	Phase *M/L2*	Phase *M/L2*	Phase *M/L2*	Phase *M/L2*	Phase *M/L2*	Phase *M/L3*	Phase *M/L3*
Jo	2G	B↑	±A			X	P
Ju	2G	B↑	±A	±I			P
Me	2G	B↑	±A				P
Mu	2G	B↑	±A			X	P
Op	2G	B↑					P
Sa	2G	B↑					P
Tia	2G	B↑			±L	X	P
Thi	2G	B↑	±A			X	P
N	8	8	5	1	1	4	8

A first striking aspect in the observed reactions is a quasi-general – save Sa, and, to a lesser extent, Thi – effect of surprise, not to say of frustration:

> Jo 181: So, I'm totally wrong!
> Ju 170: Normally, it should be absorbed.
> Me 278: Yes, I thought we would see it, given what was written.
> Op 104–6: (*my predictions*) Err . . . , they are wrong (. . .), it's pretty hard to understand.
> Thi 180: Err, it's not at all the same laws that I actually see and that I had derived.
> Mu 254: I'm lost, it's frustrating.

More positively, one student expresses the feeling that it was possible to get out of this frustrating situation:

> Tia 148, 154: It is not exactly what I had predicted, but anyhow it has something to do with it . . . . There is a relationship, that's for sure!

All of the students acknowledged the fact that the brightness of the impact was different in the two groups of pigments, thus introducing a 'more or less' perspective.

> Op 126,136: It was perhaps more related to brightness. (. . .) When I was saying 'visible impact', I meant 'increased brightness'.

In order to determine more precisely which physical concepts the students might associate with the visual impression of brightness, we looked for occurrences of comments referring to 'more or less absorption' (five out of eight), 'more or less intensity' (one out of eight), 'more or less light' (one out of eight). These cases are not exclusive and, in all, six out of eight students expressed themselves in a way that may be considered as approaching the conceptual target of this teaching experiment.

> Tia 150: When I say there will be no impact, err.. There is less light..
> Mu 248,250: They just absorb less. (. . .), we were thinking all or nothing. (. . .). It was total.
> Ju 184: If the intensity is too great, err, perhaps they *(the filters)* cannot manage . . .
> Jo 199: (*Pigments absorb*) partially.
> Int 200: So, now, you feel in agreement with/
> Jo 201: With what I think, irrespectively of the sheet *(of classical rules)* . . . Err, yes, I have already happened to play around with a laser beam and I never saw a laser disappear.
> Me 262: Perhaps, it *(red light)* was not completely absorbed.
> Thi 190: (*The pigment*) Err, The more concentrated it is, the more absorbent it is, and I know I will never get a perfect absorption.

As explained before, students were then presented with the passing bands of various filters, and invited to comment on the 'feet' of the corresponding curves.

M/L3. The Discussion with the Curves of Absorption

This phase was intended to inject the multiplicative aspect of absorption into the debate, thus going beyond the 'more or less' aspect. We estimate that, during this phase, four students clearly reached that level of comprehension. This decision relies on comments such as the following ones:

Tia 176: 10% of very intense, that adds up to something.
Thi 248: . . . When it's more luminous, the 10% are more consequential.
Mu290: It is the rate of intensities that reads (*on the curves*).
Jo 239: 5% out of a billion, you will see more than 5% out of 2.

It is worth noting that all of the students finally agreed on the condition for an experiment with beams of light cast on pigments to visibly respect the classical rules, in an 'all or nothing' perspective: the light sources should not be too intense.

Int 241: Finally, what should I use if I want to avoid these little problems (*experiments, with pigments, that do not seem to respect the classical rules*)?
Jo 242: One (*a beam*) that's not too intense.

However, for the four students (Sa, Ju, Op and Me) who had not shown a sound comprehension of the multiplicative role of a filter, this operational acquisition was very much accompanied, to say the least, by the interviewer, while notable reservations were expressed by the students themselves concerning their understanding of this crucial aspect:

Thus Sa, discussing the impact of the laser beam on the green paper:

Int 388: Do you understand (that nothing will be visible when 5% of a very weak light is reflectively diffused) (. . .)?
Sa 399: Yes, yes.
Int: (. . .) why 5% do not result in the same effect on a laser beam and on the tiny lights previously used? OK?
Sa: Yes, yes.
Int: You seem . . . ; perhaps you actually have understood?
Sa: Yes, yes. No, but it's those percentages and the . . .

