Primary colors as a source of possible misconceptions: an insight into teaching and learning about color

Berta Martini[1], Monica Tombolato[1], Rossella D'Ugo[1] [1]

[1] Department of Humanistic Studies, University of Urbino 'Carlo Bo', Italy. berta.martini@uniurb.it, monica.tombolato@uniurb.it, rossella.dugo@uniurb.it

Corresponding author: Berta Martini (berta.martini@uniurb.it)

ABSTRACT

In the field of science education, color can provide an interdisciplinary learning content, potentially suitable for overcoming disciplinary fragmentation and promoting in students a general attitude towards dealing with problems. However, because of its polysemic nature, it is very difficult to make students able to interpret, within the theoretical paradigm of modern science, a concept that they first learn to know through perceptual experience. As a pervasive phenomenon of our daily life, color vision gives rise, indeed, to a variety of naïve conceptions – similar to the pre-Newtonian ones – that act as a filter to the new learning contents. In this context we identified, through a historical-epistemological analysis, the ancient contrast between simple and compound colors as a source of potential misconceptions to be investigated empirically. We hypothesized we could detect some misconceptions due to the lack of awareness of the different contexts – physics, physiology of vision, painters' practice – in which the distinction between primary and secondary colors can be introduced, assuming different meanings in each one. We also believed that these misconceptions were relatively independent of the subjects' level of education (children/teachers). Then an empirical research was conducted by administering two different self-completed questionnaires to a non-probabilistic sampling of convenience made up of primary school teachers and fifth-grade pupils, respectively. The results of research on both teachers' and children's misconceptions seem to confirm what hypothesized.

KEYWORDS Misconceptions, Primary colors, Additive and subtractive color mixing, Teaching and learning process, Constructive theory of learning, Newton's prism

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1. Background

In the field of science education, color can provide an interdisciplinary learning content, potentially suitable for overcoming disciplinary fragmentation and promoting in students not a sterile accumulation of knowledge but a general attitude towards dealing with problems (Morin 1999). However, because of its polysemic nature, it is difficult to make students able to interpret, within the theoretical paradigm of modern science, a concept that they first learn to know through perceptual experience (Piana 2000; Martinez-Borreguero et al. 2013).

As a pervasive phenomenon of our daily life, color vision gives rise to a variety of naïve conceptions, similar to the pre-Newtonian ones, that are scientifically incorrect but of somewhat practical use. Within the constructivist paradigm we speak, in this regard, of commonsense knowledge, that is of mainly implicit knowledge that acts as a filter to the new learning contents (Mason 2006). Howard Gardner (2004) and Stella Vosniadou (2003), among others, highlight the negative influence that this implicit knowledge can have on students' learning outcomes and on their capacity to intentionally apply what they have learned to new problem-situations. According to the two psychologists, these intuitive "theories", which take shape in children's minds to give meaning to the world phenomena, are one of the main causes of students' elective failure in science. Far from disappearing during the school years, these naïve conceptions, tacitly internalized through daily experience and communicative exchanges, often emerge, at an unthinking level, as a cognitive resistance to reasoning according to the logic of the discipline (Martini 2018). This is a profound change from the traditional vision of learning. According to the constructivist learning theory, new knowledge is built upon what was previously learnt. In other words, the student is not a *tabula rasa* who passively receives the information transmitted by the teacher. On the contrary, she/he is an active knowledge builder who, before entering school, has already independently developed informal scientific concepts. These prior intuitive conceptions are highly resistant to change – as Strike and Posner suggest (1992) – because they are embedded within a broader conceptual ecology that consists of analogies, metaphors, methodological beliefs about "how science works", knowledge from other domains, epistemological and ontological presuppositions, religious and metaphysical beliefs. A similar position is shared by Vosniadou: on the basis of researches carried out in the field of elementary astronomy and mechanics, the psychologist hypothesizes that intuitive informal knowledge is articulated in mental models, specific theories and framework theories (Vosniadou 2003). Mental models – generated by the subject to solve problems, explain and/or predict phenomena of the natural world – are based on specific theories that consist of information – derived from observation or culturally transmitted – concerning the properties and behavior of physical objects. In turn, these specific theories are bound to framework theories, which are characterized by ontological and epistemological presuppositions about existing entities and the nature of knowledge. These presuppositions play an important role in constructing knowledge because they constitute the set of certainties on which everyday reasoning is based.

