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A teaching-learning sequence on colour in the context of a motivational stage for high school students

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Abstract. In this article we present a Teaching-Learning Sequence (TLS) on colour performed in the non-formal setting of a vocational stage with a sample of N=38 18-year-old high school students. Based both on previous educational research and the analysis of the characteristics of the Italian high school curriculum, the TLS adopts cooperative experimental investigation activities with low-cost equipment which help students distinguish different physical situations involving the combination of colours; furthermore, it focuses on developing a solid understanding of the connection between the physics and physiology of colour phenomena. The TLS was highly appreciated by students and, thanks in part to the inclusion of advanced topics such as photonic crystals and plasmons, it may have a significant motivational value.

1. Introduction

The teaching of colour is a long-debated issue in physics education. Since the conceptual foundations of colour theory lie at the border between physics and human physiology, the topic is often neglected or treated only in passing in physics curricula and presented as a set of phenomenological rules involving diagrams with three intersecting circles in art classes. The crucial connection of colour theory with the structure of the human eye is never addressed in the Italian curriculum. For several years, the "Physics4Teenagers" [1] group at the Department of Physics of the University of Pavia, comprising many of the authors of the present paper, has held a two-hour seminar on colour at the yearly summer school organised by the Department for motivated fourth-year high school students (18-year-old). Both from direct questions to students and from in/out questionnaires, widespread difficulties related to colour theory were observed, even within the self-selected, highly motivated sample of the summer school participants. Such difficulties, centred in particular around the over-generalisation of the rules of pigment mixing to all colour phenomena, reflect those reported in the literature. Thus, for the 2021 edition of the summer school, it was decided, in collaboration with the physics education research group in Pavia, to transform the usual seminar into a four-hour, research-based TLS on colour which, while performed in a non-formal setting, could provide a significant addition to the formal curriculum, in terms of conceptual understanding and knowledge integration. The TLS was performed with 38 students, 20 of whom were attending in person, while 18 were in distance learning. In this paper we report on the grounds for the research, the structure, and the results of the TLS.

2. Theoretical framework

2.1. Linking formal and non-formal learning: the case of colour

Colour theory is a topic for which integration of knowledge, both in a transversal (through different disciplines) and longitudinal (between different areas of the physics curriculum) sense, is of the highest importance. Unfortunately, the lack of interdisciplinary and longitudinal integration is a well-known, long-standing defect of formal curricula [2] which, despite numerous reform proposals [3] coming from science education researchers and professional teacher associations, is not expected to be solved in the near future. However, the integration of knowledge that is considered distant from traditional curricula is an area in which non-formal learning can support and complement formal education [4] and the topic of colour theory has been identified as a promising ground in this sense by previous authors. For example, in Ref. [5] the authors conduct in-depth investigations of students' understanding of concepts related to colour within activities performed in a science centre.

2.2. Previous research on the teaching-learning of colour

Students' pre-instruction knowledge of colour consists of the organisation of "spontaneous" explanatory structures from a great amount of personal everyday experiences and sensorial data. As such, the students' initial understanding may be organised in mini-theories [6] such as that colour is an intrinsic property of objects; that the mixing of different colours is governed by the rules of pigment mixing in all circumstances, i.e. also when coloured light illuminates a coloured object [4, 7]; that natural light (such as sunlight) is not composed of a mixture of colours, but considered as 'pure' and colourless [8]. Sometimes, as is the case in other fields of physics, these conceptions emulate historical theories about colour, which predate the emergence of the scientific method [9].

Misconceptions about the mechanism of vision contribute to a poor understanding of colour; a widespread model among students is that of light as a facilitator of vision: ambient light reveals colours and allows them to be seen, but it has no other special relationship to vision or the eye [10]. Traditional instruction may fail to help students develop correct scientific ideas, and instead induces the formation of hybrid models: some crucial educational risks, on which research has concentrated, are neglecting the link between physics and physiology in colour vision, which makes colour theory essentially impossible to understand [7], and proposing an all-or-nothing model of light reflection and absorption for subtractive mixing, which produces a theory unable to explain basic facts of experience [11]. Also, the poor integration of wave and ray optics in school curricula contributes to difficulties on certain problems involving colour [7]. Among the technological tools which science education researchers have developed to improve traditional teaching on colour, we mention the PhET simulations on colour vision [12] and smartphone-based experiments and activities, which have been proven to be useful in the teaching of both additive and subtractive synthesis [13, 14].

