Integrating knowledge about color within the STEM/STEAM approach: some instructional procedural principles

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ABSTRACT

This article aims to help define the STEM/STEAM approach to color education. Traditional science education seems to fail in addressing the stubborn misconceptions about color vision detected by empirical research. On the contrary, a knowledge integration approach like STEM/STEAM could provide a well-suited educational perspective for dealing with interdisciplinary issues related to color teaching and learning. Nowadays more and more schools welcome this educational paradigm as it seems to meet properly the needs of our modern knowledge society. However, this approach is somewhat ambiguous to the extent that a variety of teaching activities fall under the STEM/STEAM label. Our original contribution is to attempt to improve the conceptualization of the "STEM/STEAM approach" by identifying some instructional procedural principles that may be useful in operationally defining what we mean by "integration". Methodologically, our research consisted of three phases. In the first phase, we identified some shared features of activities classified as STEM/STEAM that we defined as the "invariants" of the STEM/STEAM approach. In the second phase, the invariants were described in terms of didactic variables drawn from the literature and some STEM/STEAM teaching activities. In the third phase, some procedural principles to guide teachers' work were formulated and discussed with reference to color teaching situations.

KEYWORDS (STEM/STEAM education, Color teaching and learning, Didactic variables, Epistemic variables, Learning variables, Procedural principles, Didactic transposition of knowledge)

RECEIVED 31/01/2022; **REVISED** 18/7/2022; **ACCEPTED** 14/10/2022

1. Some remarks on STEM/STEAM education

Interdisciplinary topics such as color vision represent a fascinating but difficult challenge to deal with while planning educational curriculum. In a previous article (Martini *et al*., 2019) we tried to make explicit the ambiguity and polysemy of the concept of color, which can take on different meanings in different contexts, imputing to this semantic complexity the multiple naïve conceptions detected by empirical research (e.g., Feher, 1992; Martinez-Borreguero *et al*., 2013).

Traditional scientific teaching about color seems not to be very effective in tackling such pervasive and stubborn misconceptions because students often fail to coherently reconcile their experiences of color perception with scientific explanations based on idealized models (Giere, 2004). This is the reason why our working hypothesis is that a knowledge integration approach like STEM/STE*A*M (Science, Technology, Engineering, *Arts*, Mathematics) – at least according to a certain interpretation of the acronym – can be a well-suited educational perspective for dealing with issues related to color teaching and learning. If it is the case, it depends on how STEM/STEAM activities are designed and performed.

We begin by briefly clarifying what we mean by the STEM paradigm to understand whether and under what conditions it can provide us with some appropriate recommendations for transforming expert knowledge about color vision into knowledge to be taught (Chevallard, 1991; Martini, 2018).

The roots of the STEM movement date back to President Dwight D. Eisenhower, and the formation of NASA and NSF in 1958 (Chesky and Wolfmeyer, 2015). In the field of science education, the acronym STEM – whose first version was SMET (Sanders, 2009) – was proposed in 2001 by either Judith Ramaley (assistant director of Education and Human Resources at NSF at the time) or Peter Faletra (then director of Workforce Development for Teachers and Scientists in the Office of Science at the Department of Energy) to refer to a group of disciplines (science, technology, engineering, mathematics) identified as fundamental to meet the challenges of the future. Historically, the STEM movement developed in parallel with the curriculum reform movement whose characteristic feature was a renewed interest in the content and purposes of education even by experts and academics. This phenomenon affected especially the Sciences and resulted in the formulation of curricula that considered scientific and cultural advances and the problems that threatened the national security in the climate of the Cold War (Bruner, 1960).

Lately, the acronym STEAM has been introduced, where the addition of the letter "A" that stands for Arts addresses the need to integrate creative thinking and applied arts into real-world situations. Some scholars believe that the addition of “A” is unnecessary, and that the application of creativity and the arts is a natural premise of STEM education. Others (e.g., Liao, 2016), however, believe it is important to highlight it, because advocating for the “A” might encourage relevant actionable pathways for transdisciplinary learning, allowing for an integration of all curricular disciplines, in line with the goals of school education (Martini, 2019).

