Exploring color concepts in physics education: Addressing common preconceptions among teachers-in-training

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Abstract:

In the field of physics education, the identification of students' preconceptions—especially regarding light and color—has been pivotal, as these foundational ideas often persist through higher education. Within teacher education, this is particularly crucial, as these early conceptions can deeply influence how future educators understand and teach these concepts, highlighting the need for an approach that weaves these initial understandings into a coherent scientific framework. Instructing students on color concepts reveals that many grapple with the fundamental optical principles. These initial understandings are integral to designing educational sequences that facilitate conceptual evolution, allowing for a deeper grasp of scientific ideas. This study aimed to examine and interpret the initial conceptions that aspiring primary and secondary educators hold about color and its optical fundamentals, while also developing and applying virtual teaching resources to promote a conceptual change about these foundational concepts. A quasi-experimental approach was employed, comprising control and experimental groups, and utilizing both qualitative and quantitative methods for a comprehensive analysis. Engaging 409 trainee teachers through non-probabilistic sampling, the study stratified participants by degree program. These groupings facilitated a comparative evaluation of the pedagogical efficacy of the educational resources developed. The study utilized an online assessment comprising single-answer multiple-choice questions, grounded in prior research, which was psychometrically validated. Educational tools were then developed and implemented to foster a deeper understanding of color concepts among prospective teachers. Results analysis highlighted the existence of preconceptions about color among participants from diverse educational backgrounds. The interventions employed were effective in catalyzing a shift in conceptual understanding and in elevating the knowledge levels of the trainee teachers.

1. Introduction

The intended audience for this paper primarily comprises physics educators, specifically those involved in the training of future primary and secondary school teachers. The study's insights and findings are tailored to address the pedagogical approaches within the physics curriculum, aiming to enhance the educators' understanding and teaching methodologies related to color concepts. While the nuanced discussions of color perception may intersect with the interests of vision scientists, the primary focus remains on the application and implications of these concepts within the domain of physics education. The paper aims to serve as a resource for teacher educators, curriculum developers, and educational researchers who are seeking to implement evidence-based strategies to improve the conceptual understanding of color in physics.

The importance of using everyday references in science education, especially in the teaching of physics, has been a constant concern of educators (Pérez Lozada & Falcón, 2009). This is due, to a significant extent, to the fact that current educational plans do not give sufficient relevance to the treatment of important topics in science education. The scientific literacy for citizenship perspective is often overlooked, which in turn limits innovation at the methodological level. Several studies point out how slight improvement has been made in the dynamics between the teacher and the student in the sciences classroom (Ghafarpour & Moinzadeh, 2020; Mellado Jiménez et al., 2014; Titsworth et al., 2010; Witt et al., 2004). This is because science is still taught in a unidirectional and expository way, centered on the teacher. Students' prior knowledge and their potential to achieve significant learning is often downplayed (Busquets et al., 2016; Cofré et al., 2010; Costa et al., 2015). Thus, for example, physics in general (and optics in particular) is one of the subjects in which students present many preconceptions and conceptual errors such as the belief that vision involves the eye emitting rays or that objects must emit light to be seen (Aydin, 2012; Duit et al., 2014; Martínez-Borreguero, Pérez-Rodríguez, et al., 2013). In addition, physics is often identified as the subject that arouses the least interest in the students (Dávila-Acedo, 2017; Osborne et al., 1998). Furthermore, the importance of acknowledging and building upon preconceptions in educational settings is essential, as meaningful learning occurs when students can relate new concepts to their prior knowledge (Bleicher & Lindgren, 2005; Bruner, 1996; Duit & Treagust, 1998; Vosniadou, 2008, 2019), a process which has significant implications for teaching complex topics such as color and optics (Bendall et al., 1993; Ceuppens et al., 2018; Colin et al., 2002; Colin & Viennot, 2001; Favale & Bondani, 2014; Galili et al., 1993; Galili & Hazan, 2000; Gil-Llinás et al., 2003; Kaltakci-Gurel et al., 2016; Perales Palacios et al., 1989).

Students' understanding of specific physics concepts such as those related to optics, from early childhood to university level and beyond, has attracted the interest of some researchers in different countries (Heywood, 2005; Langley et al., 1997; Martínez-

Borreguero, Pérez-Rodríguez, et al., 2013). In fact, there are several studies that show the presence of preconceptions about these physics contents, not only in primary and secondary school students, but also in university students such as, for example, pre-service teachers (Colin et al., 2002; Tural, 2015). According to some authors, having passed physics courses or having obtained a university degree in the area does not guarantee an appropriate understanding and proficiency in the fundamental principles and concepts for a consistent application of phenomena or natural laws (Grizalez et al., 2002). Other research (Favale & Bondani, 2014; Galili & Hazan, 2000; Uzun et al., 2013) has shown that, even after formal instruction, students maintain preconceptions about concepts related to light and color, reaching higher stages with low knowledge about these topics (Andersson & Kärrqvist, 1983; Colin et al., 2002; Osborne et al., 1993). One study (Martínez-Borreguero, Pérez-Rodríguez, et al., 2013) indicated that more than 80% of respondents had preconceptions regarding the concept of color, such as, for example, assuming that color is a property of objects (Anderson & Smith, 1984; Eaton et al., 1986; Guesne, 1985). Most individuals spontaneously (especially in childhood) produce their own explanations of how science works (Disessa et al., 2004; Driver et al., 1985), which eventually evolve into preconceptions. In most cases, these preconceptions persist throughout life. Even at higher academic levels, such as university, instruction is not always enough to make preconceptions about color disappear (Feher & Meyer, 1992; Haagen-Schützenhöfer, 2017; Mota & Lopes Dos Santos, 2014; Viennot & de Hosson, 2012).

Focusing on university students, some researchers (Kaltakci-Gurel et al., 2016) have detailed some of the difficulties and conceptual errors presented by pre-service teachers in the teaching/learning of optics. Although vision is one of our most important senses and our experience with light begins at an early age, several studies indicate that individuals have serious problems in understanding the nature of light, light propagation, vision, and optical imaging (Bendall et al., 1993; Heywood, 2005; van Zee et al., 2005). Goldberg and McDermott (1986) examined university students' understanding of images formed with plane mirrors, converging lenses and concave mirrors, concluding that this group presented various difficulties in understanding this content. According to the intervention conducted by Pesa de Danón (1999), most students consider that, when illuminating a certain object with a light source and placing a white sheet behind it, the shadow observed is a consequence of the presence of the object. In fact, it is due to the absence of light, which proves that there are alternative ideas about light propagation. Studies on learning about the nature and perception of color reveal that, despite formal teaching, the explanations that remain in students are those that are constructed based on everyday knowledge (Pesa de Danón et al., 1995). Likewise, another study by Pesa de Danón & Colombo de Cudmani (1998) found that the surveyed students presented alternative ideas regarding the formation of both real and virtual images through mirrors and lenses. Kaltakci-Gurel et al. (2016) studied preconceptions and conceptual difficulties of physics teachers-in-training about geometrical optics, focusing on plane and spherical mirrors (concave and convex) and lenses (convergent and divergent), as did Tural (2015). Uzun et al. (2013) focus on the concepts of light and vision in pre-service teachers. In addition, van Zee, et al. (2005) conducted a case study during a summer school for elementary and secondary school teachers, who were required to construct explanatory models of various optical phenomena.

Additionally, when the concept of color is explained to students at different educational levels, from elementary school to university, it is found that many have difficulties in understanding the basic concepts of optics involved. