Colour Phenomena and Partial Absorption

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Abstract
This 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 partial, instead of as total or zero. These conceptual steps, indeed, are essential to reconcile classical school knowledge about colour and observation of daily life phenomena.

Key words: colour, partial absorption, dichotomic approach.

Why this experiment?
Concerning light and colour, some prototypical statements 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. In fact, the impact of a red laser beam remains visible whatever the colour of the surface on which the light is sent might be. Such ritual comments are based on an oversimplified view of the real world involving an ‘all or nothing’ reasoning process, whereas light should be considered in a quantitative way.

In the same way, the rules of additive mixing are classically stated in an “all or nothing” style. They 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.

The experiment presented in this paper (CPA: colour and partial absorption) is intended to help students pass 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. So doing, we intend to facilitate the comprehension of absorption in the context of colour phenomena, a concept that has proved to be very difficult (Chauvet, 2006). We will see that this means to focus on the multiplicative aspect of what is somewhat improperly named subtractive synthesis.

A recent research (Viennot & de Hosson 2012) has permitted to evaluate the added value of this proposal.

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1 The MUSE group (Gorazd Planinsic, Elena Sassi and Laurence Viennot) takes responsibility for the content of this paper (June 2012). The intellectual property remains with the authors.
Prerequisite and targeted conceptual steps

The classical rules. We consider an audience of students knowing, or having just been reminded, the classical rules of additive and subtractive mixing (Box 1).

Box 1. Additive and subtractive mixing: colours associated with "thirds of the spectrum".

<table>
<thead>
<tr>
<th>Additive colour mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>The spectrum of visible white light ranges from $\lambda=400$ nm to $\lambda=700$ nm.</td>
</tr>
<tr>
<td>($\lambda$: wavelength; measured in a vacuum; 1 nm = $10^{-9}$ m).</td>
</tr>
<tr>
<td>The spectrum is here schematically divided into three thirds.</td>
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<tr>
<td>Coloured lights with a spectrum corresponding to a third of the spectrum of white light</td>
</tr>
<tr>
<td>in long wavelengths appears red</td>
</tr>
<tr>
<td>in intermediate wavelengths appears green</td>
</tr>
<tr>
<td>in short wavelengths appears blue</td>
</tr>
<tr>
<td>Combining these three lights, in various proportions, results in a large range of colours and can also give white light.</td>
</tr>
<tr>
<td>Combining two of these lights in the correct proportion respectively gives a light that is</td>
</tr>
<tr>
<td>- yellow, if green light and red light are added</td>
</tr>
<tr>
<td>- cyan, if green light and blue light are added</td>
</tr>
<tr>
<td>- magenta, if red light and blue light are added</td>
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</tbody>
</table>

| Subtractive colour mixing: A filter (or a pigment) absorbs a part of the spectrum of white light |
| - a yellow filter (or a pigment) absorbs blue light (a third) and transmits (or diffusively reflects) green and red lights. |
| - a cyan filter (or a pigment) absorbs red light (a third) and transmits (or diffusively reflects) green and blue lights. |
| - a magenta filter (or a pigment) absorbs green light (a third) and transmits (or diffusively reflects) red and blue lights. |
| When illuminated in white light, two superimposed filters or two blended paints send back (transmit or diffusely reflect) to the eye only the part of the spectrum that they have in common: |
| yellow + magenta filters or pigments $\Rightarrow$ red light |
| cyan + yellow filters or pigments $\Rightarrow$ green light |
| magenta + cyan filters or pigments $\Rightarrow$ blue light |
If necessary, it is possible to use various set-up of “coloured shadows” type (Olivieri et al. 1998, Chauvet 1996, 1999: see Figure 1, Planinsic 2004, MUSE paper: Planinsic & Viennot 2010,) to remind students with the classical rules of additive or subtractive colour mixing.