And Ju:

Int 193: What's up at 633 nm? (with a green pigment or a green filter)
Ju 194: Yeah, there is still some left (*light*).
Int 195: Some percents. Percents, it's percents.
Ju196: OK.
Int 197: So it (*green pigment or green filter*) absorbs 99%, therefore it let 1% go. If I tell you 1%, can you understand how I will see something with a laser beam and I will see nothing with another source?
Ju 198: Err . . . actually, it's not very intuitive with percents.
Int 199: I see. You don't find it very intuitive.
Ju 200: Err, with percents, err . . .
Int 201: It's hard?
Ju 202: Yeah.

We therefore consider that a mere agreement on the implications of having, or not, an intense source of light does not mean that the multiplicative role of a filter or pigment is understood.

Finally, two students, including Sa this time, commented on the curves in ways that might be related to the critical role of their feet:

Int 459: What should we do to get an "all or nothing" effect? How should the passing bands be?
Sa 460. Yes ... well sharp.
Int 287: What will make a difference between the experiment that 'works' with the cardboard box (*coloured letters lit with beams of coloured light, bulbs in a black room*) and the one that 'does not work' with the laser beam? Although, saying that it "does not work" *(is just a way of stating that the outcome is surprising)*.
Thi 288: Err, we should take wavelengths that are totally absorbed.

M/L4 Metacognitive Comments and Feelings

The last phase of the interview was orientated by the interviewer towards a discussion at a meta-cognitive level. Students were asked to briefly rate their gain in understanding and their interest and/or intellectual satisfaction at the end of the teaching interview.

Two important results emerge from this phase.

What Students Say they Have Learnt

At the end of this teaching interview, all of the students were able to complete a presence/absence perspective with a 'more or less' approach, at least in their way of describing the outcome of the experiment with the laser beam (Table 5, columns 2 and 3). Six of them had reached a more advanced conceptual stage, using the ideas of 'more or less absorption' and/or 'more or less intensity' or 'more or less light' (Table 5, columns 4 and 5). All of the students, at the very end of the discussion, came back on their conceptual acquisition with a more or less elaborate formulation:

Ju 246: With this interview, I was able to better understand the law of additive colour mixing, and to see the limits of its validity. For instance, it depends on the intensity of the light that is sent on the filter.
Tia 210: The main idea was more focused on the rate of absorption of light.
Jo 301: The difficulty discussed in this interview is how to conciliate absorption of light and colour mixing. (...) (*Red light on green pigment:)* It all depends on intensity.
Sa 471: Finally, it's not "all or nothing", that's for sure !
Op187: Because, I .... Comparing what I did previously to what I did when I performed the experiment *(with the laser beam)*, it's completely different. But I have learnt some things. Not learnt but, err, ... Because what I could write on the work sheet *(during phase M/L1)* and what I could see, it was really different.
Int188: Yes, and so ...
Op189: And so, it shows that we don't necessarily, err, we don't necessarily use the right words to explain something.
Int 190: Or, maybe, there was a missing dimension, a hidden dimension?
Op 191: Yes, this story about brightness.
Me330: *(before)* I didn't have this problem with intensity, I was not thinking of it.

Two students were more precise, mentioning more or less directly the role of the graphs they had been presented with:

Tia196: I thought, how is it that when it is more intense, it does not work the same way as it is explained here (the classical rules). But with the curves, here, of absorption, I can understand.

Mu 341: The most difficult point was the notion of a "window" of frequencies that a body can filter, and the relationship between the intensities received for various frequencies and the observed colours.

It is noteworthy that one student, when coming back to this topic, expressed a feeling of uncertainty that centred on the role of brightness, although he had previously formulated very appropriate comments in this respect.

Thi 252: Concerning brightness, I would need my documents (*on this experiment*) to think further about it.

Students' Feelings at the End of the Interview

The students were invited to express their feelings in terms of interest and/or intellectual satisfaction (Table 6).

Five interviewees expressed their feeling of surprise (four of them had done so previously), and sometimes of destabilization, like Op, quoted above:

Op187: Because, I . . . . Comparing what I did previously to what I did when I performed the experiment *(with the laser beam)*, it's completely different.
Ju 237: Me, I was not expecting that at all/the story about the laser beam, I would have thought that/like the rule/and seeing all these impacts, I was surprised, so, err, I was not expecting that.
Sa 464: The rules that we learned, they do not mean anything, actually.
Sa 473: You have to be suspicious, sure!
Mu 342: I was a little destabilised.
Tia 192: What was interesting was to see that, at least for me, for example, being a teacher, I will give theoretical lessons like that, and I will tell them, here are some lights, when green and blue are absorbed you get red, but//me, I know it, I didn't even think that/in the experiment we would not see it/even me, I was surprised when I saw this.