2.3. Design principles
The design of the TLS was developed according to the general principles presented in Ref. [15] and previously adopted in several works [16], which include the thorough analysis of the science subject matter, of previous educational research on the topic, and of the content of the formal curriculum. A strong indication, which we carry along from our previous studies, concerns the effectiveness of the Predict-Observe-Explain (POE) [17] approach to counter student misconceptions and foster conceptual understanding, and the value of investigations autonomously performed by students using their own technological devices in maintaining interest, motivation, and engagement [18].

2.4. Research questions
In this study we intend to address the two following main research questions:

1. To what degree does our sample, consisting of self-selected students with a high interest in science and beginning the final year of secondary education, hold misconceptions about basic facts of colour theory reported in the literature?
2. To what degree can our research-based learning sequence, performed within a setting of non-formal instruction in a limited time, improve students' conceptual understanding of the topic of colour?

The first research question is related to the organisation of the Italian curriculum, as discussed in Section 2.1. Before this study, our perception of the issue, based on qualitative observation of previous similar samples, was that even the most scientific-minded students, approaching the end of secondary education, hold severe misconceptions on colour theory and the mechanism of colour vision. The second research question focuses on the possible role of non-formal instruction in completing and supplementing formal education in providing an integrated perspective on the topic of colour, which is intrinsically multidisciplinary and also possesses a strong longitudinal character within the physics curriculum itself. To the two above, we add a third, auxiliary question, which was elicited by the context, i.e., the rules imposed by the COVID-19 pandemic, which forced us to perform the TLS with a sample composed of two equal subsamples of students in presence and distance learning:

3. To what degree does distance learning affect educational outcomes in a TLS also including cooperative, inquiry-based activities, which can only be observed passively by the distance sample?

Of course, we do not hope to provide a definitive answer to such a far-reaching question with the small samples at our disposal; nevertheless, we believe that data collected in such a very particular situation could give a useful indication for future research.

3. The teaching-learning sequence

3.1. Context
The sequence was tested with a sample of 38 fourth-year high school students, with 20 of them attending in person and 18 in distance learning, participating in a summer school at the Department of Physics of the University of Pavia. The sample was composed of 17-18-year-old students of Liceo Scientifico (science-oriented high school curriculum) and was also self-selected, namely it was composed of students who opted for this stage to complete the compulsory hours of orientation/competence training (PCTO in the Italian system): thus, it is reasonable to assume that they should be interested in physics and considering it as one of the possible options for their choice of university. The TLS was performed during an entire morning (from 9 to 13.30 AM) and was the only activity within the summer school which included a formal evaluation of learning, as detailed in Section 4. The rest of the school, which had a duration of seven workdays, comprised in part motivational seminaries/lectures, and in part interactive laboratories

3.2. *Content and timing*
Our TLS is schematically organised as detailed in Table 1.

Table 1. Organization of the TLS

Topic	Duration (minutes)
Tutorial on the physiological mechanism of colour vision and the production of colour sensation in the brain,	60
Review of the main elements of the wave theory of light,	30
Guided construction by students of a homemade, smartphone-based spectroscope [14],	40
Experiments on additive synthesis,	40
Experiments on subtractive synthesis and the role of illuminating light,	50
Complementary topics	20

In the following we provide details on the content of each step

3.2.1. Tutorial on the physiological mechanism of colour vision. At the beginning of the sequence, as suggested by several authors (e.g. [7, 9]), we provide students with a tutorial on the physiological mechanism of colour vision, including the distinction between long, medium, and short wavelength cones, which is crucial to understand colour models. The tutorial includes the perusal of PhET simulations on colour formation in the brain [12].

3.2.2 Review of the main elements of the wave theory of light. The second part of the sequence has the form of a lecture/seminar briefly reviewing the main elements of the wave theory of light (taught to the students in the previous year of secondary school), the relationship between wavelength and colour, and basic phenomena of interference and diffraction, which are crucial for understanding the working principle of the spectroscope students are going to build.

3.2.3 Guided construction by students of a homemade, smartphone-based spectroscope. In this part of the sequence each student builds his own spectroscope as a customised add-on to his smartphone using a piece of 500 lines/mm diffraction grating and various cardboard and stationery. The activity lasts about 30-40 minutes and proceeds essentially as described in Refs. [14, 19] but the procedure for the calibration of the spectroscope for quantitative measurements (i.e. making it a spectrometer) is entirely skipped: in the present context, the apparatus is only used for qualitative observations of spectra.

