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Detection of Misconceptions about Colour and an Experimentally Tested Proposal to Combat them

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We study the misconceptions about colour that most people hold, determining the general phenomenological laws that govern them. Concept mapping was used to combat the misconceptions which were found in the application of a test specifically designed to determine these misconceptions, while avoiding the possible misleading inductions that could have arisen from the use of everyday language. In particular, care was taken to avoid the distorting effect that the use of the verb 'to be' applied to coloured objects could have on the responses. The misconceptions found were shown to have an internal consistency in the form of authentic mini-theories (implicit theories). We compared experimentally the results of two different teaching methods applied to combat these misconceptions. This study was conducted with 470 undergraduates of the University of Extremadura. We analysed the persistence over time of their learning made to overcome those misconceptions. The students were divided randomly into an experimental group (EG) and a control group (CG). To combat their misconceptions, EG were taught following a method based on the use of concept maps, and CG were taught following traditional teaching methods. The results of a pre-test and a post-test were compared for the two groups, finding statistically significant differences. The results allowed the principal working hypothesis to be accepted—concept maps are learning tools which foster conceptual change and allow misconceptions to be eradicated via meaningful learning maintained over time, i.e. EG acquired a relative long-lasting gain in learning that was superior to that acquired by CG.

Keywords: *Misconception; Learning; Experimental study; Concept maps; Physics; Colour; Misconception; Learning*

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1. Introduction: Misconceptions and Implicit Theories

In humans, the spontaneous construction of theories to explain certain physical phenomena is a response to the functional need for organisation of our cognitive system that is present from the earliest years of life. For Ioannides and Vosniadou (2002), the term ‘theory’ is used relatively freely to denote an explanatory system with some coherence. It is assumed that children’s theories differ, in many respects, from scientific theories. In the absence of formal instruction, children’s theories are made up mainly of very simplified, implicit causal explanations that underpin procedural knowledge that is useful for everyday life (Claxton, 1984a; Karmiloff-Smith, 1992). While helping children to predict and control particular phenomena, these causal explanations—or naive physics—are, however, not necessarily coherent with the scientific explanation of the phenomenon; under certain conditions, their incorrectness may become evident. Further, children’s theories lack the systematicity of scientific theories, as well as other characteristics of scientific theories, such as their abstractness and social/institutional nature (Ioannides & Vosniadou, 2002).

However, currently, there is no consensus among researchers about the exact nature of this naive physics. The ideas that students have about physical phenomena are usually primitive and phenomenological (Di Sessa, 1993). They are primitive, because they are based on simple and intuitive explanations, and phenomenological, because they derive from the experiences that the subjects are exposed to through their interaction with the physical world (Pérez, Suero, Montanero, Pardo, & Montanero, 2010).

Many studies agree that misconceptions condition the acquisition of knowledge in specific domains. There is no consensus, however, as to whether misconceptions constitute genuine implicit theories (Lautrey & Mazens, 2004). For Di Sessa (1993), it is a case of ‘knowledge in pieces’ (rather than a logically organised body of knowledge); these pieces are generated as abstractions of common phenomena and are activated in certain characteristic cases. Other studies maintain that naive physics constitutes a narrow but relatively coherent explanatory framework that has the form of a theory (Driver & Easley, 1978; McCloskey, 1983; Novak, 1977). Vosniadou (1992) argues that spontaneous knowledge develops into spontaneous theories at two different levels: ‘framework theories’ and ‘specific theories’. Pérez et al. (2010) assert that framework theories are based on certain ontological and epistemological presuppositions that define a domain. In contrast, specific theories are constrained by framework theories; they are based on beliefs that facilitate the construction of mental models of specific physical phenomena. According to these authors, it is more difficult to change framework theories than specific theories.

By showing students the erroneous nature of their spontaneous conceptions, formal instruction may lead them to abandon their implicit theories and accept scientific theories. However, it may also cause them to experience cognitive conflict between the mini-theories that they have formed by means of spontaneous conceptions and the official instruction that they are beginning to receive. Indeed, in many cases, after receiving formal instruction on a phenomenon, there is a tendency for students to, over time, shift back from the scientific theory learned in the classroom to their initial implicit causal theory (Montanero, Suero, Pérez, & Pardo, 2002). Some studies (e.g. Hubber, 2005) have found that these misconceptions are particularly resistant to change: they do not change in the intended direction (Happs, 1985; Osborne, 1983), or they may even change in unexpected ways as a result of instruction (Gauld, 1988). In line with these findings, authors such as Litch and Thijs (1990) contend that those students who create consistent mini-theories may also possess the reasoning ability to accept scientific theories. This means that a consistent alternative conception could be considered an intermediate stage in conceptual change. Therefore, students should not only feel the need to change their implicit theories, but they should develop skills to generalise and eliminate contradictions (Finegold & Gorsky, 1991; Gauld, 1988).

One important line of research in the field of science education is the study of the misconceptions about scientific topics that students of any educational level may have that may lead to serious misunderstandings about that topic. Velasco and Garritz (2003) define misconceptions in this context as the set of ideas that people have that allows them to interpret the natural phenomena that they observe in their everyday lives, which are often in contradiction with the theories, principles, and laws of scientific knowledge. Moreira and Greca (2003) indicate that these misconceptions are a result of the perception and cognitive structuring of everyday experiences, both physical and social, that gradually form an empirical knowledge of science. That these misconceptions persist even at the undergraduate and graduate levels (Gil, Solano, Pérez, & Suero, 1998; Solano, Gil, Pérez, & Suero, 2002) is indicative of the ineffectiveness of standard teaching methods in guiding the construction of knowledge. It is generally accepted in the literature that it is far from straightforward to determine whether these misconceptions are organised into true theories or are merely case-by-case explanations that the student forms (Gil, Carrascosa, Furio, & Martínez-Torregrosa, 1991). According to Mahmud and Gutierrez (2008), misconceptions play an important role in learning, because students consciously or unconsciously construct their own ideas to understand the natural phenomena that occur in their everyday world. Students believe that these explanations are correct, because the explanations make sense in terms of understanding the behaviour of the physical world around them. For this reason, when they come across new information that contradicts their own conceptions, they may accept it, ignore it, reject it, or reinterpret it.

While students' misconceptions are found to be heterogeneous across different student factors (e.g. age, the type of instruction received), they also have certain common features. Misconceptions are personal constructs that have been developed, more or less spontaneously, through everyday interaction with the world and with other people (Pozo, Limón, & Sanz, 1991). While often scientifically inconsistent, they do not seem inconsistent from the point of view of the students—who are seeking ideas that relate to the realities of the world around them but which they have not known how to interpret in terms of the general laws they have been taught in class (Pozo et al., 1991). Misconceptions are quite stable and resistant to change and may last from childhood, through adolescence, to adulthood (Suero et al., 1991). They are shared by people of varying characteristics (i.e. age, country of origin, and educational level) and even transcend time, presenting certain similarities with beliefs that were held by the scientific community in the past. They are implicit in nature—in contrast to the explicit concepts of science—and they can only be modified by making the student aware of them, causing them to be persistent and difficult to eradicate (Matthews, 1994; Pozo, Pérez, Sanz, & Limón, 1992).

