Light the world and change its color: A case study in Italian secondary school using IBSE methodology

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Abstract. What color is it? It is not a trivial question: answer depends on the lamp used to light the world! Let’s fix a light and measure with our human instruments, eyes and ears, a colored and orchestral environment: may we distinguish, at the same time, all the colors and sounds? Here we show a case study using Inquiry Based Science Education (IBSE), a teaching methodology, focused on the wave-matter interaction in daily experience and some ways to detect it by our senses. IBSE methodology engages students eliciting investigation of physical phenomena. General expected outcomes are an improvement of students' motivation and a more successful learning experience. We planned an educational path, based on investigation, for students attending the first year of high school. The course has been developed in four lessons (2.5 hours each) for a total of 10 hours. This path has been experimented in four different parallel classes. In each class, students have been divided into 5 or 6 groups. The first phase, “engage”, is a simple trick: try to guess the color of four cards lighted with a monochromatic beam, red, blue, or green, in the dark. Once a white light is turned on, students will be surprised to see the true colors of the cards. After this “engagement”, students “explore” interaction between wave and matter, accomplishing some tasks and trying to “explain” the observed phenomena. The third and most important step is to “extend”: students directly experience additive color synthesis, with attention to pointillism, to subtractive color synthesis, and to superposition of sound. Later, each group, as in a flipped lesson, looks for answers to preliminary questions, by investigation: ear and eye behaviour, differences between electromagnetic and sound waves, electromagnetic spectrum. ICT is a valuable support in this phase. A multimedia product is requested at the end of investigation. In order to “evaluate” this educational path, it has been proposed to think about the use of a monochromatic lamp to change a colored word in another one, without some yellow and red letters. A feedback questionnaire has been also used to evaluate the educational path. The results of the questionnaire show that students are satisfied with this new methodology and activities. Satisfactory results, however, depend upon teacher's ability to motivate all students in attending classes.
1. Introduction

According to the Rocard Commission report [1], many young people do not develop interest in science. Motivations are complex, but there are clear links between teaching methods and the development of positive attitudes towards science. This trend is also detectable by analysing tests administered to about 100 students from Campania on the interest towards scientific subjects [2]. Answers to the question: “Why do you not do well in the scientific subjects?” very commonly referred to scientific disciplines being taught in a non-engaging way, often using a transmission teaching. Often Physics is reduced to a mere application of formulas, and little use is made of laboratory teaching.

For this reason, teaching based on a behaviourist approach is fading and constructivist ideas, based on an active approach, is rising up [3]. The focus is to make an epistemological switch from learning for using to using for learning, with an enhancement by concrete thinking with respect to theoretical thinking. In the last few years, several studies in Science Education in Europe supported learning based on Inquiry to contrast the indifference of young people towards Science and Maths and to develop in all the citizens a scientific literacy, necessary for long life learning [4].

Inquiry is a series of processes implemented by students in an intentional way such as: knowing how to diagnose problems, critically commenting on experiments and identifying alternative solutions, knowing how to plan an investigation, formulating conjectures, searching for information, building models, knowing how to discuss and compare between equal, formulating coherent arguments [5].

The first studies on inquiry and on the IBSE (Inquiry Based Science Education) method are due to Rosalind Driver and date back to the 1970s and 80s [6]. Interest in this method has grown over the years and it is now considered by most researchers in teaching as the most effective teaching strategy. IBSE teaching guides students to follow, step by step, the scientific process starting from observation, then enunciating the problems, checking the variables, making hypotheses and predictions, and describing the conclusions. In IBSE teaching, laboratories are an integral part of the course, too. Moreover, it encourages personal thinking, asking questions, peer discussion and debate. During these activities, students work in groups to promote the higher mental functions originated by the interaction and to allow the development of skills such as social negotiation of meanings.

2. Case study

Here we present a case study focused on wave–matter interaction in daily experiences. A group of researchers/teachers planned this multidisciplinary educational path. It has been experimented on about 100 students, attending to the first year (aged about 14) in four different high schools in Campania, a region in Southern Italy. The educational path is easily repeatable: the teaching tools are easy to find and carefully implemented and shared using cloud software; the topics are general enough to fitted well in different multi-level classes. For these reasons, this educational path could be regarded as a best practice in high schools.