Figure 1. Coloured shadows:

a) A setting to demonstrate the classical rules of colour phenomena (Chauvet, 1996)
b) A photo of what can then be observed on the screen and on the tetrahedron, with symbols suggesting, in three areas of the screen, the spectral composition of the impacting light (each coloured box indicates the fact that the corresponding coloured light reaches the considered area).
c) View of the same situation from above (credits: Pascal Sauvage)

Note that with coloured shadows, the presence of an obstacle ensures a complete blockage of some beams of coloured light in some directions. For instance, a cyan area can be seen as resulting from the impact of white light (see the white background on the screen) “minus” the “red” third of spectrum, given that the red beam has been blocked by the tetrahedron. In other terms, this setting is an “all or nothing” arrangement: a given beam reaches (additive process), or not (subtractive process), a given area.

Still more simply, the rules needed in CPA experiment are mainly those related to subtraction by a single pigment. Classically, these rules are, verbally or graphically, outlined as in Figure 2.
Figure 2. The classical rules of the subtractive role of pigments, also valid with filters

They are classically demonstrated with experiments such as the one illustrated in Figure 5.

Figure 3. Colored letters illuminated by different coloured lights (for instance red) in a dark room will be very visible (with red light: red, yellow, magenta) or not (with red light: green, blue, cyan).

**Beyond a dichotomic analysis**

With this type of presentation, white light is understood as comprising three components, red, green and blue; or, in more academic terms, three thirds of spectrum of relatively large, medium or short wavelengths in the interval 0.7µ -0.4µ. From there on, in order to analyse various situations of colour mixing, a given “third” may be considered as being “there” or not, regardless of the intensity of the corresponding component.
However, concerning additive mixing, it should be clear that if a very bright red beam of light converges on a screen with a very faint green beam, the impact zone will not be yellow but red. Similarly, concerning subtractive mixing, the impact zone of a very intense beam of, say, red light on a given pigment, say green, is red, in practice, because the absorbing power of the pigment is not 100%. By contrast, with an “all or nothing” perspective, the impact zone of a red light on a green pigment, for instance, would be predicted as black. The same remarks hold for a black area. It is often said that “black absorbs all the light”, whereas the minimum reflecting power reached for a black material is about 0.045%.

In fact, in order to guide usefully our interpretation of daily life phenomena, the classical rules should be understood as indicating the outcome of
- additive mixing of coloured lights of appropriately balanced intensities;
- subtractive process with enough absorption for a given light to become visually undetectable; keeping in mind that a statement like “a green pigment absorbs mainly red and blue lights” holds in any case.

Consequently, the main conceptual step targeted with CPA experiment is the following: The student should pass from “all or nothing” perspective to a “more or less” one. With this experiment, the work is centered on the case of subtractive mixing with pigments (other experiments might help students pass this decisive step in the context of additive mixing, a case a priori more simple). One essential aspect of the targeted comprehension is that a very low value of percentage of transmission (by a filter) or diffuse reflection (by a pigment) may result in a perceptible effect when the incident light is intense. This multiplicative aspect of colour subtractive synthesis leads to a more appropriate view with respect to both everyday life phenomena and physics.

**Materials**

- A red laser pointer (633nm), quite ordinary
- A white sheet of paper covered by a large black rectangle, itself comprising six coloured zones. These six areas are, respectively, printed with the six basic pigments of the graphics palette of a computer (red, green, blue, yellow, cyan and magenta: Figure 4 can be printed and used). The order of these colours is probably irrelevant in terms of students’ comprehension.

![Figure 4. Sheet of paper with white, black, and differently coloured (red, green, blue, yellow, cyan and magenta) areas](image)

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2 *Sciences et Avenir*, March 2008, p 23, announced this record held by a team of Rensselaer Polytechnic Institute (USA)
- A room with dim ambient light. In an ordinary room, a big cardboard box – like those used to deliver food – can be used by groups up to three people to perform the needed observations.

- A sheet displaying typical absorption curves of filters or of pigments, red, green, blue, like the one shown in Figure 5.

![Absorption curves of primary blue, green and red filters](image)

Figure 5. Absorption curves of primary blue (left), green (middle) and red (right) filters. 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.

**Staging sequence**

A possible staging for a sequence using CPA experiment comprises the following main steps:

1- Ask justified predictions concerning the impact of the red laser beam on the various zones of the sheet.

2-Ask students to perform the experiment. This should be done in dim light, so that the colours on the sheet be visible; given that too much ambient light would attenuate the targeted effect of contrast (described in the next item).