Although the instructional models and ideas put forth under the STEM label are having a profound impact on the ongoing educational practices in schools all over the world, some educational researchers (e.g., McComas and Burgin, 2020; Chesky and Wolfmeyer, 2015) have started pointing out limits and contradictions of this potentially revolutionary approach. According to them, an uncritical and politically driven acceptance of STEM is indeed occurring to the detriment of a thorough effort to empirically investigate the merits and drawbacks of this approach which appears to be neither unambiguous nor procedurally defined.

While professional meetings and science education conferences are increasingly geared toward STEM and new textbooks and websites are popping up to advise teachers on how to implement STEM practices, STEM curricula lack an awareness of what STEM is and what STEM programs should include. Specially, two main and not particularly clear definitions of STEM are at issue (McComas and Burgin, 2020). One definition of STEM recognizes some degree of epistemic similarity among any of the four subjects that makes them potentially of interest to the same group of educators, but without any expectation that these subjects must be taught together to qualify for the STEM label. In contrast, the second definition strongly recommends knowledge integration rather than a mere juxtaposition of different subject matter contents in order to achieve proper STEM/STEAM goals (National Science Teaching Association, 2020). This interdisciplinary approach is also encouraged in K-12 education, although there is no universal consensus on how many of the four subjects should be blended and what level of integration should be pursued.

In Italy, STEM/STEAM education is addressed through different approaches. Currently, the Recovery and Resilience Plan presented by Italy envisages school reform interventions that enhance STEM in response to the need both to increase students' scientific literacy and to identify approaches for teaching scientific disciplines that are more integrated and supported by digital technologies. Great emphasis is placed on the search for connections between disciplines and between theoretical concepts and concrete reality. This perspective aims to bridge the so-called “skill gap” between the notions learned in school and university and the skills required by the world of work. For example, as reported by Orizzonte Scuola – a well-known News and Information portal that is a useful online reference for school employees – STEM must mirror real-life scenarios. Because real-world jobs are interdisciplinary, children must be encouraged to learn how subjects fit together and work together. Since education is no longer about memorizing random facts, but about learning how to think critically, evaluate information and solve problems, knowledge and skills must be taught in an applied way, that is, in a real problem context.

Although we acknowledge the potential fruitfulness of STEM/STEAM education, we advocate nonetheless that integrating knowledge in real world contexts does not ensure success in learning. On the contrary, the very focus on experience in real contexts, where complex phenomena occur, requires a high control, both epistemic and didactic, over the learning situations. As mentioned above, idealized scientific models constructed to make color vision intelligible cannot be directly inferred from real world phenomena in which many variables interact simultaneously. On the contrary, these epistemic products are the correlate of disciplinary epistemic practices (Sandoval, 2016) [2] students need to become acquainted with to make sense of the scientific discourse (Tombolato, 2020).

This implies that teachers need to clarify not only the conceptual content (e.g., the additive and subtractive color model) but also how that specific content can be related to students' perceptual experience. Otherwise, students will continue to interpret scientific models based on ontological and epistemological assumptions about existing entities and the nature of knowledge that stem from intuition, common sense, or personal experiences.

According to our perspective, which is characterized by an epistemic approach to didactic problems (Martini, 2011; Tombolato, 2020), a fruitful way to improve the conceptualization of the STEM/STEAM approach is to identify some instructional procedural principles (Stenhouse, 1977) that can be useful to operationally define different ways and levels of knowledge integration. These content-related procedural principles are meant as pragmatic patterns of behavior that can support teachers while performing didactic transposition of expert knowledge about color into school knowledge, enabling them to create specific didactic situations that allow students to develop interdisciplinary learning outcomes and a more sophisticated idea of how scientific knowledge is constructed and legitimated.

2. Towards a clarification of the STEM/STEAM approach through the definition of some invariant features

Methodologically, our research aimed at identifying such procedural principles consisted of three phases. In the first phase, we reviewed the scholarly literature-both theoretical attempts to conceptualize the educational paradigm at stake and the instructional activities labeled by the authors as STEM/STEAM activities-in order to bring out some shared features. The analysis led us to identify four main hallmarks that we defined as the "invariants" of the STEM/STEAM approach.