Table 6. Main characteristics of students' reactions when asked about their feelings at the end of the interview

	Surprised by the outcomes of the experiment with a laser beam[a]	Expresses (again) his/her *surprise*	*Satisfaction/interest* expressed in comments and/or by rating 4 or 5 (on a 1–5 scale)
Student	Phase *M/L2*	Phase *M/L4*	Phase *M/L4*
Jo	Yes		Yes, but dissatisfied with his answers
Ju	Yes	Yes	Yes
Me	Yes		Yes
Mu	Yes	Yes	Needs further thought
Op	Yes	Yes	Yes
Sa	No (her experience)	Yes	Yes
Tia	Partly (thinks of his experience)	Yes	Yes
Thi	Yes		Yes, needs further thought

[a]Some previous reactions are recalled here.

When asked whether they were dissatisfied with the explanation received for such and such a question, only one student (Mu), who previously had shown a very good level of understanding, expressed a need:

> Mu 340: I will have to check it once again.

The seven other students were very positive about the teaching interview:

> Me 326: As for me, it brought me new ideas, it clarified . . .
> Ju 235: Sure, I won't forget.
> Ju 239. Before, I would not have understood, now, I do.
> Tia 190: I am pleased.
> Jo 298: Ah yes, in this respect (*the explanations*) it was perfect !
> Thi 250: In any case, I have had some fun with colours. Moreover, I had always been blocked with colours because the rules with paints and the rules with lights are not the same, and it's something that rather mixed me up. So I am rather pleased to work on this in a relaxed way.

Ju, Op, Sa and Me explicitly awarded the interview a very good mark (5 or 4/5) in terms of interest and/or intellectual satisfaction, whereas the others preferred to express their opinions only in words.

Thus, for seven out of eight students there are very clear clues as to the benefits they think they obtained during this teaching–learning interaction, beyond the first surprise effect. One of them (Thi) added that he would need to think further on these matters.

For another (Mu), the clue to his interest was an excellent, long and fruitful interaction with the interviewer, but in the end he mainly expressed his need for further thought about the physical content of this interview – this despite the fact that he had shown a sound understanding of it.

The only dissatisfied comment was when Jo declared:

> Jo 294: I was interested, but I am not pleased (. . .) with my answers.

Recapitulation and Final Remarks

This investigation is informative on two levels, the design of a research-based sequence on colour phenomena, on the one hand, and a much more general question, i.e. students' intellectual satisfaction, on the other hand.

Concerning a sequence on colour phenomena, our results come in support of our main expectations. When presented with two different experiments, one in the frame of an 'all or nothing' analysis, the other centred on the idea of 'more or less' absorption, all of the students were very surprised, even destabilized. This feeling of surprise was confirmed in the end, when students came back on their cognitive path in a metacognitive register.

More specifically, when asked to predict how the impact of a laser beam would appear on different pigments, nearly all of them took into account two groups of situations. The first group consisted of impacts on black, blue, green or cyan areas, the second comprised impacts on red, magenta and yellow areas. Apart from one student who consistently relied on her personal experience, the predictions were compatible with a total absorption of the red beam in the first group of situations. The second group gave rise to more doubts, and in some cases, to some attempts at using rules of additive mixing. Interestingly, the first allusions to a greater or lesser brightness of the impact were raised by the 'red on red' situation, that is when the colour of the impact in no way could help predict whether this impact would be visible or not. As in previous investigations by Chauvet (1996), students did not express themselves in terms of 'more or less light' – either when commenting on absorption or diffuse reflection.

Once the experiment was performed, the two groups of pigments still seemed relevant to students in order to formulate what they had seen. All of them expressed themselves in terms of a 'more or less' bright impact. Although the role of light was not salient – to say the least – in their explanations, we consider this reaction as likely to facilitate further learning. We would suggest it may act as a kind of 'anchoring cognitive reaction', a designation echoing what Clement et al. (1989) called an 'anchoring conception'.

In the end, a few of them could even explicitly explain the outcome of this experiment: the classical rules still hold, provided we now speak of 'more or less' absorption. The surprising situation proposed to students provides an example of the need for extended rules, which are – in passing – more compatible with daily life.