3-Ask students to situate their predictions with respect to what they observe. 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 across the different pigments, low for the latter group, high for the former.

4-Ask them to explain the surprising outcome of the experiment. The targeted comprehension is 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. To this end, the curves of absorption are provided at this moment. The meaning of these curves should be duly explained to students, who, most of the time, are destabilized by this confrontation (see below). What should be particularly considered in the absorption curves (see Figure 5) is the foot of the each curve which reaches the wavelength value of a red laser beam (633 nm). As said above, 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 intensity of the incident flux: 1% of “a lot of” incident light provides a non negligible amount of diffused light.

5-Conduct a final discussion about the difference between the classical experiments such as the one depicted in Figure 5 – when the classical rules (understood in an “all or nothing” register) seem to apply properly, on the one hand, and the PA experiment, which apparently invalidate these rules, on the other hand. The decisive factor – the power of the light sources – should be identified, and justified.

6-Lead students toward a conclusion: properly formulated, the classical rules are not invalidated by CPA experiment. Ask them to recapitulate their conceptual acquisitions and their feelings in this respect.

Students expectable reactions

We provide here some results of an exploratory research bearing on the sequence described in the preceding section. The research was conducted with eight prospective physics and chemistry teachers (third-year University). These students can be considered as very likely having been taught colour phenomena in a ritual way (basic rules of additive and subtractive colour mixing). Interviewed individually, they were first reminded these rules with the experiments shown in figures 3 and 5, and were given the reminder displayed in Box 1, throughout the interview.
We suggest that their reactions may be shared by various populations of students, or at least be useful to know in order to guide teachers’ reflection when observing their own students.

Predicting the outcomes of partial absorption of a laser beam (item1 of the sequence).

In this first part, it was observed that, concerning the pigments commonly described as “absorbing red light” (black, blue, green, and cyan), a majority of students (6/8) predicted, for at least three of these four areas, that the impact of the laser beam would not be visible on the background. Therefore, these students behave as if they were applying the classical rules. They were often very explicit in this regard. No mention of partial absorption was made.
Only, two students expressed some doubts concerning black, and also expressed a view linked to common experience:

We will see a little something (with black) but it will be less sharp than …
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.
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. Her approach to the problem was firmly rooted in her personal experience, without any possible discussion.

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 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 localising - or not - a red spot on a red background. Among the five students who did not call on a contrast of “brightness”, some predicted a localized impact without justification, and the others predicted that the impact would not be localized, as in this comment:

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).

Reacting to the outcome of CPA experiment (item 3).

A striking aspect in students’ reactions to the experiment, once performed, is a quasi-general effect of surprise, not to say of frustration:

So, I’m totally wrong!

Normally, it should be absorbed.

Yes, I thought we would see it, given what was written.

Err, it’s not at all the same laws that I actually see and that I had derived.

I’m lost, it’s frustrating.

One student expressed the feeling that it was possible to get out of this frustrating situation:

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. Moreover, students went further and raised the idea of “more or less absorption”. This occurred in 6/8 students who expressed themselves on this theme, with comments in terms of “more or less absorption”, “more or less brightness”, “more or less intensity”, “more or less light”.

When I say there will be no impact, err.. There is less light.

They just absorb less. (…) , we were thinking all or nothing. (…). It was total.

If the intensity is too great, err, perhaps they (the filters) cannot manage …

Perhaps, it (red light) was not completely absorbed.

I know I will never get a perfect absorption.
Discussing the absorption curves (item4).

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, only half of the students clearly reached that level of comprehension, with comments like the following:

- 10% of very intense, that adds up to something.
- 5% out of a billion, you will see more than 5% out of 2.

Clearly, the multiplicative meaning of the curves was difficult to grasp for several students, as in this dialogue:

Int: 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?
Student: Err …actually, it’s not very intuitive with percents.
Int: I see. You don’t find it very intuitive.
Student: Err, with percents, err …
Int: It’s hard?
Student: Yeah.

Briefly put, the interpretation of the curves turned out to be a difficult step. We have no clue that the analogy between a filter and a pigment might have been an obstacle. The stumbling block seemed to be the multiplicative meaning of the curves.

Discussing the difference between experiments: the critical role of the sources (item5).

Despite this difficulty, 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.