There are different approaches that can be used to eliminate or prevent misconceptions and to promote meaningful learning. One of the most successful instructional methods used for this purpose is the conceptual change approach. Through conceptual change, the student replaces already existing conceptions with scientific theories, linking new propositions to his or her present conceptual frame. For successful conceptual change to occur, Posner, Strike, Hewson, and Gertzog (1982) suggested that the scientific conceptions must be intelligible (clear enough to make sense to the learner), plausible (seem acceptably true), and fruitful (appear potentially productive for solving problems). The main goal of the conceptual change approach is to create a cognitive conflict that makes the student dissatisfied with his existing conceptions.

Work specifically on physics education (Picquart, 2008) has demonstrated that students' misconceptions persist for many years and are an obstacle in their meaningful learning of the subject. Indeed, some research devoted to the study of students' difficulties with scientific concepts pertains to physics concepts. Considering optics in particular, work on misconceptions concerns myriad topics, notably the emission and propagation of light (Bendall, Goldberg, & Galili, 1993; Eylon, Ronen, & Ganiel, 1996; Gil, Pérez, Suero, Solano, & Pardo, 2010; Krapaz, 1985; Watts, 1985), mirrors and the laws of reflection (Galili & Bendall, 1993; Goldberg & McDermott, 1983, 1986), vision (Driver, Guesne, & Tiberghien, 1985; Feher & Rice, 1988, 1992; Galili & Hazan, 2000), optical aberrations (Martínez, Naranjo, Pérez, Suero, & Pardo, 2011), and colour (Anderson & Kärrqvist, 1983; Feher & Rice, 1992). It is precisely this last topic, misconceptions concerning colour, that is the focus of the present work.

In previous studies, our research group designed and implemented a test to determine misconceptions about the concepts of optics in general. One of our findings was that over 80% of the individuals tested had incorrect misconceptions concerning the concept of colour. If these misconceptions were organised into coherent theories (Ioannides & Vosniadou, 2002) that guide the students' interpretation of colour, then we should expect them to answer the test's questions about colour in a relatively uniform and internally consistent manner. If not, we should expect logically inconsistent responses guided by a multiplicity of fragmented interpretations (Di Sessa, Gillespie, & Esterly 2004) of the meaning of colour. In our studies, we found that the students' misconceptions about colour possessed some degree of internal consistency, which lends more support to the coherent theories interpretation.

Moreover, to our surprise, students' misconceptions about colour were not only present among primary school children but were also present among secondary school students, undergraduates, graduates, and even physics teachers. Such high percentages of incorrect responses to questions on such a basic scientific concept led us to consider that, perhaps, we were doing something wrong. We wondered whether the way in which we were expressing the items on our questionnaire might be inducing incorrect responses to those items concerning the concept of colour. We therefore, decided to invent a system of symbols that would allow us to present the same type of test without using words to describe the colour characteristics of the illuminant and the illuminated object, to avoid the possible misleading inductions that could have arisen from the use of everyday language. In particular, care was taken to avoid the distorting effect that applying the use of the verb 'to be' to coloured objects could have on individuals' responses, in sentences such as 'the apple is red'.

2. Method

2.1 *Objectives*

The objectives of the study were the following:

- To identify possible misconceptions regarding colour.
- To determine whether these possible misconceptions are organised to form implicit theories.
- To identify the implicit laws governing certain possible misconceptions.
- To identify the implicit theories organised on the basis of the possible implicit laws.
- To determine an effective teaching method to both combat the identified misconceptions about colour and ensure the sustainability of what is learned over time.

2.2 *Hypotheses*

According to the theoretical research framework guiding this study, misconceptions are accepted as constituting clusters that form so-called implicit theories (Claxton, 1984b) and possess some degree of internal consistency.

We posited the following hypotheses:

- First Hypothesis: Because individuals are exposed, from birth, to direct physical experiences of colour, it is very likely that each student will have their own misconceptions about this physical concept.
- Second Hypothesis: Misconceptions about colour will be organised in the form of implicit theories with their corresponding laws.
- Third Hypothesis: In an appropriately designed test to detect misconceptions about colour, the responses that students give to the different scenarios will have an internal consistency, allowing researchers to interpret the laws constituting students' implicit theories.
- Fourth Hypothesis: There will be statistically significant differences between the results obtained with different teaching strategies targeted at overcoming students' misconceptions about colour.

A respondent's responses are consistent when equivalent items (although they have two different perceptual elements) elicit the same option (correctly or incorrectly). From the observation of a respondent's responses consistency can be determined, because there are certain patterns that repeat throughout the test and certain sequences that repeat from one respondent to another.

2.3 Research Design

The research design for this study was quasi-experimental. It consisted of a comparison of the results of a pre-test and a post-test for two groups, one experimental group (EG) and one control group (CG), with whom two different teaching strategies were used to combat misconceptions about colour. The study was conducted during the academic years 2008/2009, 2009/2010, and 2010/2011, with graduate students (23–25 years old) attending the University at Spain who were taking one of the following three Master's courses: Secondary Education Teacher Training; Science Research (in the Science Faculty); or Introduction to Teaching/Learning Research in the Experimental, Social, and Mathematics Sciences (Education Faculty). These graduate students studied science as undergraduates (majoring in Mathematics, Chemistry or Biology). The sample consisted of 470 students who were divided, at random, into two groups; there were 224 students in the CG and 246 in the EG.

The independent variable was the teaching strategy used to combat the misconceptions about colour that were found during the pre-test of the two groups. For the CG, the teaching strategy was based on traditional methods, and for the EG, it was based on the use of concept mapping to promote meaningful learning. The dependent variable was the correction of misconceptions about colour as measured by differences between the pre- and post-tests.

Table 1 presents a description of the research design.

To verify the uniformity and equivalence of the two groups, we applied, for the pre-test, a newly elaborated assessment tool designed to identify misconceptions about colour. This was followed by the experimental treatment consisting of students' exposure to two different approaches to teaching colour: one type of instruction for

Table 1. The research design

Group	Pre-test	Teaching strategy to combat misconceptions	Post-test time elapsed: one month	Post-test time elapsed: five months
CG	Test: misconceptions about colour	Traditional teaching methodology	Test: misconceptions about colour	Test: misconceptions about colour
EG	Test: misconceptions about colour	Teaching methodology based on the use of concept maps	Test: misconceptions about colour	Test: misconceptions about colour

the CG and one for the EG. After this, the same assessment tool used in the pre-test was applied as a post-test at two different time intervals: one month after completing the instruction and five months after completing instruction. The data from the pre- and post-tests allowed us to test the validity of the research hypotheses and the durability of the students' learning over time.

