Students’ conceptions on white light and implications for teaching and learning about colour

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Abstract
The quality of learning processes is mainly determined by the extent to which students’ conceptions are addressed and thus conceptual change is triggered. Colour phenomena are a topic within initial instruction of optics which is challenging. A physically adequate concept of white light is crucial for being able to grasp the processes underlying colour formation. Our previous research suggests that misconceptions on white light may influence the conceptual understanding of colour phenomena. For the design of a learning environment on light and colours, the literature was reviewed. Then an explorative interview study with participants (N = 32), with and without instruction in introductory optics, was carried out. In addition, the representations used for white light in Austrian physics schoolbooks were analysed. Based on the results of the literature review, the interview study and the schoolbook analysis, a learning environment was designed and tested in teaching experiments. The results indicate that learners often lack an adequate concept of white light even after instruction in introductory optics. This seems to cause learning difficulties concerning colour phenomena. On the other hand, the evaluation of our learning environment showed that students are able to gain a good conceptual understanding of colour phenomena if instruction takes these content specific learning difficulties into account.

Supplementary material for this article is available online

1. Introduction
Our daily life depends on light: Social and professional life can only happen if there is daylight or artificial light which illuminates our surroundings. The reception of light is a precondition for the human visual sensation. The characteristics of illumination influence our visual sensation. Optical phenomena are usually fascinating. At the same time, most learners do not have adequate ideas about the characteristics of the light we are usually surrounded by. Consequently, it is difficult to understand the mechanism underlying colour phenomena. For successful learning processes, teaching has to take these learning problems into account and ‘teach […] accordingly’ (Ausbubel 1968, zit. n. (Duit 1995)).
Teaching colour phenomena is usually based on the key idea that white light can be split into different prismatic colours or into the primary colours red (R), green (G) and blue (B). A scientifically sound concept of white light is thus essential for students’ understanding of colour phenomena (Kamata and Matsunaga 2007, Mota and Lopes 2014).

This article will give an overview of the state of research on students’ misconceptions about light. Then current studies on misconceptions about white light and implications for students’ learning are reported. Finally, instructional strategies to introduce the concept of white light and colour for students aged between 12 and 14 years are discussed.

2. Known misconceptions of (white) light and colour

The focus of this section is learners’ misconceptions at the level of lower secondary school (aged 12–14), when they usually get their first formal instruction in optics. In most school systems, this first encounter with optics is a geometrical one which does not include the wave nature of light.

As white light is not a term used in everyday conversation, it seems to be necessary to portray students’ ideas on related terms taken from their everyday language. The kind of light physicists define as white light is usually conceptualized as ordinary light, ‘normal light’ (Feher and Meyer 1992) or simply as light. In our everyday language we also use the terms daylight or sunlight for light with similar properties as white light.

Although little research has been done on notions about day-, sun- and white light, there are several findings on students’ ideas about light in general. For most students the term light activates the notion of a colourless and bright (Feher and Meyer 1992, Blumör 1993) entity that is transparent so that ‘you can see through it’ (Gilbert and Watts 1983). Learners usually do not connect any colour impression with the term light.

In her research, Guesne (1985) investigated the relation students (aged 13–14) draw between daylight and sunlight. The findings show that students see a connection between both, but sunlight and daylight are not necessarily identical for them. Guesne could extract ‘a cause and effect relationship between sun- and daylight, but this relationship remains rather vague’ (Guesne 1985). It is a big challenge for students to understand that there is daylight, which is caused by the sun even when it is cloudy or foggy and the sun is not visible.

Only a few studies treat students’ misconceptions about the colour of sunlight. Sunlight is, unlike light, frequently connected with colour impressions: ‘Yellow is light like the sun, bright and warm.’ (Feher and Meyer 1992). These findings have important implications for teaching and learning. According to Eaton et al (1986) high school students tend to reject the idea of light being white: ‘The light is not white it is just briseic,’ (Eaton et al 1986). In the majority of cases white light is also described as ‘pure, clear, or colorless’ (Eaton et al 1986).

Another property attributed to white light is that it ‘lets you see the colours of the object’ (Feher and Meyer 1992). We normally see objects under white light. This promotes the idea that objects have a fixed colour which becomes visible with ‘ordinary’ light (e.g. Guesne 1985, Mota and Lopes 2014). Learners also tend to reject the idea that white light is a mixture of other colours, even after formal instruction in introductory optics (Eaton et al 1986, Feher and Meyer 1992, Wiesner 1995).