3.2.4 Experiments on additive synthesis. Students perform experiments on additive synthesis with RGB torches, and observations of a multicolour RGB LED lamp and other sources using the homemade spectroscope. We experimentally address the issue of magenta, which is a primary colour in the CMY model, but not a spectral colour, discussing its case in comparison with yellow, for which instead we can find two sources (a yellow LED, and coupled red/green LEDs) which look almost identical to the human eye, but very different when observed through a spectroscope.

3.2.5 Experiments on subtractive synthesis and the role of illuminating light. This step is meant to address a different physical situation, where students often improperly use resources from the rules for the mixing of pigments: a coloured object illuminated by coloured light. Framing this situation requires a deep understanding of the physical and physiological origin of the rules of subtractive synthesis, while blind application of the same rules leads to severe misunderstanding. We start this step with a POE activity in which students are required to guess the appearance of coloured spots on a paper sheet, when filmed within an otherwise dark box, illuminated by red, green, or blue light. The object which let us carry out this activity is the “trichromatic black box” depicted in Figure 1, which we believe may play a significant role in the teaching of colour phenomena. This object was built with a shoe box with a small opening on the lid that could fit a smartphone camera. Inside the shoe box a remote-controlled multi-colour RGB LED bulb was placed on one side. Under the aperture we placed a paper sheet with coloured dots. This experimental setup is very cheap and easy to build, but can provide exceptional results in terms of comparing the students' alternate models with physical reality, mainly because it constitutes a setting in which students can easily observe pigments illuminated by light of a given colour, and no other spurious lighting sources. At the anecdotal level, the level of surprise shown by several students when observing a completely different effect from what they predicted was extremely interesting, and the discussion within small groups with the objective of explaining the discrepancies between the predicted and observed colour appeared to be one of the most important moments of construction of new knowledge for the students. Other activities in this part of the sequence are the study of the behaviour of light passing through colour filters, and the red laser dot on coloured spots experiment suggested by Viennot [11] with the objective of differentiating total (as implied by the name "subtractive synthesis") from partial absorption of a certain wavelength range by a pigment.

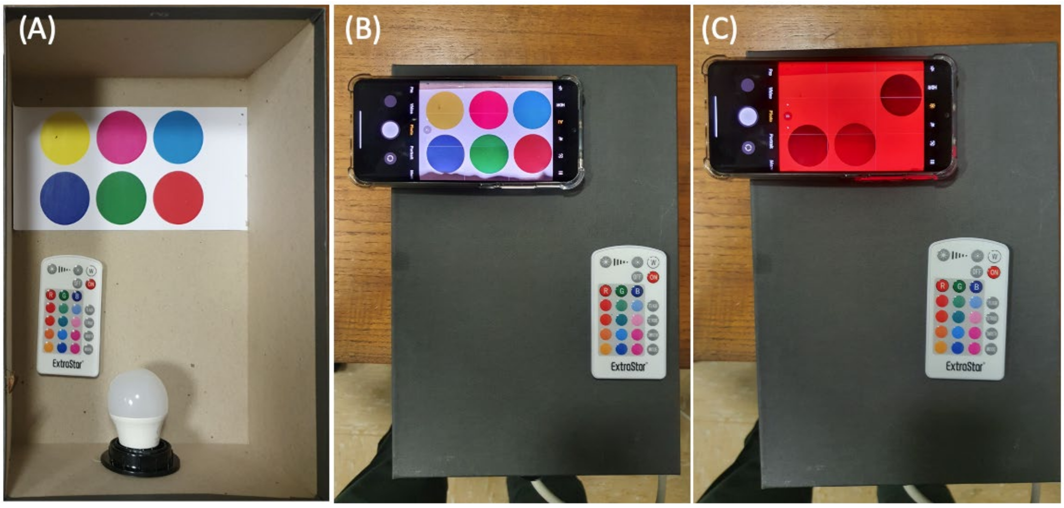

Figure 1. "The trichromatic black box". (A) The open box. (B) Closed box photographed by a smartphone camera through a hole on the lid, when internal illuminating light is white. (C) Same as (B), when internal illuminating light is red.