The transmission curves were intended to clench a multiplicative approach to absorption among the students. It is not very risky to assert that, without the discussion initiated about the absorption curves and their 'feet', the surprise generated by the observations described above would not have sufficed to foster the students' understanding. But the interpretation of the curves turned out to be a very difficult step. This level of difficulty was not quite expected. Clearly, it has to be very seriously taken into account in any attempt at using such a tool, especially with still more novice students. We had no clue that the analogy between a filter and a pigment might be an obstacle. The stumbling block seemed to be the multiplicative meaning of the curves.

Very few students were able to explain clearly the surprising outcome of the experiment with the laser beam, with reference to the multiplicative effect of absorption. But all of them recognized the role of the brightness of the source in the contrasted results of the two experiments. We consider this fact to be the second important 'anchoring cognitive reaction' on which to build our forthcoming sequence.

Our results orientate the choice of the *a priori* hypotheses for the design of a possible teaching learning sequence. Certain elements of this teaching experiment should, we think, be injected in a sequence targeted to the same conceptual objectives. In particular, briefly put, we suggest that the succession of the 'ritual' experiment and the experiment with the laser beam should be taken up. The effect of surprise and a perception of the role of the intensity of light could be counted on. At a more fine-grained level, using the 'red on red' situation is considered as favouring, *a priori*, an emergence of the idea of brightness and that of 'more or less' light and/or of 'more or less absorption'.

However, given the difficulties observed, particularly regarding the transmission/diffusion curves, we think it is necessary to give special attention to the comprehension of the 'more or less' aspect; namely, to its multiplicative implications. To this end, certain activities with filters, including measurements, might be usefully implemented. Indeed, filters are more easily associated with the absorption of light than pigments (Chauvet, 1994), and this point might be worth considering even if the students did not express any particular difficulty concerning the analogy between these two kinds of absorbing objects. Our investigation also suggests that we should be very careful with the type of audience targeted, so that a proportional reasoning is not, *de facto*, beyond the students' grasp. These points should be discussed, of course, keeping in mind the available teaching time and other systemic constraints bearing on the implementation of such a sequence.

Concerning the feelings expressed at the end of the teaching interview, students unanimously confirmed the surprise they had felt, and nearly all of them expressed a very high level of satisfaction, despite the required intellectual effort. In particular, the fact that their initial knowledge was not invalidated but completed was very much appreciated. We would like to stress the more nuanced comments given by three students. One was dissatisfied with his own responses, the others said they would like to think further, whereas their responses had been among the best that we collected in this sample. We suggest that aiming at provoking in-depth reflection may clench a renewed exigency. We consider this result worth exploring further. As previously argued, there are not many investigations exploring this connection between affective and cognitive reactions, in the register of what might be called 'intellectual satisfaction'. We therefore suggest that more investigations be focused on this theme.

The help received from the reviewers is gratefully acknowledged.

Notes

1. http://maths-sciences.fr/documents/quatrieme/sources-de-lumiere-4eme.pdf, http://www.sciences92.ac-versailles.fr/spip/spip.php?article27. Links verified on December 8th of 2011.
2. See for example: http://www.physicsclassroom.com/class/light/u12l2e.cfm

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Appendix. Additive and subtractive mixing: the classical rules

Here, the colours are associated with 'thirds of the spectrum'

Additive mixing

Separating the various radiations that constitute "white" light gives a "spectrum". The spectrum of white light ranges from $\lambda = 400$ nm to $\lambda = 700$ nm. (λ: wavelength in empty space; 1 nm = 10^{-9} m)

Here the spectrum is divided diagrammatically into three equal parts.

Coloured lights with a spectrum corresponding to a third of the preceding one are seen respectively as

red in the long wavelengths

green in the medium wavelengths

blue in the short wavelengths

Combining these three lights in various proportions produces a wide range of colours and, when the proportions are right, white.

Adding two of these lights in correct proportion gives respectively a light seen as

- yellow if you add red light and green light
- cyan, if you add blue light and green light
- magenta, if you add red light and blue light

Substractive mixing

A filter (or a pigment) absorbs a part of the spectrum of white light :

- a yellow filter absorbs blue light (a third) and diffusely reflects green and red lights.
- a cyan filter absorbs red light (a third) and diffusely reflects blue and green lights.
- a magenta filter absorbs green light (a third) and diffusely reflects blue and red lights.

When illuminated in white light, two superposed filters or two blended pigments send back (transmit or diffusely reflect) to the eye only the part of the spectrum they have in common:

yellow+magenta filters => red light

cyan + yellow filters => green light

magenta + cyan filters => blue light