In the next section, we present the set of symbols invented for the assessment tool. At this point, the reader might like to complete the test (see Figure 2) before continuing reading the article to self-detect if he or she might have any possible misconceptions related to colour.

We shall then present the results of our research, in which we have used this test with thousands of people over the last 10 of the 25 years included in this study, followed by a proposal to help combat the misconceptions detected.

2.4 Assessment Tool: The Apple Test

As an evaluation instrument, we elaborated upon a test that we have named, 'The Apple Test', which is aimed at obtaining information about the misconceptions students have concerning colour.

2.4.1 Test structure. To obviate the influence that the interpretation of textual language may have in inducing specific erroneous responses, we invented a purpose-designed set of symbols (Figure 1).

Part A of the test (Figure 1) shows coloured sketches (with a letter inside) of an object that emits light; when this emitted light reaches the eye, one perceives the sensation of a certain colour. When that object has a W inside it, the perceived colour is white; when the letter is G, the perceived colour is green; when the letter is R, the perceived colour is red; and when the letter is B, the perceived colour is blue. Thus, in spoken language, these four symbols represent what one would call a white bulb, a green bulb, a red bulb, and a blue bulb. The use of these symbols, therefore, precludes the necessity to write: '. . . a red bulb illuminates. . .'. We simply need to display its symbol, and its meaning is clear.

Part B of the test is a representation of RGB additive colour mixing. We found during previous uses of these types of test that the respondents often requested clarification as to what colour is obtained by adding together a given pair of colours. For this reason, we added the RGB additive colour mixing representation to the final version of the test. However, to prevent the presence of this information on the test from interfering with students' potential results, it was emphasised to the students that the presence of this information did not necessarily indicate that it had to be used.

Finally, in Part C of the test, we define a second type of symbol: apples. These symbols also have a letter differentiating one symbol from another according to the colour that the eye sees when the symbol is illuminated by a bulb that emits white light. In the sheet of symbols, the colour is not expressed in words but by its corresponding symbol (as defined in Part A). For example, the symbol in Part C containing

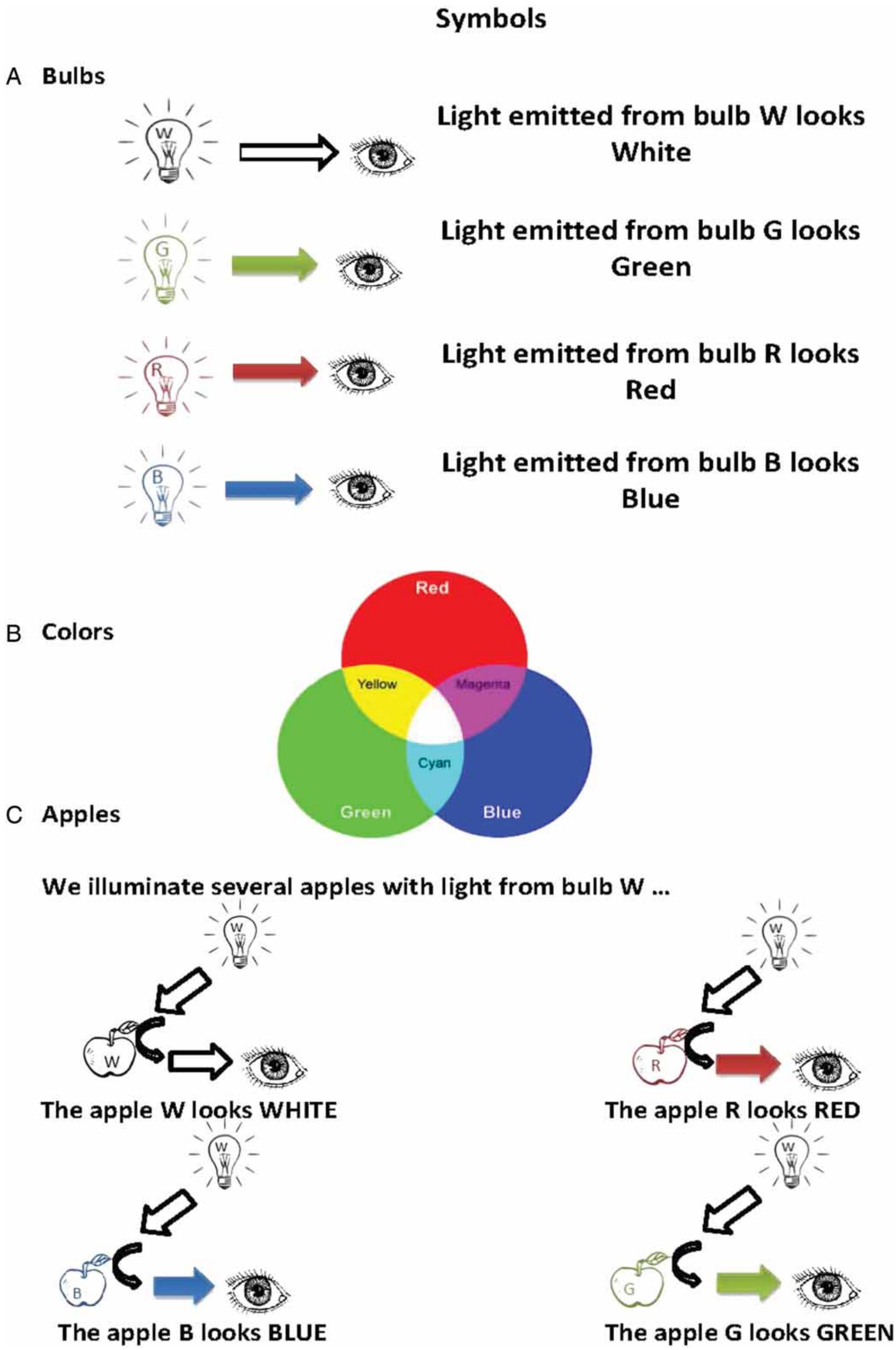


Figure 1. Symbols used in the apple test

an R represents an object, which when illuminated by a white light bulb, is seen by the eye to be red in colour. Using words, one would call the symbol a red apple.

Although the symbol sheet depicted in Figure 1 incorporates colour, it was designed so that this information was redundant. The diagrams also contained letters (R, G, B, and W) to indicate the different colours, so Figure 1 is perfectly understandable in monochrome.

Using this set of symbols, we created a 10-item test; on the test sheet, the scene statements were presented using figures: an apple of one of the three primary colours was illuminated by a light bulb of one of those same primary colours. For simplicity, a very basic model was used in which the light used as the illuminant was composed only of the three basic primary colours: red, green, and blue. Each of these primary colours are assumed excite exclusively one type of cone in the retina; the apples in the test are of these same ideally monochromatic primary colours. The question asked in the test is always the same: 'What colour will the apple look?' (The corresponding fully worded response would be, 'The apple will look white/blue/red/green'.)