3.2.6 Complementary topics. In the final part of the sequence, we discussed more advanced topics such as the absorption spectra of important pigments such as carotenoids and chlorophyll, luminescence (with the well-known experiment of laser in tonic water [20]), photonic crystals and plasmons. Except for focusing on absorption spectra to explain the properties of pigments, the final step of the sequence has a mainly motivational value. It is meant to more properly fulfil the goals of the summer school which served as a context for the TLS: showing students areas and problems in physics which have been clarified more recently, or in which research is still active. Presumably, with an adaptation of the TLS to a context of formal learning, this step could be considerably shortened with little detriment to educational gains.

4. Data collection and results

4.1. Data collection

The pre-post test, reported in the Appendix (available online at this link: https://bit.ly/3WvP3s0), was based on a combination of questions taken from the literature [5-11, 21, 22] and original items. The areas investigated in the test can be described as follows: distinction between additive synthesis and pigment mixing rules (Q2, Q4); mechanism of colour vision and the role of illuminating light (Q1, Q3, Q5); characteristics of white light (Q5); distinction between the roles of absorption and reflection in colour vision (Q6), connection of colour theory with wave theory of light (Q7, Q8, Q9); coloured shadows (Q10). The issue of coloured shadows, which has a long history in physics education dating back to the works of Matilde Vicentini [23], was included, although the problem is not explicitly treated in the sequence, to check for the hypothesis that an integrated understanding of the topic of colour could help students autonomously make sense autonomously of the issue of coloured shadows. However, the answer is insofar negative, as reported in the next Section.

4.2. Results

In the following we will discuss the results of the TLS from the point of view of disciplinary learning. For all the activities in the stage, including the TLS on colour, students were also asked to provide feedback on general appreciation of the content (clarity of presentation, interest in the topic) by rating them on a five-point scale ranging from 0 (poor) to 4 (excellent). The activity on colour received an average rating of 3.6/4, ranking among the highest-rated activities of the summer school (average ratings given by students to the 21 activities of the stage were in the range of 2.5 to 3.8 out of 4).

4.2.1 Pre-post test results. The pre-test results confirmed previous observational evidence that even high school students selected for interest in science hold basic misconceptions about elements of colour theory. Over 70% of students believe that red and green spotlights mix to a brown spot on a white screen (Q4), with a mere 16% providing the correct answer (yellow), in full agreement with the findings reported by Chauvet [7]. More than 30% of the sample believe that a yellow object will appear green when seen under blue light (Q3) and 25% state that the object will look yellow with blue reflexes, with only 27% correctly answering that the object will appear black or very dark blue. Note that this result is found although, in Q1, only 10% of students generally state that when an object is illuminated by coloured light the two colours, namely that of the light and that of the object, mix similarly to pigments. This means that when examining a concrete situation students use a different model than the one expressed by their declarative knowledge. Taken together, Q3 and Q4 provide strong evidence that students have difficulties in adopting models of colour combination different from those related to the mixing of pigments. Furthermore, half the students think that the primary colours are “red, yellow and blue” (Q2) presumably based on approximate recollections from art classes, and half of the students incorrectly identify the conditions for light to appear white, with 20% stating that it must be “pure and unfiltered”, as reported in Ref. [8]. More than 60% of students think that a coloured spot drawn on a thin sheet of white paper and looked in transparency, interposed between the eye and a source of white light, will either be seen in a different colour (20%) or will not show any colour at all (30%). Students appear comparatively stronger in questions related to more advanced physics knowledge: for example, almost half the sample correctly identifies blue as the shortest wavelength colour among those enumerated in the statement of Q8, and a similar percentage can provide a reasonable explanation of the blue colour of the sky (Q9), although both topics have presumably not yet been treated in their formal curriculum (the first one belongs to the final year of secondary school, and the second one may or may not be addressed in the same year). Also, students in this sample do not seem to hold, at least at the level of declarative knowledge, severe misconceptions on the basic mechanism of colour vision, which is stated correctly by more than 85% of students in Q1. It is worth mentioning, however, that in a subsequent test of this sequence with a non-self-selected sample of second-year high school students, which will not be further discussed in this article apart from this brief comment, we found that 35% of students in the pre-test believed that we see colour from light naturally emitted by all objects, and 15% believed we see colour through rays emitted from the eyes and reflected by the object. Thus, more research is needed to investigate to which extent secondary instruction succeeds in overcoming misconceptions about the basic mechanism of colour vision.