Another prerequisite for understanding colour phenomena is the idea that objects that do not produce light themselves are able to absorb and (re-)emit light selectively. Besides misconceptions about this sender-receiver mechanism of vision (Guesne 1985, Colin et al 2002, de Hosson and Kaminski 2007, Viennot and de Hosson 2012a, 2012b), students have incorporated a number of alternative ideas about how colour phenomena come into existence, especially when objects are not seen under white light. Feher and Meyer (1992) identified the misconceptions that coloured light (1) mixes with the colour of the object; (2) gives its colour to the object; (3) has no effect on the appearance of objects.

In summary, it can be said that the findings indicate potentially problematic conceptual dispositions, which may conflict with learning processes about colour phenomena.
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3. Investigations on misconceptions about white light and its representation

Taking the idea of constructivist learning and educational reconstruction seriously means that students’ conceptual basis on white light needs to be investigated in more detail. Therefore an explorative study with guided interviews and a schoolbook analysis was carried out.

3.1. Guided interviews on light and light sources

The guided interviews with 32 randomly chosen participants focused on students’ conceptions about (white) light. In total, 32 test persons were asked to describe the characteristics of light in general as well as of daylight, sunlight and light. Twelve of the test persons were without prior formal instruction in optics (\(m_{\text{age}} = 13.0\)). They attended year 7 or year 8 of high school. Twenty test persons had already had formal instruction in optics (\(m_{\text{age}} = 28.32\)). In order to get a longitudinal perspective we chose people belonging to two different categories: subgroup one consisted of people after introductory optics in year 8 but before wave optics in year 11 (\(N = 10\)) and subgroup two (\(N = 10\)) consisted of participants who had taken A-levels five years ago and longer. So all test persons of the instruction group had had introductory optics at lower secondary level, treating topics of geometrical optics excluding the wave nature of light: propagation of light, light and shadow, refraction, image formation with lenses and mirrors, dispersion, colour addition and subtraction. The participants with A-levels had additionally had wave optics at higher secondary. None of them had studied or worked in scientific or technical disciplines. Data analysis shows that both subgroups with instruction in optics do not significantly differ in their response behaviour or in their knowledge, therefore they are aggregated as one group for the findings reported.

3.1.1. Findings. As opening question participants with (isntr\(^{+}\)) and without (isntr\(^{-}\)) instruction in introductory optics were asked to describe light in general. The majority of both groups associated light with brightness (75% isntr\(^{+}\), 85% isntr\(^{-}\)). About half of both groups categorized light as physical phenomenon or used colour attributions to describe light. Other categories used for the description of light were light as prerequisite for vision (42% isntr\(^{+}\), 15% isntr\(^{-}\)) and individual sensations related to light (25% isntr\(^{+}\), 45% isntr\(^{-}\)). Interestingly we find the idea that light is a prerequisite for vision only with those participants of the group with instruction, who had taken geometrical optics and wave optics. Both groups also named light sources to describe light (25% isntr\(^{+}\), 45% isntr\(^{-}\)). The categories identified are in accordance with findings of previous research as described above. The results demonstrate that the term light does not activate domain specific associations about its characteristics (straight, continuous propagation, constant speed of light in a medium . . .) or its ontology (electromagnetic radiation, energy . . .) in neither group.

In a next step, descriptions and definitions of light, daylight and sunlight were asked. In figure 1 the analysis concerning colour attributions can be seen. It is striking that at first sight the profiles of light and daylight resemble each other, while sunlight was described quite differently in its characteristics. Colourless is the most frequently mentioned property for light (25% isntr\(^{+}\) and 15% isntr\(^{-}\)) and daylight (25% isntr\(^{-}\) and 20% isntr\(^{+}\)). This can be seen as a first hint towards the inconsistency and content dependence of participants’ conceptions.

The characteristic colourless was not mentioned by a single participant for sunlight. Sunlight was described as yellow by more than half of the participants of both groups (55% isntr\(^{+}\) and 58% isntr\(^{-}\)). Yellow was associated less often with daylight (25% isntr\(^{-}\) and 20% isntr\(^{+}\)) or with light in general (17% isntr\(^{-}\) and 15% isntr\(^{+}\)). An exemption is the idea of light being skyblue. This attribution was used only for daylight and only by participants who had taken geometrical optics and wave optics.