Note that this does not necessarily mean a complete comprehension of the multiplicative status of absorption. Only a few comments really witness a sound comprehension of this aspect, as with two students who discussed the critical role of the feet in the curves:

Int: What should we do to get an « all or nothing » effect? How should the passing bands be?
Student: Yes … well sharp.

Int : What will make a difference between the experiment that “works” (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).
Student: Err, we should take wavelengths that are totally absorbed.

Students’ concluding comments

At the end of the interview the students expressed again their surprise:
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.

There was a quasi general expression of intellectual satisfaction:

As for me, it brought me new ideas, it clarified …

Sure, I won’t forget.

Before, I would not have understood, now, I do.

Only one student has some reservations, although he had shown a very good level of understanding:

I will have to check it once again.

Recapitulation: added value, difficulties and students’ facilitating reactions

To sum up, the expected added value for such a sequence is to overcome a dichotomic view on colour phenomena; i.e. a way of reasoning by presence/absence of light (if not of “a colour”). Instead, the targeted comprehension relies on the idea of “more or less” light, and more specifically, regarding CPA experiment, of partial absorption with a multiplicative status. Note that this focus may be seen as a factor likely to promote a way of reasoning based on light itself, instead of a mere algorithmic manipulation of rules concerning “colours”. Also, we think it noteworthy that some reactions may be observed in students: showing from the start a high level of comprehension, these students express in the end an increased exigency. We therefore suggest that aiming at provoking in-depth reflection may clench a renewed exigency even in “good” students.

The difficulties should not be underestimated. They are, in particular, linked to the following aspects:

- The novelty of the approach, be it for students or for teachers. It is ritual to present the rules concerning colour phenomena in a reduced way, be it verbally or diagrammatically, without mentioning the power of the light sources and the implications of this aspect in the observed phenomena.
- More globally, this ritualistic – dichotomic - approach extends to many topics in physics, for instance shadows exclusively seen as total, or with discontinuous transitions to penumbra (Planinsic & Viennot 2010).
- The multiplicative meaning of absorption coefficients is far from obvious to students. Probably this state of affairs has to do with the well known general difficulties concerning proportionality.
- In the context of light phenomena, the very use of light as a base for reasoning is not straightforward to students (see for instance Chauvet 1996). The same can be said, a fortiori, concerning a certain rate of incident light.

We can thus predict that, most probably, this type of sequence (with experiment CPA) is relatively exigent in term of intellectual process. It is then advisable to anticipate by planning a substantial time for explanations, even if the experiment itself is very simple to perform.

In this intellectual process, some students’ reactions appear as likely to facilitate their progression:

- Although they are very surprised by the outcome of CPA experiment, all of the students easily perceive the existence of two groups of pigments, corresponding to two levels of brightness, high with the “non absorbing pigments” (in dichotomic terminology), low with the “absorbing pigments”. The question of the impact of a red beam on a red pigment efficiently clench a “more or less” approach in students. With a presence/absence perspective only, indeed, the red impact would not
be predicted as visible on the red background, a fact contrary to what some students predict and to what all of them observe (in our limited investigation).
- The role of the power of the sources is acknowledged by all of the students when it comes to discuss the difference between the experiments classically used to demonstrate the basic rules of colour phenomena, on the one hand, and the CPA experiment, on the other hand.

It is therefore recommended to use these points as conceptual back-ups in a sequence using this experiment.

**Links with other experiments**

Further reflection and experimentation should be conducted to associate this type of conceptual progression to a similar one concerning filters. With filters, the same type of discussion and of progression seems quite relevant. A red laser beam “passes through” a green filter, being strongly attenuated. Although no research results is available (to our knowledge), informal information suggests that students are much less surprised with this result than with pigments. The analogy between pigments and filters is then worth discussing with students. However, the case of a black area impacted by a laser beam is less easy to mimic with filters than with pigments, given that any solid ordinary obstacle will totally block off the beam of an ordinary laser pointer.

At an elementary level, the idea that more or less light produces various effects in terms of vision – in particular dazzling - is also worth discussing. This has been experimented by de Hosson and Kaminski (2007), with the goal to convince children that for vision to occur, it is necessary that some light coming from the object enters the observer's eye.

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**References**