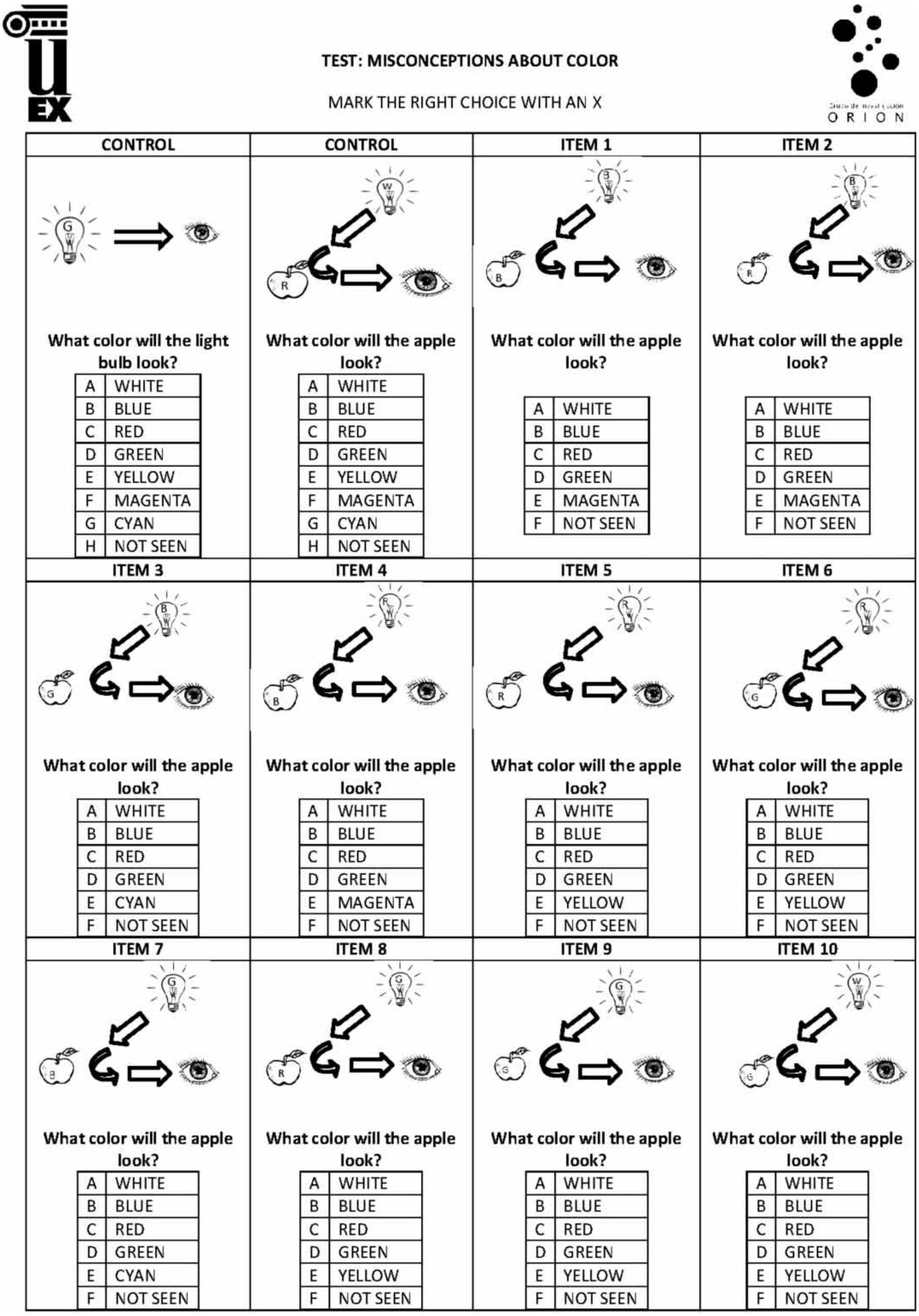
The six response options offered are also always the same:

(A) White.
(B) Blue.
(C) Red.
(D) Green.
(E) The colour sum of the object plus the illuminant.
(F) It will not be seen.

2.4.2 How the test is applied. Figure 2 shows the actual test with the items presented using the symbols whose meaning is described above.

The test (Figure 2) begins with two control items and is aimed to ensure that no problems arise in the interpretation of the symbols. If the response to either of these two questions is incorrect, that test will not be marked, because the symbols have not been understood, and therefore, the responses will be invalid. To date, there have not been any instances of incorrect control responses, providing evidence of the trivial clarity of the symbol set. Following the two control questions, there are another 10 items that constitute the actual test. In responding to the questions, the respondent places a cross in the square corresponding to the colour in which he or she thinks the eye will see the apple.

2.4.3 How the test is marked. First, we must remark that Item 10 is an undeclared control question (it is actually the definition of one of the symbols). It was decided that if the response to this item was incorrect, the corresponding test should not counted. Although we found no test with either of the two aforementioned control questions incorrectly responded to, we did find some (albeit, very few: seven over the 10 years) wrong answers to this undeclared control item. Curiously, in all seven



TEST: MISCONCEPTIONS ABOUT COLOR

MARK THE RIGHT CHOICE WITH AN X

CONTROL

What color will the light bulb look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	YELLOW
F	MAGENTA
G	CYAN
H	NOT SEEN

CONTROL

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	YELLOW
F	MAGENTA
G	CYAN
H	NOT SEEN

ITEM 1

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	MAGENTA
F	NOT SEEN

ITEM 2

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	MAGENTA
F	NOT SEEN

ITEM 3

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	CYAN
F	NOT SEEN

ITEM 4

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	MAGENTA
F	NOT SEEN

ITEM 5

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	YELLOW
F	NOT SEEN

ITEM 6

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	YELLOW
F	NOT SEEN

ITEM 7

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	CYAN
F	NOT SEEN

ITEM 8

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	YELLOW
F	NOT SEEN

ITEM 9

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	YELLOW
F	NOT SEEN

ITEM 10

What color will the apple look?

A	WHITE
B	BLUE
C	RED
D	GREEN
E	YELLOW
F	NOT SEEN

Figure 2. The Apple Test

cases, these errors occurred on tests that were otherwise perfectly correctly answered; the only error was made on this last undeclared control question. As such, we made the decision to consider the responses to these tests as valid; it may be that the error was due to another factor (e.g. a failure of concentration) rather than to any lack of understanding of the symbols.

The remaining nine test items can be grouped into two subsets according to the physical situation they represent:

- Scenario 1: Items 1, 5, and 9—A light bulb that emits light of the same colour as the apple it illuminates.
- Scenario 2: Items 2, 3, 4, 6, 7, and 8—A light bulb that emits light of a different colour than the apple it illuminates.

Thus, the test actually consists of nine questions, three of them (1, 5, and 9) corresponding to situations in which the colour of the bulb and the colour of the apple coincide. Initially, we believed that these three items would elicit only one response: respondents would indicate that the colour the eye sees is the common colour of the bulb and the apple. We were so definite that this would be the outcome that we included the responses to these three items in the template to be used for marking misconceptions (Figure 3). We did not expect anyone to contradict these responses. The items intended to provide information about how a particular person understands colour perception and their corresponding misconceptions about colour were items 2, 3, 4, 6, 7, and 8.