The timetable was scheduled in four lessons, each of 2.5 hours, for a total of 10 hours. In order to achieve a better learning experience, we chose to arrange students in working groups of 5 to 6. The students carried out experiments and thought about a natural concept, well known since they were children: color. Through the steps listed below, they deduced that color is not an intrinsic feature, but it depends on the light shining on the objects. They experimented with additive and subtractive color models and light diffraction. Nevertheless, they deduced the main wave characteristics, extending to the electromagnetic wave spectrum. They compared an electromagnetic wave as light with an elastic wave as sound and eye with ear behavior, too. Surprisingly, they found something they were not looking for, a classic example of serendipity.

Color also depends on eye physiology and on the brain (for example, chromatic perception changes with light intensity). Therefore, color analysis involves both light-matter interaction and human vision mechanisms. In this work we mainly focused on light-matter interactions, whereas physiological aspects have been developed by using a flipped methodology.
3. Methodology

IBSE methodology has been used using the 5E Model [7], and TEMI (Teaching Enquiry with Mysteries Incorporated) [8]. Students have been involved in “re-discovering” natural phenomena in the world around them, these phases being strictly connected to scientific Galileo’s method. Moreover, these phases reflect mental steps that not only scientists, but also ordinary citizens follow when they acquire a new knowledge and a new skill, by organizing data, planning hypotheses, and verifying solutions:

1) Engage: the teacher creates a “surprising” scenario, taking care of all details, in order to highlight the main characteristics of phenomena to be analysed. In this phase, according to TEMI’s idea [8], a mystery must be included in the script. It is well known that mystery creates expectation, astonishment, and curiosity, and we agree that necessity may be the mother of invention, but curiosity is the mother of discovery. Thanks to a mysterious scene, students are engaged and discuss “what is interesting in the observed phenomenon”.

2) Explore: students “explore” by themselves, organizing specific experiments to verify their preliminary idea and trying to discover “what is happening”. The teacher is simply a moderator both in this phase and in the next one.

3) Explain: students try to explain main results of previous experiments, they make some hypotheses and create a simplified model of the reality, just searching an explanation to the question “what is causing it”.

4) Extend: probably the most interesting phase, because students acquire skills. The guide question is “what is similar about the previously discovered phenomena?”. They apply results of previous experiments, in different areas of interest. Multidisciplinary and interdisciplinary activities are expected in this phase. Because of several and different extensions, starting from the same Explore/Explain phase, we prefer to call this phase Extends. The 5E model is indeed circular, so new Engages could arise from Extend phases.

5) Evaluate: the education path has to be evaluated, both by fitting tasks in all the phases and final experimental requests or questionnaire.

Because of its variety, different active methodologies have been tried in the Extend phase, in order to achieve better student involvement: laboratory activities, learning by doing, problem investigation and solving, flipped classrooms, peer to peer education, debate. Vicariance has been also used in this phase. The term vicariance, used in ethology about living organisms, in education philosophy and theory context represents the creative ability of the brain to use multiple and often unusual strategies to reach a goal, to replace a sense or to replace one process with another.

Last but not least, a “learning by playing” methodology has been applied in all experiments. Playing, children can develop social and cognitive skills, become emotionally mature, and get the self-confidence required to engage in new experiences and environments.

4. Instruments and ICT

For each group, laboratory desks have been equipped with RGB lamps, colored inks, thick paper, and pencils. The tasks, white paper, questionnaires, students’ notes, and products have been collected in colored small folders. Nevertheless, the main instruments used by students are their eyes and ears, in order to have “wave measurements”.

Our students are digital natives; moreover, the Italian Ministry of University and Research (MIUR) published guidelines to introduce education by media. Following these guidelines and taking account of students’ talents, ICT has been employed for communication, documentation and sharing information. Lessons have been taken in multimedia labs, where a LIM and several PCs were placed, but we also used smartphones and tablets as in Bring Your Own Device (BYOD) practices.

All phases have been well-documented by using cloud software (Padlet), a virtual wall where students may post comments, files, figures, links, pictures, and video. All students, supervised by teachers, had access to the same wall, and could visualize all posts, but they couldn’t modify other people’s posts. Details of all educational paths, together with proofs of students’ enthusiasm, passion and curiosity are on the Padlet walls.
5. 5E Phases
Here we briefly describe the 5E phases, with particular emphasis on the Extend phase.