If we extend these considerations to color vision, we can interpret the intuitive models generated by learners within two framework theories, which are compatible with some misconceptions discovered through empirical research (e.g., Anderson and Smith 1986; Şahin et al. 2008; Martinez-Borreguero et al. 2013). The first framework theory is an ontology made up of assumptions derived from informal learning through our experiences and our social interactions. It describes various characteristics of the objects, including that of having their intrinsic color [3] (e.g. Hawkins 1985, Anderson and Smith 1986; La Rosa and Meyer 1991; Feher, E. and Meyer, K. R. 1992; Haagen, C. 2014). The second, instead, concerns the epistemological dimension of knowledge and assumes that things are as perceptually appear to be. These implicit presuppositions, developed in parallel with both everyday experience and ordinary language learning, act as a filter to scientific notions taught at school, which, in turn, can be vitiated by misconceptions due to the polysemy of the concept of color. In this context, we intend to analyze students' learning difficulties by using the concept of epistemological obstacle. For this purpose, we propose a reassessment of the original concept, aimed at integrating Bachelard's and Brousseau's perspectives in light of an intentional theory of knowledge (Tombolato 2018).

The notion of epistemological obstacle is originally introduced by the French epistemologist (Bachelard 2002) to identify the causes of stagnation and even of regression that lie at the very heart of the act of cognition. In this way, Bachelard focuses attention on the psychological conditions in which scientific progress is made, concluding finally that the evolution of scientific thought requires to "know against" prior pre-scientific knowledge, which is highly resistant to change since rooted in everyday experience. Brousseau (1983) later adapts the notion of epistemological obstacle to indicate the difficulties associated with the structural complexity of concepts in the field of mathematics education. He also undermines the key role that a historical analysis of the evolution of the discipline can play in highlighting these obstacles [4]. Now, if we assume the subject-object intentional relation as a structural feature of knowledge, it is possible to make a synthesis between Bachelard's and Brousseau's perspectives, in order to increase the hermeneutic and heuristic power of the concept. Within this framework the notion of epistemological obstacle can indeed be subjected to a double interpretation. On the one hand, it alludes to the idea that scientific contents can be conceptually understood as the objective correlates of peculiar epistemic practices [5] that appeared very "revolutionary" even to the scientists who first conceived them. On the other, it alludes to the misconceptions discovered through empirical research, which reveal the spontaneous tendency of subjects in learning to think in terms of reified concepts. Because of commonsense habits and, sometimes, as a consequence of "naïve" teaching, we, indeed, are often inclined to ignore the processes that lead to the construction of such scientific contents and provide them with their meanings (Tombolato 2018). At a methodological level, this implies two possibilities. We can employ heuristically naive physics conceptions to identify conceptual stumbling blocks within expert knowledge domain. Otherwise, we can undertake a historical-epistemological analysis of the evolution of the discipline in order to infer potential misconceptions to be subjected to empirical testing. We selected this second option and decided to focus on the dispute between Hooke and Newton on the heterogeneous nature of white light as a source of possible misconceptions.