At the end of the marking template (Figure 3), we indicated response sequences corresponding to each of the four erroneous misconceptions we expected to find (initially, only the first three were included). They are described in Table 2.

The misconceptions that can be detected with this test are as follows:

- The colour perceived by the observer is the sum of the colour of the bulb plus the colour of the apple (both 'emit' their own colour, which the eye then adds together).
- The colour perceived by the observer is always that of the apple (the colour of a body is an intrinsic property).
- The colour perceived by the observer is the colour with which the bulb illuminates the apple, because it is the only colour emitted (the colour is a property of the illuminant).
- If the colour of the bulb coincides with that of the apple, the apple is not seen (the bulb fills the surrounding space with its colour, and if the apple is the same colour, then it is not seen due to lack of contrast). This misconception was not initially included in our initial template, because we did not even think of its possible existence. It was later added after being detected experimentally.

Using the template, tests could be marked immediately; after checking for errors in the three control items, which of the four response sequences was used by a given respondent could be easily ascertained. Sometimes student responses did not conform exactly to any of the specified sequences. Most often in these cases, it seemed that the respondent had begun to respond according to one sequence,

COURSE			I	T	E	M	S			
Student	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	COMMENTS
1	B				C				D	
2	B				C				D	
3	B				C				D	
4	B				C				D	
5	B				C				D	
6	B				C				D	
7	B				C				D	
8	B				C				D	
9	B				C				D	
10	B				C				D	
11	B				C				D	
12	B				C				D	
13	B				C				D	
14	B				C				D	
15	B				C				D	
16	B				C				D	
17	B				C				D	
18	B				C				D	
19	B				C				D	
20	B				C				D	
21	B				C				D	
22	B				C				D	
23	B				C				D	
24	B				C				D	
25	B				C				D	
26	B				C				D	
27	B				C				D	
28	B				C				D	
29	B				C				D	
30	B				C				D	
MISCONCEPTION1	B	**E**	**E**	**E**	C	**E**	**E**	**E**	D	*SUM OF COLORS*
MISCONCEPTION2	B	**C**	**D**	**B**	C	**D**	**B**	**C**	D	*APPLE COLOR*
MISCONCEPTION3	B	**B**	**B**	**C**	C	**C**	**D**	**D**	D	*BULB COLOR*
MISCONCEPTION4	**F**				**F**				**F**	*IF EQUAL, NOT SEEN*

Figure 3. Template to mark colour misconceptions for 'The Apple Test'

and then, halfway through the test, had switched to another; it is possible that the misconceptions of those students were related to fragmented theories instead of a coherent framework. As previously indicated, in items 1, 5, and 9, the colour of the bulb and the apple match. We initially assumed that all participants were going to give the response indicating that the colour seen by the eye is the colour common to the bulb and the apple. Occasionally, however, we encountered cases where respondents indicated that when the colour of the bulb and the apple matched, the apple would not be seen. Due to the low proportion of this pattern of response (approximately 1%), it took us several years to ascertain that these

Table 2. Summary of the possible misconceptions about colour and their corresponding test response sequences

Options	Description	Response sequence
Misconception 1	The colour that the eye sees is the sum of the colour of the bulb plus the colour of the apple	Sequence: 1 2 3 4 5 6 7 8 9 B **E** **E** **E** C **E** **E** **E** D
Misconception 2	The colour that the eye sees is the colour of the apple	Sequence: 1 2 3 4 5 6 7 8 9 B **C** **D** **B** C **D** **B** **C** D
Misconception 3	The colour that the eye sees is the colour that the bulb illuminates with	Sequence: 1 2 3 4 5 6 7 8 9 B **B** **B** **C** C **C** **D** **D** D
Misconception 4	If the colours of the bulb and the apple are equal, the latter is not seen	Sequence: 1 2 3 4 5 6 7 8 9 F - - - F - - - F
Correct	The apple will not be seen if the bulb is of a different simple colour from that which the apple reflects, or if the colour composition of the bulb does not include this latter colour.	Sequence: 1 2 3 4 5 6 7 8 9 B **F** **F** **F** C **F** **F** **F** D

responses indicated a particular form of reasoning. To do so, we located the people who responded in such a fashion and performed a short interview, where we asked them why they thought that the apple would not be seen. From the answers from these interviews, we gathered sufficient evidence to include a fourth misconception about colour that is detectable with this test.

2.4.4 The correct responses. Instruction in optics reveals that the perceived colours of common objects (such as the apples in the test) are due to their reflection of certain wavelengths contained in the light illuminating them (usually sunlight or another white light), with the rest of the light being absorbed. These reflected wavelengths are what reaches the eye, and their sum is what determines the colour that the eye perceives. It is clear, then, that in the present test, for a certain colour to reach the eye, the wavelengths conforming to it must both be emitted by the light bulb and reflected by the apple.

Normal white light (daylight or sunlight) is the result of the sum of all colours. When an object is illuminated with white light, it receives all the colours. An apple illuminated with white light is seen as green if (to keep things simple) it absorbs all the colours except green. If this apple is illuminated with green light, it will reflect the green light and still be seen as green. However, if green is not among the colours making up the illuminant, the apple will reflect nothing and will therefore not be seen.

The correct responses to the nine non-control test items are therefore as follows: in the three instances when the colour of the bulb coincides with that of the apple, it will be seen as the common colour; otherwise, the apple will not be seen.

The apple will not be seen if either the bulb is of a different colour from that which the apple reflects or the colour composition of the bulb does not include this latter colour. For Item 10 (the undeclared control item), in which a white bulb illuminates a green apple, the apple will be seen as green (this was the given definition of the green apple symbol). However, an oversight might lead us to respond that, because the colours of the apple and the bulb do not match, the apple will not be seen (applying inappropriately the reasoning that resulted in correct answers for Items 2, 3, 4, 6, 7, and 8).

The origin of these misconceptions is born from extrapolating from usual observations in which the illuminant is (white) sunlight to other situations in which the illuminant has changed and does not contain the full range of colours that sunlight does. When one uses the verb 'to be' to indicate the colour of an object, one is (implicitly) assuming that the object is being illuminated by the light of day. The expression, 'Lemons are yellow', really means 'Lemons are yellow when illuminated by sunlight', but the last part of the sentence is generally ignored.

If, as advised at the beginning of the article, our reader has taken the test and has not responded correctly, please do not worry (and especially, do not become angry). Instead, read on, and you will find that you are far from alone. No one doubts that you know what colours are. Simply, you have found that, despite the instruction you have received, your misconceptions about colour have managed to maintain their presence. To detect these misconceptions with a multi-item questionnaire, one has to de-contextualise the items from an instructional context, so that the responses to them will originate from the implicit (not explicit) interpretations that everyone creates to explain the phenomena they directly perceive. In most cases, these interpretations persist regardless of formal instruction that may be contrary to them.