A first characteristic concerns the “integration between disciplines” to overcome their separation and fragmentation. However, constructing interdisciplinary teaching situations implies distinguishing different degrees of integration that concern both the types and the in-depth level of disciplinary knowledge involved.

A second characteristic relates to "the integration of theory and practice." Often, in education curriculum, the former is treated separately from the latter without considering the relationship that exists in the process of knowledge construction between content and disciplinary epistemic practices. In addition, practice is usually referred exclusively to some kind of manual manipulative skills. In contrast, commenting on laboratory activities conducted in schools, Vicentini and Cutroni (1996, p. 167) observe that "acting with the hands must be always accompanied by acting with the mind, while acting with the mind can be accompanied by acting with the hands". From an educational perspective, for this invariant to be complied with, it is therefore necessary for disciplinary content to emerge as a result of expert practices in specific contexts.

A third characteristic concerns the "integration of disciplinary knowledge into real world contexts". However, referring to real world contexts is not in itself sufficient to ensure successful students learning. The possibility for students to grasp the problem and properly act within the context depends on their prior knowledge and on their awareness of how scientific theorization refer to reality. From an educational perspective, this means controlling the repeated processes of decontextualization and recontextualization of knowledge (Chevallard, 1991; Martini, 2018).

Finally, a fourth characteristic concerns the "integration of technologies into teaching". However, making available and using technologies does not imply better learning, if one is not aware of how technological devices act on both the teaching content and the learner's mind.

These features, which pinpoint four different ways of integrating knowledge to be taught and learned, are assumed to be "invariants" of the variety of situations that fall under the STEM/STEAM label. From an educational perspective, the question at hand is how to ensure that these "invariants" are fulfilled. Indeed, as they are formulated, these invariants are still too vague and abstract to provide teachers with some useful operational guidelines for designing effective teaching situations. To achieve our goal, we decided to manage the problem of constructing teaching situations consistent with the invariants by identifying for each of them some didactic variables. Since teaching action affects the relationships that are built within the Teacher-Student-Knowledge system (the so-called didactic triangle used to conceptualize teaching and learning), both epistemic and learning variables play a key role in this representation. If we agree to represent the problem in this way, then the compliance with the invariants will depend on the variables considered and their relationships. In schematic terms, we can interpret each of these invariants as a function of the relationship between some epistemic and learning variables.

If we denote by I_{id} the "integration between disciplines" invariant, by v_{ex} a certain epistemic variable x, and by v_{ly} a certain learning variable y, then we can write

$$I_{id} = f\,[R\,(v_{ex}, v_{ly})]$$

Similarly, for the other invariants:

$I_{itp} = f\,[R\,(v_{ex}, v_{ly})]$ Integration of theory and practice

$I_{idr} = f\,[R\,(v_{ex}, v_{ly})]$ Integration of disciplinary knowledge into real world contexts

$I_{itt} = f\,[R\,(v_{ex}, v_{ly})]$ Integration of technologies into teaching

3. Operationalizing the invariants: the identification of the didactic variables

This phase of the research consisted in identifying the didactic variables that allow us to consider both the aspects related to the object of learning and the aspects related to the subject of learning. Once the didactic variables were identified, they were combined to give rise to some procedural principles that can provide teachers with some useful tips for designing teaching activities on light and color that are consistent with the four invariants characterizing the STEM/STEAM approach.

The didactic variables were drawn from the educational literature and from the analysis of some concrete teaching activities labeled as STEM/STEAM and published in scientific journals or made public on dedicated web portals. Here we refer, by way of example, to three experiences aimed at students at different school levels (Koyunkaya *et al*., 2019; Dark, 2019; www.stem.org.uk/resources/community/collection/286171/colour) as they enabled us to evaluate the STEM/STEAM approach to the teaching of content related to light and colors that differ in the degree of depth with which they are covered (simpler or more complex). We also examined the different types of activities and learning environments (e.g., whether they were more or less structured, whether they involved the use of some more or less advanced technological devices, etc.) designed under this approach.