The post-test analysis displayed a normalised gain [24] $g=0.47$ which, although moderate, can be considered satisfactory for a one-morning activity. The highest gains were on Q4 (from 16% to 83% of correct answers); Q2 (21% to 64%); Q3 (27% to 60%), which all revolve around the idea that simple pigment mixing rules and models are not universally valid and in particular do not apply to situations

involving coloured light. Significant gains were also obtained on the properties of white light and the relationship to receptors in the human eye (Q5, 50% to 89%) and the issue of colour vision in transparency, related to a mental model of selective absorption more precise than selective reflection (Q6, 34% to 60%). On the contrary, educational gains on the issue of coloured shadows were insignificant (Q10, 11% to 14%). Separate consideration of the two subsamples of students in presence and distance reveals normalised gains g_1=0.60 for the first group and g_2=0.31 for the second group, with marked differences especially on Q2 (correct answers in post-test 75% vs. 50%), Q3 (75% vs. 38%). In Figure 2 we report the results for all questions comparing pre-test with post-test results, and reporting for the latter the results for the full sample and the two subsamples (differences between the two subsamples at pre-test level are not statistically significant as expected for a random distribution).
Looking at individual item gains, pre-post differences for the full sample are statistically significant at $p < 0.05$ level (two population proportions Z-test) for Q2, Q3, Q4, Q5, Q7 and Q8. Post-test differences between the presence and online subsamples are statistically significant at the same level of confidence only for Q2 and Q3.

4.2.2 Discussion and answer to research questions. We are now able to discuss in greater detail our research questions and working hypotheses. Concerning research question (1), we have observed that our sample of self-selected, science-motivated 18-year-old secondary school students holds basic misconceptions on colour theory to a significant degree. In particular, a majority of these students are observed to have only one working model of colour combination available for any situation: the rules for colour mixing. They regularly use this model for analysing situations in which it does not apply, like the mixing of coloured lights, and the illumination of objects with coloured light. Thus, students have difficulties in understanding not only additive synthesis, but also the theoretical foundations of subtractive synthesis, since they do not know how to take into account the spectral composition of illuminating light, and are confused with the problem of seeing colour in transparency. However, a majority of students in this sample does not hold basic misconceptions on the mechanism of human vision, can distinguish between objects which naturally emit visible light and objects which we see through diffused light, and has a reasonable working knowledge of the correspondence between colour and the electromagnetic spectrum of visible light, including the properties of white light (although misconceptions reported in the literature do appear for a significant minority of students in the pre-test).