5.1. Engage
The teacher, wearing a wizard’s hat and a mysterious bag, appeared on a dark stage... all students were waiting for something. Using a red beam, the teacher illuminated four colored thick pieces of paper on a white wall. The students were asked to answer a simple question: “What colors are they?” The same question was asked when teacher used green and blue monochromatic light. Finally, white light was switched on and students observed what they called the “real colors”. Fig. 1 illustrates this Engage phase.

![Engage phase: colored paper illuminated by (a) red, (b) green and (c) blue monochromatic light, and (d) white light. b) also shows a teacher wearing the wizard hat. Fluorescence can be evidenced in c.](image)

Students were surprised that the colors were different, depending on the light. Moreover, they also observed that one of the sheets of paper was fluorescent, but only under blue light. The engage phase was fundamental to going beyond students’ misconceptions; in particular, they realized that color is not a material property. It is known that Newton first observed that colors are due to interaction between light and objects [9]. The main details about color vision may be found in [10].

5.2. Explore
In this phase, students explored light-matter interaction, supported by lab data sheets. Each group had a set of 12 colored sheets of paper, and they explored how their colors changed depending on the light. They had to write on a form (SCH1) what color they observed and if the colors were dark or light under red, green, blue and white lamps, respectively. Students were invited to compile an “Explore Form”, allowing them to add their observations about the experiments.

All students, in different schools, successfully did these simple experiments. An analysis of the forms compiled shows that students tended to distinguish different color hues; this is more evident when girls are in the groups.

5.3. Explain
A sheet with some tasks and questions guided students to “discover” the main characteristics of the light-color connection, following the idea of What, Why, How:

a) Are there papers that are always dark/light under all the beams?
b) Why are we interested in them?
c) How are the color of the light and the color of the paper connected?
d) What is different under white light?
e) Why is the color of the sheet different depending on the color of the light?

The aim of this phase was to relate the observed colors together with the frequencies of the absorbed and emitted light.

By analysing the students’ answers, we deduced that all groups answered all the questions, but their explanations of the phenomenon were not always satisfying. Debate and peer-to-peer education were effective and incisive to overcome these eventual doubts and misunderstandings of the students.
5.4. Extend

In this phase, experimental evidence previously obtained was applied to different frameworks. A first natural question is: “What happens if two or three monochromatic lights are superimposed?” Students investigated the Additive Color Model by experimentally superimposing RGB lights. They were surprised that addition of all RGB lamps generated white light.

Applications of the Additive Color Model can be found in art, especially in pointillism, a technique of painting developed in France in 1886 by Seurat and Signac: small, distinct dots of color are applied in patterns to form an image. This technique relies on the ability of the eye and mind of the viewer to blend the color spots into a fuller range of tones.

Some pointillism pictures, in contrast with an orchestral midi (Musical Instrument Digital Interface) were presented to the students. They observed that eye and ear behave differently: the eyes perceive the mean of colors of adjacent spots whereas the ears may clearly distinguish all sounds. Moreover, the “investigated waves” were different: electromagnetic waves instead of elastic waves. Interesting debates and discussions suggested us to use a flipped classroom methodology: students were invited to search information about ear-eye behavior and electromagnetic vs. elastic waves. A final product was requested from the students.

The flipped lessons were obviously different, depending on the schools. Some students focused on human vision mechanisms and eye physiology, whereas other students found interesting new information about perceptual phenomena, or got more deeply involved in ICT elements.

Concerning human vision, a group of students was interested in a specific phenomenon, such as metamerism and how eyes make additive color mixtures: our retina, which covers the back of the eye, contains light receptors called rods and cones. Rods are used for night vision and they only let you see in shades of gray. On the contrary, all three types of cones respond to a wide range of wavelengths, but one type is the most sensitive to long wavelengths (the red end of the spectrum), one to medium wavelengths, and one to short wavelengths (the blue end of the spectrum). With just these three types of cones, we are able to perceive more than a million different colors.

Another group found something useful without looking for it (serendipity): they were investigating hearing and eyesight and they found the “McGurk effect”, which is a perceptual phenomenon that demonstrated interaction between hearing and vision in speech perception. A future teaching path will be devoted to this effect [11]. Noteworthy also is a group that realized a transduction experiment: a word pronounced in a microphone switched on a lamp. It was a good and very original product and it was realized just by using simple instruments (a paper box, a lamp, a battery, a microphone and a simple circuit).