The analysis led to the identification of the didactic variables shown in Tab. 1. We distinguished between epistemic variables, related to the object of teaching/learning, and learning variables, related to the subject who learns. The former identifies the factors that constrain the teacher's choices about the transposition of scholarly knowledge; the latter refer to the factors on which the learning of each student depends. The latter are therefore crosscutting to all the four invariants.

4. Definig some procedural principles for designing color STEM/STEAM activities

In the last phase of our research, we formulated some instructional procedural principles based on epistemic and learning variables, which can provide operational guidance for fulfilling the "invariants" that characterize the STEM/STEAM approach, according to our hypothesis. We point out that the invariants and consequently the procedural principles have been isolated from a strictly logical point of view. However, they are closely intertwined, which is why in teaching practice almost every activity exemplifies more than one.

In the following, we provide examples of possible procedural principles that can be developed from the didactic variables shown in the table.

Each of them is discussed with reference to experiences in color education, to clarify the meaning of the four invariants and to support teachers with operational guidelines and practical examples for the design of color learning activities.

STEM/STEAM Approach	**Didactic variables**	
INVARIANTS	**Epistemic variables**	**Learning variables**
Integration between disciplines (interdisciplinarity)	- Disciplines involved (which and how many) - Level of depth and complexity of the teaching content involved" (basic/advanced) - Interplay between disciplines (curricular continuity/discontinuity) - Forms of disciplinary reasoning (analogy, induction, deduction, abduction, by trial and error, probabilistic, by falsification, by models, probabilistic, etc.)	- Level of students' prior knowledge - Ability level - Skill level - Language mastery - Learning pace - Preferred learning modes (different sensitivity to didactic mediators) - Interest and motivation - Misconceptions - Ability to use technology
Integration of theory and practice (knowing and doing)	- Types of knowledge to be integrated - Type of practical knowledge (expert practice and practice as teaching expedient) - Degree of formalization of knowledge	
Integration of disciplinary knowledge into real world contexts.	- Historical evolution of the discipline (problems and contexts of genesis and development of knowledge) - Degree of complexity of the problem-situations	
Integration of technologies into teaching	- Type of technologies (non-digital, analogical, and digital) used as a means to learn certain content - Technologies used to represent knowledge - Technologies used to construct knowledge	

Tab. 1. The didactic variables referred to each invariant.

4.1. *Integration between disciplines*

1.1 Given equal individual learning factors, a teaching activity is consistent with the STEM/STEAM approach, if it involves multiple disciplines whose different perspectives combined make a specific piece of instructional content more comprehensible than it would be when tackled by any one of them independently.

1.2. Given equal individual learning factors, a teaching activity is consistent with the STEM/STEAM approach, if the contribution of the disciplines involved is targeted to the specific teaching content.

1.3. A teaching activity is consistent with the STEM/STEAM approach if the selected topics are covered at the same level of depth within each discipline and if such level of depth is appropriate to students' prior knowledge.

1.4. A teaching activity is consistent with the STEM/STEAM approach if it has different degrees of complexity that allow it to promote various forms of disciplinary reasoning in learners.

A typical integration between disciplines involves Science and Art. This pairing, though potentially fruitful, requires precise control of the content and its relationships. For example, placing the explanation of the mechanisms of color vision alongside the explanation of pigment mixing without distinguishing the different perspectives from which color is approached is ineffective for both teaching and learning. On the one hand, the content of color teaching is not organized in a logically coherent way. On the other, learning is prone to generating cognitive conflicts that risk turning into stubborn misconceptions (Martini *et al*., 2019). Therefore, procedural principles (1.1. and 1.2) require us to examine whether and how Science and Art contribute to the understanding of different "descriptions" of color. In other words, we need to make explicit the difference between colored lights and chromatic pigments, as well as what we mean by primary colors, specifying whether we are referring to additive or subtractive synthesis processes, respectively.