Newton proposes the analogy between the mixing of pigments and that of colored lights, defending his thesis against the objections – empirically founded – raised by his antagonist Hooke. This is a clear evidence of how difficult is reformulating the artists' practical knowledge of working with pigments within a scientific framework (Giudice 2009) [6]. The difference between additive mixing of lights and subtractive mixture of pigments, clarified by Hermann von Helmholtz only in 1852, is therefore historically linked to the ancient contraposition between primary and secondary colors. This distinction is still a source of confusion for a lot of students because it can be introduced in different contexts – physics, physiology of vision, painters' practice – assuming different meanings in each one. By taking into consideration Shapiro's article (1994), we will give a brief historical account of the genesis of this classification in order to clarify the three different perspectives (physics, physiology of the visual system, artists' practice) from which it can be analyzed. In the "New theory about light and colors" Newton affirms the existence of two sorts of colors: "the one original and simple, the other compounded of these" (Newton 1672, p. 3082). This first general definition is subsequently modified to face the objections raised by Hooke about the nature and number of primary colors, whose difference from the compound ones is now explained in terms of refrangibility: primary colors are those whose rays are all alike refrangible, while compound colors are those whose rays undergo a different refraction. Experimentally this leads to a double possibility. Let a beam of green light pass through a prism, it will undergo a refraction but not a dispersion, or it will be decomposed into rays of different colors (yellow and blue). Therefore, Newton argues, two rays of colored light that are perceptually identical may, however, differ in their physical composition. As Shapiro points out, by primary (simple) Newton means the "physically irreducible" colors, that is the differently refrangible monochromatic spectral colors in which white light is decomposed by a prism (Shapiro 1994, p. 618). As a consequence of Newton's definition, there is an infinite number of primary colors due to the continuity of the visible spectrum. This statement sounds odd to Hooke, who, on the contrary, referring to the arts tradition of pigment mixing, defines as primary the basic colors from which all the others can be obtained by composition. The gap between the two standpoints is partially due to the polysemy of the term "color" which can be used with very different meanings. Strictly speaking, we should employ the locution "chromatic pigments" to refer to the colored substances used in painting, which clearly differ from the "visual color" that is the color perceived by the eye when it is stimulated by the various wavelengths reflected by such pigments. Pigments work, indeed, by selectively absorbing some wavelengths from the white light, while reflecting others which evoke in human eye the corresponding colors. (De Grandis 2000, p. 17). Although Newton and Hooke disagree on the number and nature of primaries, both make no distinction between mixing pigments and mixing lights. This assumption, almost universally accepted, will be questioned by Helmholtz only two centuries later, when he finds out the different rules applying to subtractive (pigments) and additive (lights) color-mixing processes. Thus, his discovery let us move on to a third possible way to define primary colors.

According to Young-Helmholtz's trichromatic theory, the primary colors of the spectrum are the triad of monochromatic radiations Red, Green, Blue (RGB), which, additively combined (alternately and in different proportions), produce the entire range of colors and, as a limit case, a white light. In this sense, therefore, when referring to the primary colors of the spectrum we are concerned not with physical properties of light waves, but with the perceptual effects they produce on the visual system (De Grandis 2000, p. 75). Based on what outlined so far, we will try to unravel the ambiguity that lurks in the ancient distinction between simple and compound colors, by making explicit the different meanings underlying such a classification. Our hypothesis, indeed, is that these different meanings can be correlated with potential misconceptions to be investigated empirically.

In Newton's definition of primary colors is outlined the distinction between monochromatic spectral colors (simple), characterized by a particular wavelength (between 380 nm and 780 nm), and colors obtained by mixing lights (compound). Although, sometimes, colors belonging to the second group may appear perceptually identical to the pure spectral colors of the first group, they differ from a strictly physical standpoint, however. In other words, there is no one-to-one correspondence between wavelengths and perceived colors: an object may appear yellow, for example, because it reflects light of wavelengths around 580 nm, while absorbing all the others, or because it reflects both red and green light, whose combination yields the same chromatic sensationwith different lightness perception. Therefore, the same color sensation can be produced by entirely different physical stimuli. Moving from physics to physiology of the visual system in our framework we just introduced the basic concepts of the theory of additive light colors mixing from primaries red, green and blue (RGB) and subtractive subtractive color mixing that predicts the spectral power distribution of light after it passes through successive layers of partially absorbing media from primary colors cyan, magenta and yellow (CMY). Identified as the set of subtractive primary colors by a commission of international experts, the pigment colors cyan, magenta and yellow act as filters to white light in order to produce the additive triad (RGB). Superimposing magenta and yellow filters we get red light, cyan and yellow filters we get green light, magenta and cyan filters we get blue light. Finally, black results from the superposition of the three subtractive colors respectively (De Grandis 2000, p. 18).