It is remarkable that white was not chosen as key feature for any of the three types of light and that sunlight was not at all identified as white by the participants with instruction in optics. A similar effect was revealed for the category mixture of spectral colours. This kind of attribution occurs only in the group of participants with instruction in optics. The frequencies show however that only a minority makes this choice (daylight: 5% isntr\(^{-}\); light: 20% isntr\(^{+}\)). Sunlight is again an exception, since it was not categorized as mixture of spectral colours by any participant. All in all, it is the
exception that light is related to the colour white. The notion of sunlight being yellow is deeply rooted, even after instruction in optics. At a later stage of the interview the term and concept of white light was in the focus of interest. When asked if the term white light was familiar, 60% of the participants with introductory optics classes agreed to know the term, whereas not even 10% of the pre-instructional group did so. Two thirds of the participants who claimed to be familiar with white light named school as source of their knowledge. The fact that 40% of the participants with instruction in optics do not recognize the term suggests that instruction is frequently not successful in making the concept of white light fruitful and intelligible.

The analysis of the descriptions and definitions of white light shows insecurities in both groups (see figure 2). In the group of participants with instruction in optics 45% did not even attempt to describe white light. However, this is a significantly lower proportion than in the group without instruction (67%).

Only participants with instruction (15%) were able to identify white light as a mixture of spectral colours. Another category focused on properties of white light like brightness. All these answers are in agreement with the literature. All in all, it can be said that even those participants with instruction in optics who showed high confidence about their knowledge, carry conceptions about white light conflicting with science. The high percentage of missing data in combination with contradictory statements may also hint at a conceptual gap, which is filled with different ad-hoc constructions in different situations of the interview.

After giving the participants a description of white light as addition of spectral or primary colours, 55% of the group with and 25% of the group without instruction classified this definition as acceptable. Among the group with instruction, especially the participants who had taken

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**Figure 1.** Conceptions about light, daylight and sunlight of participants with (instr+) and without (instr−) instruction in introductory optics.
geometrical optics and wave optics were in favour of this definition (80%), in contrast to those who had only taken geometrical optics classes (30%). When we asked for alternative, more suitable terms for *white light* more than three quarters of the participants did not give an answer. The other participants named *bright light* (13%), *transparent light* (6%) and *daylight* (3%) as alternative suggestions. A closer analysis revealed that the colour component in the term *white light* is misleading for learners and seems to activate conceptual frames counterproductive for learning.

### 3.2. Visual representations of white light in school textbooks

Previous research indicates that the representation of light in schoolbooks may deepen existing misconceptions about white light. Therefore an analysis of schoolbooks was carried out. As corpus data we chose the five highest circulating Austrian physics school textbooks of year 8 (stacks.iop.org/PhysED/52/044003/mmedia) (Haagen-Schützenhöfer and Holzmeier 2013).

**3.2.1. Findings.** The analysis of the selected books showed that sunlight and light of bulbs, candles and so on was represented either by red light rays or by yellow ones (see figure 3). Two books used both types of representations. Interestingly, we did not find any kind of verbal hints that white light was represented in red and/or yellow. In addition, no explanation was given why white light was represented that way. The teachers’ resource books did not treat this issue either. From these findings it can be deduced that it is regarded as ‘normal’ that white light is represented by yellow rays. So, this kind or representation is obviously passed on without reflecting about consequences for students’ learning processes.

### 4. Ideas for teaching colour phenomena

Conventional instruction is frequently not successful in improving the lack of adequate concepts about light, vision and colour as discussed above. One reason seems to be that instructional designs do not take students’ conceptions and domain specific learning difficulties into account.

The teaching strategy for white light and colour phenomena presented here was developed within a design-based research project on introductory optics (Haagen and Hopf 2015). The concept was evaluated with the help of teaching experiments in micro-teaching settings. Integrating the findings of our interview study, the core ideas of the intervention were to avoid the term *white light* in the initial phases of instruction and to develop a scientifically sound concept of white light which is related to everyday experiences. The term white light is introduced at a later stage.

In the process of educational reconstruction the content specifications were aligned with students’ misconceptions. That resulted in a basic set of 12 core ideas for the instruction of the concept of white light and colour phenomena for year 8 students (see figure 4). The following section gives an overview of these key ideas and provides tips for the practical implementation.

Simple hands-on experiments were used as trigger for learning processes. The experiments provide students with real colour phenomena and
relate these phenomena to processes of selective absorption and reflection of white light (Haagen 2015).