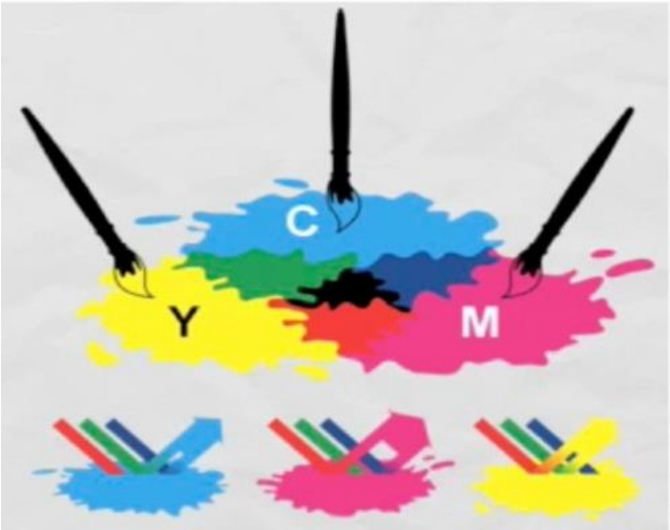

Fig. 1. Subtractive color mixing

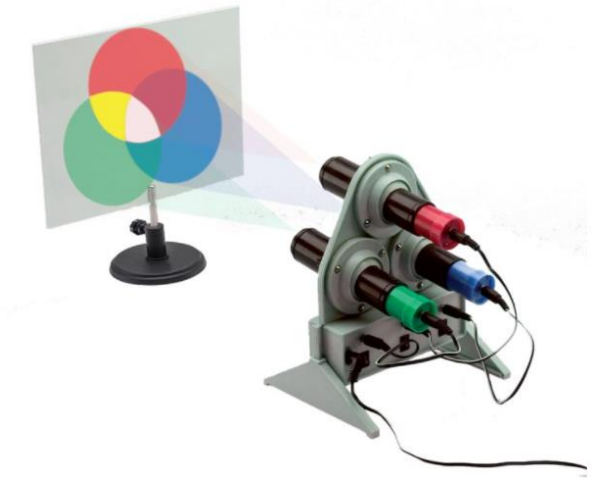

Fig. 2. Additive color mixing

Another example involves the integration of Science and Mathematics. The possibility of integrating these disciplines to promote meaningful learning in students requires controlling the levels of mastery of the knowledge involved (1.3 and 1.4). For example, additive and subtractive synthesis are usually represented through graphical diagrams, such as Euler-Venn diagrams, which students must be able to understand from a logical standpoint (e.g., Koyunkaya *et al*., 2019, where shadows are represented with three sets and their intersections). If students are not comfortable enough with this type of set representation, they will fail to grasp the rules behind the processes of additive and subtractive color mixing.

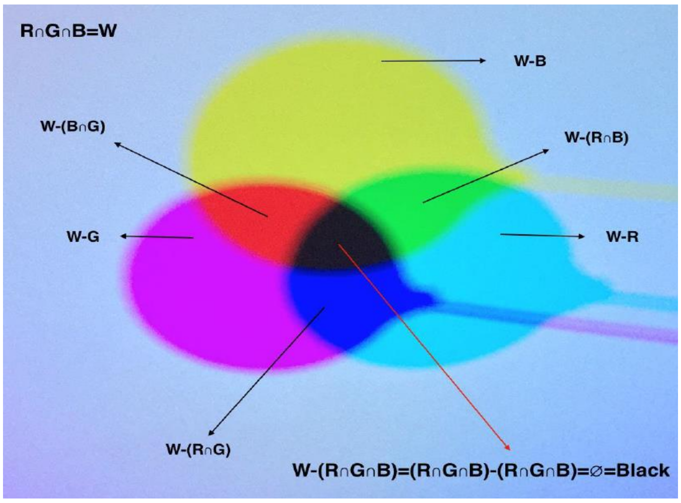

Fig. 3. Representing subtractive color mixing with sets (Koyunkaya et al. 2019, p. 114).

Likewise in a teaching situation that proposes a diffraction experiment. To fully understand the quantitative relationship between perceived color and the wavelength of light, students must know the basic concepts of trigonometry and be able to work with them enough to calculate the wavelengths of individual light rays. In this regard, an example of good practice is the open lab on light and color described in Dark (2019), where students grasp the relevance of trigonometry as they attempt to answer the challenging question "Can light be modeled as a wave?".

4.2. *Integration of theory and practice*

2.1 A teaching activity is consistent with the STEM/STEAM approach if it consistently involves disciplinary content and student-performed practices.