This part of the Extend phase had a great success: students generally produced high quality video or Power Point files, or both. Their products show a capability to summarize; originality; and scientific and Information Technology talents. Some unusual strategies were developed by our students (vicariance). The Additive color model also suggested to our students the possibility to interpret a physics phenomenon by using mathematics, in particular set theory. This Extend aspect will be also an objective of a future educational path.

The Extend phase continued with a new question: “What happens if we put an obstacle between light and wall?”, where lights were red, green and blue lamps and/or a superimposition of them. Our students were surprised about “colored shadows” (see Fig. 2). In fact, by using three RGB monochromatic lights it is possible to have shadows of seven different colors: by blocking two lights, you can see a shadow of the third color; if you block only one of the lights, you get a shadow whose color is a mixture of the other two (for example, by blocking the red light, the blue and green light mix to create cyan). If you block all three lights, you get a classical black shadow.
Fig. 2. Colored shadows obtained by putting hands or body between monochromatic lights and a white wall.

The additive color model is also used in IT, in particular in all monitors, screens and displays (from smartphone to LCD TV and PC). In a flipped lesson a group explored these specific applications. On the opposite, the subtractive color model is used in printers. Our students also investigated the subtractive model, using colored inks and pencils. Some results are shown in Fig. 3. Nevertheless, color mixtures have been also compared with colored filters (as used in photography): if a white lamp illuminates a colored filter, only frequencies corresponding to the filter’s color may pass, whereas complimentary colors are stopped; e.g., a superimposition of cyan and yellow filter let green light pass, similarly to what is obtained by mixing cyan and yellow colors.

Fig. 3 Subtractive model investigated with inks, pencils, acrylic colors ... and filters.

5.5. Evaluate
This educational path gave our students the opportunity to acquire new skills. Completed forms and tasks, Padlet walls, flipped lessons, together with their emotional engagement are integral part of evaluation. In particular, their Padlet work are concrete evidence of improvement of students’ motivation and vicariance. As an example, in Fig. 4 there are three posts on a Padlet, stating students’ passion for physics and their creative and unusual capacity to investigate previously described phenomena (e.g. fluorescence, absorption).

Fig. 4: Physics in the heart - posts on a Padlet wall as evidence of improvement of students’ motivations and vicariance.

Nevertheless, at the end of this path, a final evaluation exam has also taken place in the form of an experimental skill test: starting from a set of colored letters, each group had to think about and answer this question: “What light has to be used to read just a subset of them?” An example is shown in Fig. 5a: all groups answered, “red light” to change LABORATORIO into ARATRO. They had also to give a motivation of their answer and experimentally investigate if they were right. They all agreed that red letters and the letters containing red disappeared if they light the colored world with a red lamp. A picture of their experimental evidence is shown in Fig. 5b).
6. Feedback
The success of educational path has also been revealed by students’ feedback. A feedback form has been completed by each group, in each high school. Here we show the main questions and results:

1) Were your expectations met? 100% answered YES
2) Evaluate the lab activities: 60% answered 9/10, 40% answered 10/10
3) Why? (Give a motivation about your previous evaluation) Among motivations of their satisfaction, there was: teacher care and the ability to motivate all students in attending the class and lab activities were very interesting.
4) Have the methodologies used been useful? 100% answered YES
5) Why? The main favourite methodological aspects have been:
   a) “learning by playing”: students were happy to learn physics just by playing with simple instruments,
   b) student involvement in the experiments: they were satisfied, because they were the main actors in this innovative educational process.
6) Which topics would you like to discuss in addition? Students wrote that they were completely satisfied and very happy about this path and no topics have been suggested to be added.
7) How do you evaluate this educational path? 100% answered “very good” and “very useful”

From these forms, we deduce that all students agree about the following results:
- this path met their expectations,
- the methodologies used were effective.

7. Conclusions
An innovative learning physics path about wave-matter interaction has been implemented with about 100 students attending the first year of high school. The main methodology has been IBSE (5E and TEMI models).

Students successfully carried out experiments on the interaction between light and color and deduced that color is not an intrinsic material property. They also extended their knowledge with multidisciplinary activities, connected with art, computer science, biological science and maths. An effective experience of flipped classrooms has been also realized, with examples of serendipity and vicariance. We achieved an improvement in students’ motivation and a better learning experience. Another strength of this path was the application of ICT.

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