In summary, in the first case a physical definition of "simple" colors in terms of monochromatic rays of light (that is rays of a determinate wavelength) is provided. In the second case, with reference to the physiology of the visual system, the primary colors are identified with the RGB additive color model in which red, green and blue light are added together in various ways to produce all the other colors. Finally, the subtractive primaries are those basic colors (De Grandis 2000, p. 17 note 1) used in painting and more generally in printing, photography and cinematography (CMY) which, by filtering white light as described above, allow the three additive colors RGB to be obtained as the result of light subtraction by absorption.

2. Research hypothesis

In this context, we carried out an empirical research aimed at detecting possible misconceptions about color held by primary school pupils and teachers. The hypothesis of the research is that some misconceptions are linked to the lack of explicit distinction between physics, physiology of the visual system and painters' practice standpoint, respectively. We also believe that these misconceptions are relatively independent of the subjects' level of education (children/teachers).

In particular, we expected to detect the following children's misconceptions:

(1) the belief that color is an intrinsic property of objects and the confusion between light colors and pigment colors (QC1, QC2). These misconceptions are well known in scientific literature (see note 3) (e.g. Hawkins 1985, Anderson and Smith 1986; La Rosa and Meyer 1991; Feher, E. and Meyer, K. R. 1992; Haagen, C. 2014);
(2) difficulty in distinguishing between mixing of pigments and mixing of lights (QC3, QC4, QC5);
(3) the knowledge of primary colors limited to the painters' practice standpoint taught in arts education (QC4);
(4) the merely superficial knowledge of the physical interpretation of color (QC6).

As for teachers' misconceptions, we expected to detect:

(1) poor knowledge of the scientific interpretation of the color vision phenomenon (QT1, QT2);
(2) knowledge of primary colors only as pigment colors out of which all the others can be made (QT3, QT4);
(3) inability to distinguish between "almost pure colors" (characterized by a dominant wavelenght and a narrow band) and colors produced by the addition of lights (QT5, QT6, QT8);
(4) confusion between the mixture of pigments and that of colored lights (i.e. between additive and subtractive synthesis). In particular, our hypothesis is that the colored light is mixed with the "color of the object", as expected from the pigment mixing model. This implies teachers hold the (more or less implicit) belief that color is a quality of objects independent of both the type of light source that illuminates the object and the characteristics of human vision (see note 3) (QT7, QT9).

3. Methodology and tools

The research was conducted by administering two different self-completed questionnaires (Corbetta 2003, p. 179) allowing subjects to answer questions independently, without the need for an interviewer to be present. The two questionnaires were addressed to primary school teachers and to fifth-grade pupils, respectively, according to a non-probabilistic sampling of convenience.

The sample consisted of:

- 30 primary school teachers from the Province of Pesaro-Urbino.
- 92 fifth-grade pupils. In particular, 18 children attending the school complex in Cattolica (Rn), 11 attending the school complex Binotti in Pergola (PU), 22 attending the school complex Olivieri in Pesaro (PU), 21 attending the school complex Pascoli in Urbino (PU) and 20 attending the school complex Villa San Martino (PU).

Data from the two groups were collected as follows: teachers answered the questionnaire under the guidance of an Internship Tutor from "Education Sciences for Nursery and Primary School" at Urbino University, who had previously been "trained" by the authors of this article. The children were informed in advance about the purpose of the investigation and assisted in filling in the questionnaire by their own teachers, who were given precise instructions to carry out a data collection as error-free as possible.

4. Children's misconceptions research results

Below we provide the children's answers to the questionnaire (QC), organized according to response types gained from the reading of the data.