2.2 A teaching activity is consistent with the STEM/STEAM approach if it integrates the theoretical knowledge and practical experience of students in a suitable way to capture their interest and motivation.

2.3 A teaching activity is consistent with the STEM/STEAM approach if it integrates the theoretical knowledge and practical experience of learners in a suitable way to their preferred mode of learning.

2.4. A teaching activity is consistent with the STEM/STEAM approach if the degree of formalization of knowledge is appropriate to students' prior knowledge and if it considers their different sensitivity to the use of didactic mediators (active, iconic, symbolic mediators).

Regarding the integration of theory and practice, the procedural principles suggest that we should check for consistency between the theoretical content of instruction and the activities in which the teacher engages students to exemplify or represent that content (2.1, 2.2, 2.3, and 2.4). E.g., it is common for teachers to use Newton's disk and colored reflectors to help students understand additive color mixing. We endorse these learning strategies because they are likely to capture students' attention and match their different preferred learning modes through the employment of various didactic mediators. However, if these hands-on activities are not consistent with the theoretical explanation, they can generate misconceptions and false beliefs. For this reason, it is necessary to make students aware of the epistemic goal of the teaching activity by providing them with the relevant knowledge to correctly interpret what they see. For example, in the case mentioned above, you need to make explicit the difference between emitted and reflected light and the different effect you obtain as a result.

4.3. *Integration of disciplinary knowledge into real world contexts*

3.1. A teaching activity is consistent with the STEM/STEAM approach if it involves real-world problem situations that allow students to make sense of disciplinary knowledge.

3.2. A teaching activity is consistent with the STEM/STEAM approach if it involves monitoring the degree of "similarity" between the phenomenon reproduced during the activity and the target phenomenon.

Integrating disciplinary knowledge into real-world contexts requires strong disciplinary, epistemological and instructional expertise on the part of the teacher. A virtuous example of such integration is accomplished by Dark (2019) in her *Physics and the Arts course* at Spelman University. The connection between arts and science throughout history allows us to become aware of the real problems that scientists and artists had to solve and to grasp the complex relationship between perceived reality and scientific theorizing (3.1 and 3.2).

E.g., in secondary and higher education, history can be deployed to help students understand how and to what extent the evolution of scientific understanding of light as a physical phenomenon changed painting techniques and, conversely, how art contributed to the advancement of physics (Shlain, 2007). Another example of this third type of integration could be the design of a lab in which students must find the best solutions to illuminate a picture with certain characteristics and located in a certain environment, providing theoretical and empirical evidence to justify their choices.

Fig. 4. Children making Newton's disk

Fig. 5 Children experiencing additive color mixing with Newton's disk

4.4. *Integration of technologies into teaching*

4.1. A teaching activity is consistent with the STEM/STEAM approach if it is supported by technology.

4.2. A teaching activity is consistent with the STEM/STEAM approach if technologies are used by teachers to present knowledge content in a format that is engaging to students and that fosters their understanding.

4.3. A teaching activity is consistent with the STEM/STEAM approach if technologies are used by students in knowledge-building practices.

Regarding the use of technologies in color education, some devices allow us to support the teaching practice in a way that ensures consistency with the logical organization of the theoretical content. For example, the representation of additive and subtractive synthesis processes, which usually generate multiple misconceptions due to the inadequacy of the devices employed, can be supported using monochromatic spotlights of adjustable intensity and high reflective screens.