3. Results and Discussion

3.1 Test Results Collected Over the Last Ten Years at Various Educational Levels

Over the past 10 years, we have given The Apple Test to 2,596 people. The results demonstrate that a high proportion of individuals (of all ages and educational backgrounds, and from different European and American countries) have misconceptions with respect to the formation of colour. Table 3 lists the test results broken down by the educational level of the respondents. The data are given in terms of relative frequencies (*fr*) for the correct response being given and the associated relative frequencies of the different misconceptions about colour explained above.

We observe that the percentage of incorrect answers for the test is very high at all educational levels of the sample. It is noteworthy that misconceptions about colour exist not only among primary school children but also among secondary school

Table 3. Results obtained in applying The Apple Test to 2,596 respondents of various educational levels to obtain the relative frequencies—*fr* (%)—of the different misconceptions about colour

Sample's educational level	Primary $n = 74$ *fr* (%)	Secondary $n = 86$ *fr* (%)	Pre-university $n = 142$ *fr* (%)	University $n = 147$ *fr* (%)	Master's/doctorate $n = 174$ *fr* (%)	Master's teaching $n = 1{,}848$ *fr* (%)	Secondary teacher $n = 64$ *fr* (%)	University teacher $n = 61$ *fr* (%)	Total $n = 2{,}596$ fr (%)
Correct	0.0	1.2	1.4	8.2	8.2	7.9	17.2	13.1	7.2
Miscon 1	62.2	60.5	57.7	50.3	50.3	53.4	46.9	52.5	53.5
Miscon 2	8.1	8.1	10.6	11.6	11.6	8.5	12.5	14.8	9.4
Miscon 3	6.8	9.3	9.2	12.9	12.9	8.4	14.1	11.5	9.1
Miscon 4	4.1	2.3	0.7	2.0	2.0	0.4	6.3	4.9	1.0
Other	18.9	18.6	20.4	15.0	15.0	21.4	3.1	3.3	19.8

students, undergraduates, graduates, and even teachers (most of them science teachers) from both high school and college.

Of the 2,596 people surveyed, 187 responded correctly to all test questions, representing 7.2% of the sample population. The remaining 2,409 respondents incorrectly answered one or more of the items. If these people had responded to the test items without any implicit rule(s) as a basis for answering, then one would expect a very high dispersion of responses. However, 1,895 of study responders used one of the four response sequences described below, confirming the second working hypothesis (see Section 2.2): that individuals' misconceptions about colour will be organised in the form of implicit theories with corresponding laws. There is a percentage of incorrect answers that are grouped into the category 'Others' in Table 3. This category is composed of the following individuals: those who did not use any logical sequence in their answers; those who responded randomly; those who switched criteria during the test; and those who did not finish the test.

The four (incorrect) sequences of responses identified are as follows:

- Sequence 1: -[EEE]-[EEE]- produced by 53.5% of the respondents.
- Sequence 2: -[CDB]-[DBC]- produced by 9.4% of the respondents.
- Sequence 3: -[BBC]-[CDD]- produced by 9.1% of the respondents.
- Sequence 4: F[---]F[---]F produced by 1.0% of the respondents.

It is easy to identify in Sequence 2 the known misconception that colour is a physical property of a body, similar to its mass: the object 'is' of its colour. Thus, Misconception 2 is that the colour that the eye sees is always the colour of the apple. These results agree with Anderson and Smith (1983). They found that a high percentage of children (13–15-years) who participated in their study believed that colour was a property of the object viewed. Guesne (1985) also noticed that when children observe coloured objects under a white light, they take the colour to be a quality of the object, independent of the source of light or the receiver. This misconception also appears at higher educational levels; for example, Eaton, Sheldon and Anderson (1986) found that non-science major university level students also held the view that colour is a property of objects.

Sequence 3 is the pattern of answers indicating that respondents attribute the colour in which the apple is seen, to the colour of the light emitted by the bulb, regardless of the nature of the apple. This way of thinking would indicate that the object, in this case the apple, reflects or returns the incoming light from the bulb unchanged (at least in colour), thus behaving as a 'neutral' element of reflection with respect to colour. As such, Misconception 3 is that the colour that the eye sees is always the colour of the illuminating bulb.

Sequence 1 indicates that respondents attribute the colour of the apple which the eye sees, to the sum of the colours of the bulb and of the apple. This misconception can be thought of as the sum of the second and third misconceptions described above: both colours, that which the apple 'possesses' (and 'emits') and that which it 'reflects' from the bulb, each reach the eye—which sees their sum. Thus, Misconception 1 is that the colour that the eye sees is the sum of the illuminating bulb's colour plus the apple's colour. This is consistent with (Feher & Meyer, 1992), who detected a general belief that the colour of an object is the property of the object that remains unchanged under white light (related to Misconception 2), but can be changed by coloured light (related to Misconception 3).

These first three sequences correspond to tests items corresponding to a physical situation in which the colours of the bulb and the apple are different. Sequence 4, however, corresponds to a physical situation in which they are the same. In this case, both the correct response and the response expected by an individual holding one of the three previously discussed misconceptions coincide. As such, this situation does not *a priori* provide useful information for detecting misconceptions. However, a small proportion of test respondents, some 1%, consistently gave a response different than what was expected: they indicated that an apple illuminated by a bulb of the same colour would not be seen.

What type of reasoning could be behind this? After interviewing 20 of the 25 respondents who responded in this fashion, we concluded that their reasoning was based on a misconception regarding the nature of light. Some people consider light to be, not something that travels from the source to an object, and thence to the eye, but rather something static that fills the surrounding space. Therefore, these respondents believe that if there is a green light that is filling the space surrounding an object (e.g. an apple) and if we put an apple of the same green colour into this 'full' space, the apple will not be seen, because of the lack of any contrast.

Therefore, there is a fourth misconception that may coexist with any of the other three. For example, there are people who think that, when the colour of the bulb coincides with the colour of the apple, the latter will not be seen, whereas when the two colours do not coincide, the colour that the eye sees will be the result of adding the colours of the bulb and the apple.

The empirical data showed that the implicit theories used to explain the perception of colour are governed by the following laws:

- First law: Colour is a physical property of bodies, similar to their mass. This colour is 'emitted' by the object regardless of the type of illuminant reaching it. This law is defined by Sequence 2: -[CDB]-[DBC]- and is related to Misconception 2.
- Second Law: Bodies reflect the light reaching them from a light source in a 'neutral' fashion, i.e. in all cases, they reflect, unchanged, the colour from the illuminant. This law is defined by Sequence 3: -[BBC]-[CDD]- and is related to Misconception 3.
- Third Law: An object is seen when the colour reaching the eye from that object is different from the colour 'filling' the surrounding that object from an illuminant. This law is defined by Sequence 4: F[---]F[---]F and is related to Misconception 4.

These laws were deduced from the test responses given by the respondents and from interviews with some of them. They originate from the spontaneous implicit mini-theories described in Table 4.