QC1. What is color for you?		
Color is linked to emotions	32	35%
An object property/A tool that colors things	13	14%
Color is a light/colored light	11	12%
Paint/colored spot/colored substance	11	12%
Tautological answers: e.g., "color is a colored form"	5	5%
Answers that identify a function of the color: "the color is needed to ..."	3	3%
Don't know	3	3%
Not relevant	2	2%
Other	12	13%
QC2. Why do we see objects of different colors?		
Because everything has its color	20	22%
By means of light/sun	16	17%
Because of emotional reasons	14	15%
Because they are painted	13	14%
Because our eyes can do it	12	13%
In order to distinguish them	8	9%
Don't know	5	6%
Other	4	5%

The first two questions were aimed at detecting children's naive conceptions about color. First, a marked variety of response types (especially regarding the first question) may easily be noted. Among the answers the most common (35% for the first question and 14% for the second question) were those that interpret color as a source of feelings and emotions: "color is a source of joy". The idea of color as an intrinsic quality/property of objects is widespread as well (14% for the first question and 22% for the second): "because everything has its color"; "Because God wanted so". This naïve idea is implied, more or less implicitly, also by the answers (about 14% of the total) according to which we see objects of different colors because they have been painted/colored. The concept of color as light occurs in 12% of responses to the first question and in 17% of responses to the second question. The answers, however, highlight naïve conceptions: "color is a light that colors things"; "Color is a colored light"; "We see objects of different colors because the light 'touches' an object and gives it color".

Questions QC3, QC4 and QC5 have been proposed to detect children's misconceptions related to the analogy between light mixing and pigment mixing.

QC3. Is it possible to get a black light by mixing colored lights?		
Yes	55	60%
No	35	38%
Don't know	1	
Don't answer	1	
QC4. What are primary colors? What primary colors do you know?		
They are those colors that allow to produce all the others/Those which cannot be derived from any others	27	29%
Don't know	17	18%
They provide only color occurrences	14	15%
They are the most used colors	7	8%
They are the lightest colors	6	7%
They are the ones that come first	5	5%
They are the "prime" colors	2	2%
Other	14	15%
Among children who claim to know primary colors:		
They mention the triad red-green-blue	2	2%c
They mention the triad red-yellow-blue	19	21%
They provide incorrect examples of colors	50	54%
QC5. Let's imagine putting a very big traffic light in the classroom and turning off the light. When the red light comes on, what color does the blue chair appear to be?		
Violet	38	41%
Red/Red and blue	8	9%
Black	7	8%
Brown/orange	7	8%
Green	6	7%
Yellow	4	4%
Blue	3	3%
Don't know	6	7%
Don't answer	4	4%
Other	9	10%

Regarding question QC4, children respond adequately in 29% of cases. The reason may lie in the fact that the answer corresponds to a traditional teaching content. As we will see later, this datum is confirmed by the answers provided by the teachers. However, this does not mean that the underlying conception is fully correct. As a matter of fact, even when children provide a plausible explanation of what primary colors are, they identify incorrect colors. Another interesting result concerns the triads mentioned: red-green-blue (2%) and red-yellow-blue (21%). They identified two distinct categories of primaries, the first referring to the additive synthesis of lights, while the second to the subtractive mixture of pigments. However, the occurrence of these two triads in children's responses is not justified on the basis of this distinction.

The fifth question (QC5) was intended to ascertain the confusion between the mixture of pigments and that of colored lights. Evidence in favor of this hypothesis comes from 41% of the responses, where children state that in the described circumstances they chair would appear violet, exactly as would result by overlapping the red of the light and the blue color of the chair. Further evidence is provided by the high percentage of affirmative responses (60%) to QC3, showing that the pigment mixture model is used even when lights rather than pigments are mixed.

The responses to the last question (QC6) are displayed in table below. The answers show that 10 children refer to the scientific phenomenon of light decomposition: 4 explicitly allude to the visible spectrum and 6 allude to the phenomenon of decomposition. However, even in this case, their responses reveal a merely superficial knowledge. "Inside the prism, the white light reflects to the glass and so gives rise to the visible spectrum"; "Passing through the prism, white light splits into the visible spectrum". Some children (9) answer that they have already heard of Newton's prism, which is, indeed, a traditional learning content taught at school.