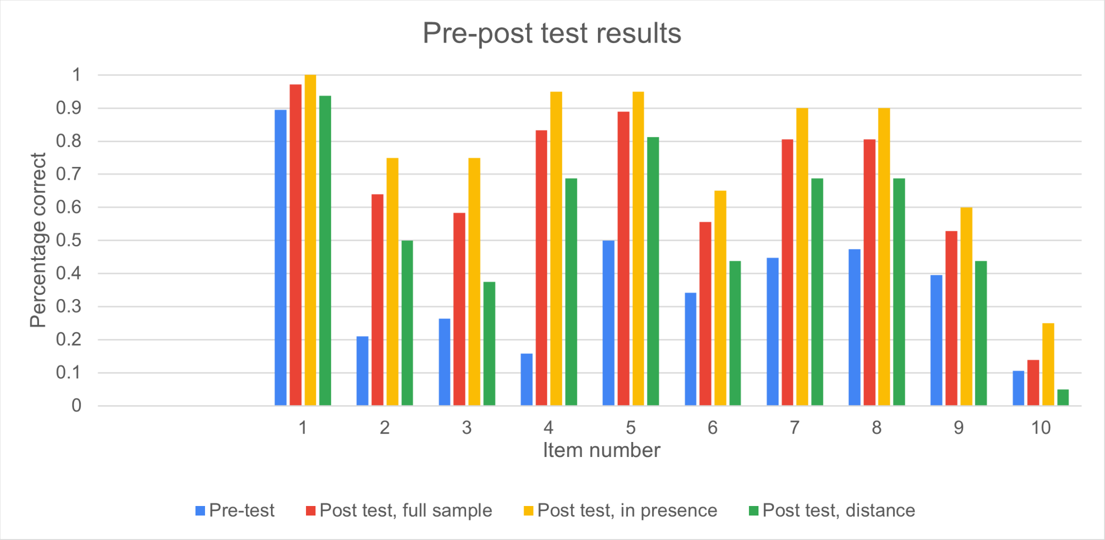

Figure 2. Summary of pre/post test results item by item

Coming to the discussion of research question (2), data analysis has provided us with the encouraging result of a normalised gain g=0.47 (g_1=0.60 for the subsample of students in person). Students appear to have significantly expanded their ability to deal with situations involving the combination of colours, acquiring a working knowledge of additive synthesis for the mixing of light colours, and of subtractive/multiplicative [11] synthesis in the special context of a coloured object illuminated by coloured light, which was the goal of the trichromatic box experiment. Statistically significant pre-post test gains were registered for 6 items out of 10 in the pre/post questionnaire, with particularly satisfactory improvements for Q4 and Q5. In some areas, the results leave room for refining and improving the sequence: gains were registered, but were not statistically significant, for the issue of colour seen in transparency (Q6) and the difference between spectral and perceived colours (Q9). Furthermore, our working hypothesis that a better and more integrated understanding of colour theory would have led students to make sense of the phenomenon of coloured shadows (Q10) without touching the topic explicitly, does not have any support at the present time. It is possible, as other researchers have argued, that difficulties with ray optics also pose an obstacle to understanding the problem of coloured shadows, and that only an even more integrated and longitudinal approach to colour phenomena can lead to an understanding of such an enigma. Another issue which deserves more attention in future research is the question of learning retention. How persistent in time are educational gains we obtained during a one-morning activity, in a context of non-formal learning? This is a research question for the future.

Finally, we briefly discuss the auxiliary research question (3). The difference in overall normalised gain between the subsamples in presence and at distance was relevant (g_1=0.60 vs g_2=0.31) and, notwithstanding the relative smallness of subsamples, statistically significant differences were also observed on individual items Q2 and Q3. This is hardly surprising, since students in presence had the opportunity to perform the active learning elements of our teaching-learning sequence, such as the study of sources with the hand-made smartphone-based spectroscope, and the predict-observe-explain activity using the “trichromatic black box”, which is the key for understanding the problem posed in Q3. In this sense, these results are nothing else than a confirmation of the importance and effectiveness of hands-on and cooperative experimental activities in the teaching-learning of physics.

5. Conclusions

We have presented a research-based, mixed theoretical/experimental TLS on colour phenomena meant to improve students’ understanding of the topic, and use learning in a non-formal context as a tool to provide a wider perspective on a seemingly marginal, but actually extremely rich topic of the formal curriculum.

One of the main motivations in the initial design of the sequence was to provide students with a link between the physics and physiology of colour phenomena, which is ignored in formal instruction. From the analysis of the results, we see that the only question dealing directly with the physiology of vision (Q5) had a statistically significant pre-post gain ($G = 0.5$ for the sample in presence) and we believe the consolidation of the mechanism of colour vision had a positive effect also on other items for which high gains were found (Q1, Q2, Q3, Q4). Less satisfying results were obtained in the item concerning the distinction between spectral colours and colour sensations (Q9, $G = 0.3$ for the sample in presence) which may warrant, in future revisions of the sequence, to consider expanding the activities centred on the physics-physiology connection.

Reflections on means to overcome the tendency of students to treat all cases involving combination of different colours (mixing of coloured lights, illumination of coloured objects with coloured lights) using the rules of pigment mixing, led us to the design of a tool, the trichromatic black box, especially suitable for POE activities and, according to the data available to us, highly effective in improving conceptual understanding of the interaction of pigments with coloured light.

The TLS has a total duration of four hours (plus half an hour total for the pre- and post- tests), has a significant motivational value and is appreciated by students; it can be performed throughout one morning or afternoon (4-5 hours) in the context of students’ visits or open days in the University. Furthermore, given the relevance of the topics treated and the simplicity of the materials required, it could be easily adapted for curricular school teaching. We collected and analysed data on both the educational outcomes, using a pre/post-test approach with items based on research literature and the interest/engagement of students in the activities; although results are encouraging, the data analysis also highlights areas of possible improvement, and further questions. In particular, we have focused our attention on two elements resulting from data analysis. First, the item on ‘coloured shadows’ displayed negligible pre-post improvements, which were also reproduced in a subsequent teaching experiment. Literature [25] suggests that students’ difficulties with this item may be related to a lack of conceptual understanding not only of colour, but also of ray optics; thus, they would require an even higher degree of knowledge integration. One possibility would be to design an experimental activity revolving on coloured shadows, structured as a short sequence of POE steps, starting from the case of the superposition of two shadows only. Secondly, the results on the distinction between spectral colours and colour sensations appear sub-optimal, and the sequence may be improved in this respect by further reinforcing the connection between the physics and physiology of colour, as stated above in this Section. These issues will be addressed in future research.

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