Table 4. Implicit theories and deduced laws

Implicit theory	Defining sequence	Accepts the 1st law?	Accepts the 2nd law?	Accepts the 3rd law?
1	-[EEE]-[EEE]-	YES	YES	NO
2	-[CDB]-[DBC]-	YES	NO	NO
3	-[BBC]-[CDD]-	NO	YES	NO
4	F[---]F[---]F	NO	NO	YES

3.2 How Can One Combat these Misconceptions?

To combat the misconceptions about colour that were found in our research, we used two different teaching methods, determining statistically which one was better suited to foster conceptual change in our students. To this end, we conducted a study with a quasi-experimental design involving 470 students, randomly divided into two groups: a CG and an EG. Before instruction started, both groups responded to The Apple Test as a pre-test. The resulting data were analysed to check the equivalence of the two groups. In particular, we applied the *z*-test for the comparison of proportions from independent samples, calculating the *z*-statistic with a significance level of $\alpha = 0.05$. The null hypothesis in this analysis (H0) was that the proportion of correct answers for the CG and EG was the same; the alternative hypothesis (H1) was that the proportion of correct answers for the groups was different. Thus, if z was in the interval $[-1.96, 1.96]$, then H0 was accepted; otherwise, H1 was accepted. The results of this analysis and the corresponding *z*-statistic are given in Table 5, along with the absolute frequency (*fi*) and relative frequency (*fr*) of each sequence.

Results of the *z*-tests indicate that the percentages of responses are very similar between the two groups for all types of misconceptions and for the correctly answered tests. In all cases, the *z*-statistic lies within the interval $[-1.96, 1.96]$, so that the null hypothesis H0 is accepted.

Table 5. The absolute and relative frequencies of answer sequences for the pre-test given to the CG and the EG, with the corresponding *z*-statistic evaluating whether there were initial differences between the two groups

Test results	Initial test CG		Initial Test EG		Test statistic
	Fi	*fr* (%)	*fi*	*fr* (%)	*z*
Correct	8	3.6	10	4.1	0.196
Misconception 1	140	62.5	144	58.5	−0.621
Misconception 2	22	9.8	26	10.6	0.190
Misconception 3	24	10.7	28	11.4	0.163
Misconception 4	2	0.9	4	1.6	0.500
Other sequences	28	12.5	34	13.8	0.298
Total	$n = 224$		$n = 246$		

Following the pre-test, instruction was begun (one 1-hour session for each group) that corresponded to, and was specifically designed to combat, the misconceptions about colour that had been found in the study.

The work with the CG followed a traditional teaching method. The students in this group received traditional teacher-centred oral explanations of the misconceptions that had been found and of the correct responses, using examples on the chalkboard illustrating these misconceptions. For example, to address Misconception 2, it was orally explained to the students that when we say that an object is of a certain colour (i.e. 'this object is green'), what we really mean is that the object appears to be that colour when illuminated by daylight or other similar light (i.e. 'this object appears green when illuminated by the light of day'). It was explained that this mechanism is usually understated and is not expressed in colloquial language.

The work with the EG followed a teaching method based on the use of concept maps to promote meaningful learning. Novak (2002) stated that conceptual change is necessary for meaningful learning to occur, requiring a well-organised, relevant knowledge structure and a high commitment to finding relationships between new and existing concepts. Concept maps (Novak, Gowin, & Johansen, 1983) require students to identify important concepts and show interrelationships among them. In this way, concept maps are helpful in understanding what a concept entails. Concept maps are considered to be effective teaching tools with which to combat misconceptions (Martínez, Pérez, Suero, & Pardo, 2012). Moreover, in using concept maps, students may interpret, organise, and structure knowledge into their cognitive structure as interrelated concepts with the help of what they already know. We worked with the EG following several steps:

First, the students were asked to prepare individual concept maps relating the following three concepts: 'BODIES', 'COLOURS', and 'LIGHT (e.g. SUNLIGHT)', labelling appropriately the hierarchy of links between these concepts. The goal of this stage of instruction was for the students to make explicit the propositions that they thought were the most suitable. This stage lasted 10–15 minutes.

Second, in another stage lasting 15 minutes, the students carried out a group discussion with the goal of producing a commonly agreed upon concept map. In most cases, the maps our students constructed were similar to the 'Initial Concept Map' depicted in Figure 4 (left). This map visually depicts how the three concepts are often believed to be related according to the corresponding student's cognitive structure; particularly, students hold the misconception that colour is a property of the object, indicative of the first law.

Third, to combat this misconception, the teacher proposed an alternative concept map, the 'Modified Concept Map', also depicted in Figure 4 (right). The teacher then provided opportunities for students to be involved in discussions in the classroom. In this stage, lasting approximately 30 minutes, the students discussed the changes proposed on the new map, and each student had to justify his or her acceptance or rejection of the suggested change. The conceptual change that we proposed in this stage was that colours are in the illuminant light, not the bodies of objects in the world around us, as can be induced from observation. This experimental approach is

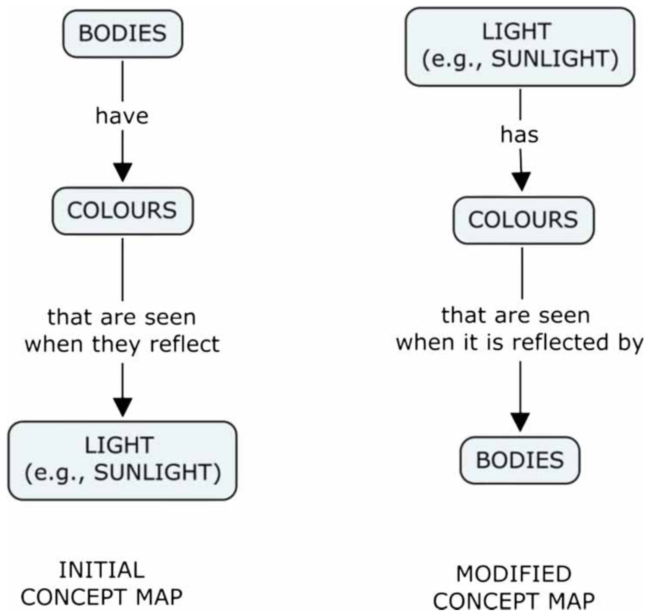
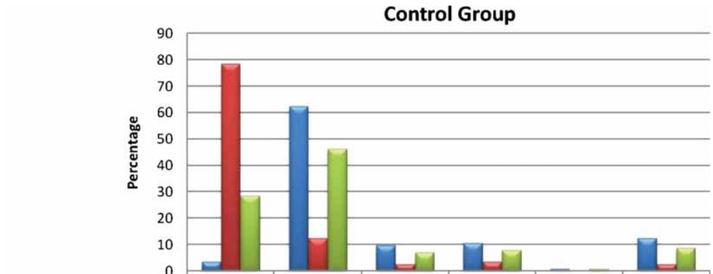


Figure 4. (Left) Initial concept map relating the concepts of 'bodies', 'colours', and 'light'. (Right) Modified concept map linking these concepts

based on Posner et al.'s (1982) proposition. Our students had the chance to compare their original ideas with scientific concepts and then were able to improve their learning by the use of concept maps.