QC6. Do you know Newton's prism?		
They say they don't know Newton's prism	24	26%
They claim to know Newton's prism	9	10%
Don't answer	59	64%
Can you tell what happens to white light when it passes through the prism?		
The light becomes colored / turns into a rainbow	33	36%
I don't know	16	17%
Light splits into colors	6	7%
The visible spectrum is formed	4	4%
They describe different phenomena	21	23%
Other	12	13%

Our supposing that children fail to show a meaningful understanding of the scientific phenomenon is supported by the fact that if we compare these answers with those given by the same children to the previous questions, internal inconsistencies emerge. For example, with reference to the first of the responses cited above – "Inside the prism, the white light reflects to the glass and so gives rise to the visible spectrum" –, the same pupil to the question "What is color" (QC1) answers: "An ink that paints things".

5. Teachers's misconceptions research results

We provide the results of the teachers' questionnaire (QT) without specifying the percentage data because of the narrowness of the sample.

As regards the first question (QT1) – "Why do we see objects of different colors?" (A question corresponding to QC2 of the children's questionnaire) – most teachers (21 out of 30) make a general reference to light absorption and reflection phenomena. Deep knowledge gaps emerge from 7 answers. In just 2 cases, teachers offer more precise responses including each of the three elements involved in color vision (light source, human eye, objects absorbing and reflecting wavelengths of light). For example: "because our eye has the ability to see the colors of light reflected by various objects". If asked about the nature of black and white – "How can black and white be defined with reference to what is represented by figure 1?" (QT2) – two teachers provide correct definitions: in one case, White = light, black = absence of light; in the other, white is the mixture of all colors, black is the absence of light and thus of color. Many recognize black and white as non-colors but providing incorrect justifications or not providing any. In 7 other cases the teachers refer to white and black as colors of objects.

Concerning questions QT3 and QT4 aimed at investigating naïve ideas about primary colors (see figures 2 and 3), most answers show they are mainly defined as the colors from which all the others derive.

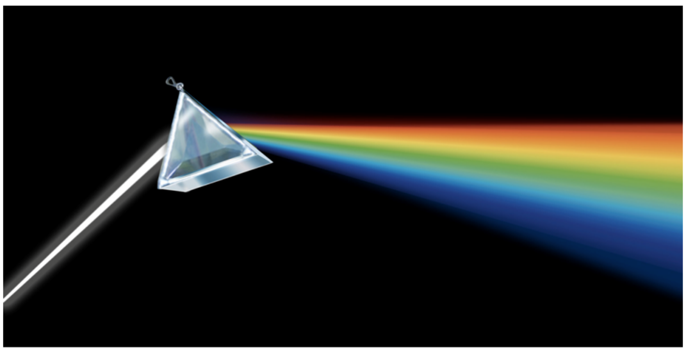

Fig. 1. Prismatic decomposition of light

There is no clear awareness about the difference between light colors and pigment colors, however. Except for two cases, teachers, indeed, do not distinguish between additive and subtractive primaries. Moreover, similarly to what emerges from children's responses, the predominantly cited primaries are the traditional painters' ones (red, yellow and blue), as a further proof of the dominance of the pigment mixing model.

The question QT5 asks if "two perceptually identical colors can be different from a physical standpoint". Teachers respond "yes" in 23 cases out of 30. However, if we compare these answers with those given to questions QT6 and QT8, it is hard to suppose they really understand the difference. When asked the reason why a lemon appears yellow (QT6), only 2 teachers are aware of the double possibility that the lemon reflects the wavelength corresponding to yellow light or the wavelengths corresponding to red and green lights (proving to interpret yellow as a result of the additive synthesis of these two light colors). Moreover, considering question QT8 – "Is there a difference from a physical standpoint between the yellow color in Figure 1 and the yellow color in Figure 2? If yes why?" – which actually provides an exemplification of question QT5, only 9 teachers answer yes and, among these, only 2 partially justify their choice.