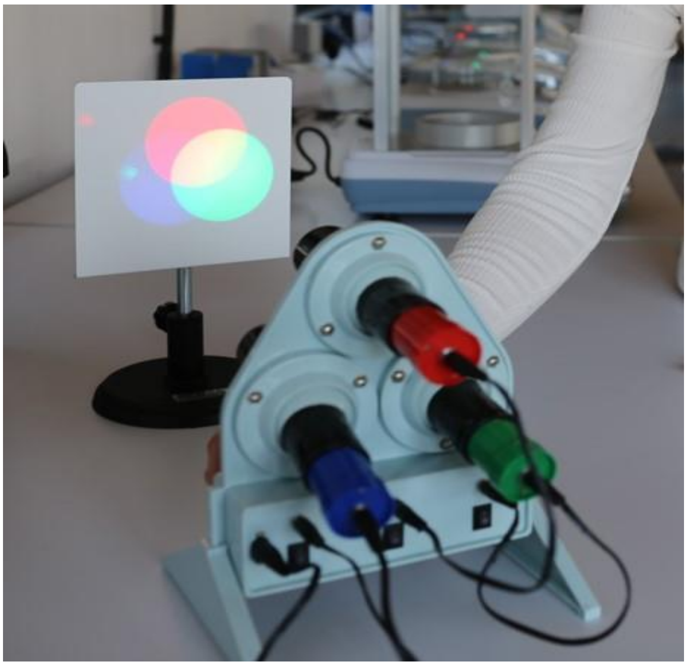

Fig. 6. Experimenting with RGB Spotlights

As an alternative to the pigment mixture usually proposed in classes, an example of subtractive synthesis can be obtained by illuminating an object from three monochromatic light sources (red, green, blue) simultaneously. The presence of the obstacle allows the formation of shadows that overlapping make available a dynamic representation of the static image usually used to represent the subtractive color mixing. Specifically, the areas where the shadows intersect are black, while the areas surrounding the black shadow are colored shadows composed of primary and secondary colors (Koyunkaya *et al*., 2019). In this case, the use of technological devices helps us to highlight the close relationship between the color of the light and the pigment color that many people fail to grasp. Indeed, the different types of shadows that appear with the obstruction of light correspond to the absorption of the colors of the light according to the "rules" of pigment mixing.

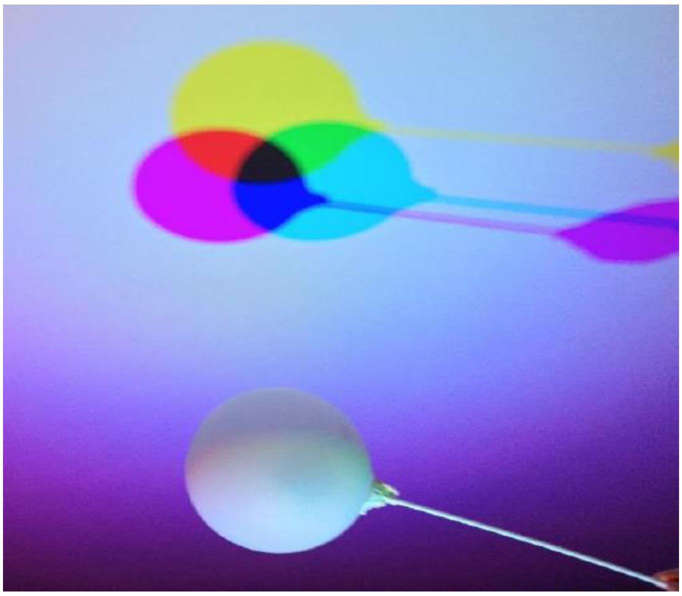

Fig. 7. The shadow experiment (Koyunkaya et al. 2019, p. 113).

5. Conclusion

In our contribution, we sought to better define the STEM/STEAM approach to color education by providing teachers with some procedural principles for designing effective instructional activities about color. These principles, conceived as pragmatic patterns of behavior, were formulated by combining epistemic and learning variables that can be traced to the four invariant features of the STEM/STEAM approach previously identified. The research is still ongoing and next goals include identifying more epistemic variables and formulating additional procedural principles to be discussed in relation to color STEM/STEAM activities carried out at different school levels.

6. Conflict of interest declaration

The authors declare that nothing affected their objectivity or independence and original work. Therefore, no conflict of interest exists.

7. Funding source declaration

This research did not receive any specific grant from founding agencies in the public or not-for profit sectors.

8. Short biography of the authors

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Notes

[1] The paper was written by the authors jointly. Specifically, B. Martini wrote section 1; R. D'Ugo wrote sections 2; M. Tombolato wrote sections 3, 4 and 5.
[2] By epistemic practices we mean those practices enacted by members of different scientific communities to construct, validate, evaluate, and justify knowledge within a specific field.

Licensing terms

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