We independently analysed the corresponding propositions of both maps. For example, analysing the first proposition of the 'Modified Concept Map', (i.e. sunlight has colours) with the first proposition of the 'Initial Concept Maps' (i.e. bodies have colours) allowed us to create a cognitive conflict among the students who followed reasoning according to the First Law (Misconception 2: Colour is a physical property of bodies). In contrast, the second proposition of the 'Modified Concept Map' (i.e. colours are seen when light is reflected by the bodies) allowed us establish a discussion among the students on whether this reflection was 'neutral' (Misconception 3 governed by the Second Law) or 'not neutral' (i.e. only certain wavelengths of the light from the source may be reflected, with the rest being absorbed). Although the difference between the two concept maps may appear to be very small, the conceptual change involved in the proposed modification is profound, as it affects a very deep zone of our cognitive structure.

One month after completing the instruction, the two groups were again given the Apple Test. This post-test was used to compare the results with those of the pre-test to assess whether there were statistically significant differences between the learning gains of the two groups, and hence, to determine experimentally which of the two teaching methods was more effective. Five months after instruction, the test was given again to determine which of the two teaching methods resulted in more long-lasting conceptual change.

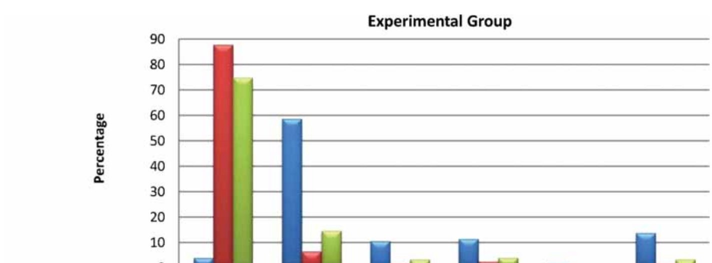


	Correct (%)	Misconc. 1 (%)	Misconc. 2 (%)	Misconc. 3 (%)	Misconc. 4 (%)	Other seq. (%)
C.G. initial test	3.6	62.5	9.8	10.7	0.9	12.5
C.G. post-test (1 month)	78.6	12.5	2.7	3.6	0.0	2.7
C.G. post-test (5 months)	28.6	46.4	7.1	8.0	0.9	8.9

Figure 5. The relative frequencies (%) of the CG's results

Figures 5 (CG) and 6 (EG) show the histograms for the pre-test and the two post-test results.

It is clear from the figures that there are differences in the results between the pre-test and the post-tests. To quantify these differences, we calculated the normalised gain, often called the Hake factor g (Bao, 2006; Hake, 1998), to enable a consistent comparison. This factor is defined as the measure of the relative gain in learning from the pre-test to the two post-tests, following the equation: $g =$ (Post-test score − Pre-test score)/(Maximum score − Pre-test score). Its value can range from 0 to 1, with the value 0 representing no conceptual change whatsoever and the value 1 corresponding to the maximum possible conceptual change towards comprehension (Lara-Barragán & Santiago, 2010). The three test scores (i.e. maximum, post-test, and pre-test) could be defined either for an individual student or as an average measure for a group. Table 6 lists the Hake factors (g) for the CG and the EG that were calculated using the average scores for each group for the post-tests at one month after instruction and five months after instruction.



	Correct (%)	Misconc. 1 (%)	Misconc. 2 (%)	Misconc. 3 (%)	Misconc. 4 (%)	Other seq. (%)
E.G. initial test	4.1	58.5	10.6	11.4	1.6	13.8
E.G. post-test (1 month)	87.8	6.5	1.6	2.4	0.0	1.6
E.G. post-test (5 months)	74.8	14.6	3.3	4.1	0.0	3.3

Figure 6. The relative frequencies (%) of the EG's results

Table 6. Hake factors for the CG and the EG

Hake factor	CG	EG
g (post-test at one month)	0.77	0.87
g (post-test at five months)	0.26	0.74

Results indicate that the one-month Hake factors for both groups are high (see Table 6). This finding suggests that both teaching strategies were very effective in promoting conceptual change in students' misconceptions about colour. At five months, however, the Hake factor for the CG ($g = 0.26$) reflects only a low level of improvement, while the Hake factor for the EG still reflects a high level of improvement ($g = 0.74$). The analyses performed to compare the proportions of correct responses and misconceptions at a significance level of $\alpha = 0.05$ indicated that $z = -7.091$ for the proportions of correct responses and $z = 5.324$ for the proportion of Misconception 1. These values indicate that the differences between the 5-month post-test results for the CG and the EG were statistically significant. In particular, the teaching method used with the EG, based on the use of concept maps to help students overcome their misconceptions, was significantly more effective than the traditional method used with the CG and provided meaningful learning that lasted over time. Thus, the fourth research hypothesis (see Section 2.2) is accepted.

4. Conclusions

From the results of this study, one may draw the following conclusions:

(1) A large majority of people have misconceptions about colour. The reason for this may be that colour is an important source of information from the earliest age. This leads individuals spontaneously to a type of 'subconscious explanation' about how the perception of colour functions, which in turn, leads to the creation of misconceptions. In most cases, these misconceptions persist throughout life. The present results show that even at the highest level of university, sometimes instruction is not sufficient to cause misconceptions about colour to disappear.

(2) Misconceptions are structured in the form of authentic implicit theories: the vast majority of incorrect response patterns on our test corresponded to just four sequences, reflecting the existence of four respective mini-theories about colour.

(3) Both the sequences of responses and their associated mini-theories (i.e. implicit theories) were explicitly revealed by the present work and were found to have high internal consistency.

(4) The detected misconceptions about colour were as follows:

   (a) Colour is a property of bodies (similar to their mass)—a body 'is' its colour and will always be perceived as that colour. The normal use of the verb 'to be' to describe the colour of an object adds greatly to this misconception.

   (b)

The colour that an object appears to be depends only on the light that illuminates it. Objects behave in a 'neutral' fashion with respect to how they reflect the light that reaches them and will always be seen to have the colour of the illuminant.

(c) Bodies 'emit' their colour, which reaches the eye of the observer together with the colour of the light from the illuminant, so that the colour finally perceived by the observer is the sum of the two.

(d) When the space surrounding an object is 'full' of the colour of the illuminant, and an object of that same colour is located within that space, then that object will not be seen, because of the lack of contrast. This misconception can coexist with any of the previous three misconceptions.

(5) The use of concept maps helps a person with these misconceptions to overcome them more effectively than does the use of traditional teaching methods. This may be due to the way concept maps help to make the origin of the misconceptions more explicit, thereby making it easier to overcome misconceptions through learning new relationships between the concepts involved. The result is a more durable conceptual change in a person's cognitive structure.

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