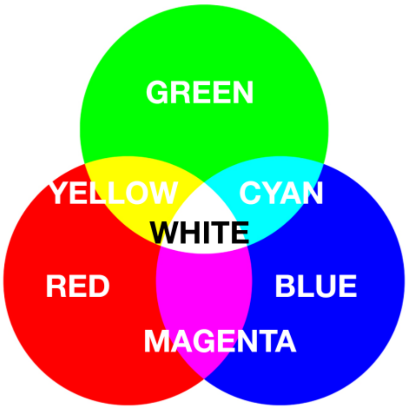

Fig. 2. Additive color mixing

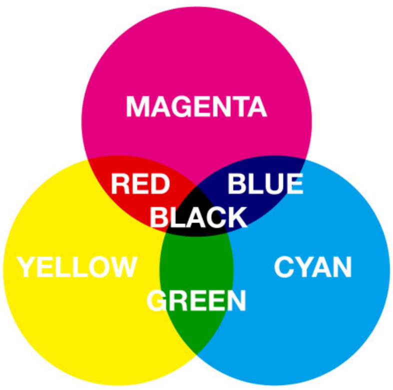

Fig. 3. Subtractive color mixing

Regarding question QT7 – "If an object illuminated by sunlight appear blue, what color will it appear to be if illuminated by a light source emitting only red-light beams?" –, 11 teachers answer the object will appear violet. Among the others, 6 teachers opt for black, 4 for blue, 2 for green, 1 for brown and 1 for pink, respectively. Finally, 3 teachers admit not to knowing the answer and 1 does not respond. It is noted that also in this case, as in the case of question QC5 addressed to children, most responses converge on the same choice that is violet. This confirms that the dominance of the pigment mixing model is relatively independent of the level of schooling attained.

Our hypothesis is further corroborated by the answers to the last question QT9 – "How will appear a magenta colored object that absorbs the wavelengths corresponding to the green, if illuminated with monochromatic radiation, i.e., light of a single color such as red, blue or green respectively? And finally, how will it appear in sunlight?" –, most of which are null (they do not know or do not answer) or irrelevant. In 4 cases, teachers' predictions highlight the pigment mixture model underlying their reasoning. For example: "(...) If the magenta object were illuminated by green light, we should see it black because magenta is made up of red and blue, so, adding green light, we would obtain the triad that produces the black color (...)".

6. Discussion and conclusive remarks

As regards the hypotheses formulated in section 2, the following conclusions can be advanced for the research carried out on children and teachers respectively.

(1) The conception of color as an intrinsic property of objects emerges both explicitly from some responses and implicitly, as a presupposition underlying other misconceptions.

(2) The confusion between light and pigment colors is highlighted by the high response rate to question QC3. This tendency is confirmed by the evident lack of distinction between additive and subtractive primaries as shown in QC4, as well as by the dominance of the pigment mixing model in QC5, where reference is made to the overlap between the red light and the blue color of the chair (conceived as an intrinsic quality of the object).

(3) Unlike what was hypothesized, not all children in our sample know primary colors. Some of them provide interpretations partially relevant, while others make references to other fields of experience. Those who show to have some, albeit superficial, knowledge of primary colors confirm that it is circumscribed to the painters' triad (red, yellow, blue), probably acquired during school arts activities.

(4) A small minority of children refers to the spectral decomposition of light passing through a prism. However, we assume that theirs is a merely superficial knowledge due to the lack of consistency

with the answers previously given, which point out the persistence of the misconceptions highlighted above.

As regards the hypotheses formulated about the teachers, the following conclusions are advanced.

(1) The scientific mastery of the color vision process is somewhat partial. Teachers, indeed, refer to the three basic elements of color vision (light source, human eye, objects absorbing and reflecting wavelengths of light) in only two cases. This is also confirmed by the limited relevance of the responses to the second question, i.e. about the definition of white and black with reference to the prismatic decomposition of light.

(2) The knowledge of primary colors is almost exclusively limited to their interpretation as the basic pigment colors whose mixture produces all the others. As a matter of fact, teachers mainly mention the painters' triad red-yellow-blue, showing no awareness of the difference between additive and subtractive primaries.

(3) Teachers confuse physical and physiological aspects of color vision since they do not distinguish between spectral monochromatic colors (colors with single wavelengths) and non-spectral colors that can be obtained as a result by adding lights of different wavelengths. Although in some cases non-spectral colors are perceptually identical to monochromatic colors, they are different from a physical standpoint, however.