**Key ideas (a) and (b):** At the beginning, students are asked to peep through a peephole into a box where they can see a yellowish light spot. Then they are asked to predict what is inside the box. Inside the box are a red and a green light source that add to yellow light. When revealing the inside of the box, students’ observations are usually in conflict with their prediction. This provides a good basis for introducing the key ideas: *Light can have a colour. Coloured light can be mixed and adds to another light colour.*

**Key idea (c) and (d):** Research shows that most students claim that ‘sun-like’ light (white light) is similar to yellow light. In the next step students carry out experiments that illustrate the difference: light similar to daylight (flashlight) and yellow light (flashlight with yellow filter foil) are beamed next to each other on a surface which is white under white light by definition (e.g. white paper ISO11475:2004).

**Key idea (e)–(g):** Students are introduced to the concept of white light by showing that the spectral colours of dispersed daylight can be added with the help of a lens to daylight again. It is a mixture of all prismatic colours where no single light colour prevails. Such a mixture of basic colours results in light which appears to be free from colour or, as students put it, colourless. Another expression for ‘free from colour’ is ‘achromatic’. In art, white and black are called achromatic, since they lack any strong chromatic content. What is interpreted by our eye-brain detector as transparent and colourless is a mixture of all prismatic colours and thus called ‘white light’ in physics.

**Key ideas (h)–(j):** After students are aware that there are cones for colour perception which are sensitive to red, blue and green light, they work with the PhET Colour Vision simulation (University of Colorado) and create different colour impressions by addition.

**Key idea (k):** The colour vision simulation can also be a first step in approaching the idea...
that there are different ‘shades of white’: when all slides are turned to maximum and the intensity of one primary colour is slightly changed, we still get the impression of white, but different types of white. In a next step, students can explore their individual perception of different illuminants (e.g. cold white or warm white) in the darkened classroom and analyse the spectral distribution.

Key idea (i): A sequence of simple hands-on experiments was developed to trigger conceptual change on the mechanism of body colour based on solid understanding of the concept of white light (see Haagen (2015)). The hands-on are based on a white illuminant. Students are usually quite familiar with the idea that different objects ‘have’ different colours. The challenge is now to make them aware of the fact that this colour perception is related to the selective reflective behaviour of the object itself.

The hands-on consists of a small box with a window. A torch which emits white light is put through this window, illuminating the bottom of the box (see figure 5). Depending on the piece of paper at the bottom of the box, the observer can see the box being illuminated in different colours. A demonstration experiment is shown with a piece of paper being red under white light and a piece of paper being blue under white light. In a third situation, the students can see the box illuminated in magenta. Then they are asked to predict what kind of paper was put on the bottom of the box this time.

Usually students predict a magenta piece of paper on the bottom of the box. Then they are shown that this is only one possible option and a chequerboard pattern of small blue and red squares produces a similar perception. So, they start searching for a fruitful explanation for this phenomenon.

The following explanation turns out to be comprehensible and acceptable for students: We perceive an object in a certain colour as we receive a certain mixture of basic colours from it. The kind of light we perceive from an object depends on two main conditions: firstly, on the kind of light we illuminate the object with (=quality of illuminant) and secondly, the kind of light the object sends off again (=emission characteristics of body). Each body is characterised by the different colours it is able to (re-)emit.

5. Discussion and conclusion

The summary of the research literature and the results of an explorative interview study show that a variety of conceptions about light are held. First of all, it is striking that the terms light, daylight and sunlight seem to activate different mental models. Here it is interesting that the terms light and daylight cause different associations compared to the term sunlight. The latter is strongly connected to the notion of yellow light. Especially common representations of (sun-)light seem to support this misconception. The concept of white light as a mixture of spectral colours is used by a small minority of participants with instruction in optics only.

With some exceptions, participants with and without instruction show similar results. However, most conceptions are not solid ones,
but they are partly inconsistent in themselves and situative ad hoc constructions. This indicates on the one hand that everyday conceptions, which differ significantly from scientific concepts, are solid and prove traditional instruction. On the other hand, these findings support the initial presumption that the concept of white light is not a trivial one, which is in control of learners without instruction.

In the learning environment presented, the strategy to emphasize the status of white light as not being of the same category as prismatic colours, by substituting the colour word ‘white’ with ‘similar to daylight’, proved to be effective. The chosen content structure and the instructional strategies used support students in grasping the idea of white light as a mixture of different prismatic colours. The main aim was to support students in relating their visual perception to processes of selective absorption and reflection. The intervention carried out worked well for the students of the sample and was quite effective in addressing their alternative conceptions.

As proved in numerous different contexts, it is of high importance to teach according to students’ learning needs. This is also true for teaching colours. A sound concept of white light is essential to grasp the mechanisms of selective absorption and (re-)emission of light and of physiological processes in the human visual system responsible of colour vision.

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