(4) The hypothesis of the misleading analogy between the mixing of lights and the mixing of pigments (i.e., between additive and subtractive synthesis) is confirmed. Similar to what was observed with children, many teachers tend to mix the color of the light illuminating the object with the color of the object considered as its intrinsic property.

From what is outlined above, the following conclusion can be drawn: both teachers and students show misconceptions and naïve ideas about color vision due to the lack of explicit distinction between physics, physiology of the visual system and painters' practice standpoint, respectively. More, this confirms that the misconceptions highlighted in this paper are relatively independent of people's level of education; on the other hand, it points out the necessity to make these three different perspectives explicit in teaching and learning process, in order to foster a meaningful knowledge about color.

7. Conflict of interest declaration

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

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9. Short biography of the authors

Berta Martini - Full Professor at University of Urbino – Dept. of Humanistic Studies – where she teaches General Didactic and Pedagogy of Knowledge. She is co-director of the online scientific journal Pedagogia più didattica, and she is a member of the scientific boards of peer review journals and publishing series. Her main fields of research are the processes of transmission of knowledge and in curriculum studies.

Rossella D'Ugo - Researcher in Experimental Pedagogy at University of Urbino – Dept. of Humanistic Studies – where she teaches Docimology and Experimental Pedagogy. Her research is mainly oriented to the study of evaluation and self-evaluation tools and methods to ensure the quality of educational contexts as well as of the teaching practices of educators and teachers.

Monica Tombolato - PhD in Epistemology and in Education (University of Urbino). She is currently a Postdoctoral Fellow and a contract professor for the Pedagogy of Knowledge Lab and Physics Education Lab at University of Urbino – Department of Humanistic Studies. She is the author of essays and articles concerning the philosophy and pedagogy of knowledge.

Notes

[1] The paper was written by the authors jointly. Specifically, B. Martini wrote sections 4 and 6; M. Tombolato wrote sections 1 and 5; R. D'Ugo wrote sections 2 and 3.

[2] In this context, assuming intentionality as a structural feature of knowledge means highlighting the "perspectival character" of scientific knowledge. As suggests the philosopher of science Evandro Agazzi (2014, p. 83), different disciplines investigate 'things' from different perspectives. The same 'thing' can thus become the object of a variety of sciences when considered from different standpoints.

[3] From a didactic standpoint, this means that the color of an object is conceived as being independent of both the type of light source that illuminates the object and the characteristics of human vision. Making the example of a person looking at a colored object in white light, Anderson and Smith (1986) highlight two different interpretations capable of explaining the observed phenomenon:

"1. A scientific interpretation: White light is a mixture of colors of light. Objects absorb some of those colors of light and reflect others, and people see the colors of the reflected light.
2. A naive interpretation: White light is clear or colorless. It brightens objects and in so doing reveals their colors, which are innate properties of the objects themselves. People's eyes see the colors of the objects".
As Haagen (2014) points out: "One prerequisite for understanding optics, including color phenomena, on a basic level is the idea that objects which do not produce light themselves are able to absorb and reemit light. Only when light (re)emitted by an object enters the eye of an observer, he or she can perceive the object. This sender-receiver mechanism also determines the kind of color we see, as the color depends on the kind of light we receive. Consequently, without this basic concept of a sender - selective (re)emission - receiver model, it seems to be difficult to develop scientifically adequate ideas concerning color and colored objects".
[4] On the distinction between 'obstacle' and 'mistake' from an educational standpoint, see Martini 2000, pp. 89-102.
[5] Consider, for example, Galileo's approach to science based on the use of idealized models and thought experiments in order to interpret natural world phenomena. (McMullin 1985). Both idealized models and thought experiments are used in teaching about color and color vision, at least on a basic level.
[6] Numerous experiments showed that if two primary color lights (for example, red and green) are combined, new colors are obtained. On the contrary, by mixing the two corresponding pigment colors only dirty grays are obtained (De Grandis 2000, p. 17).

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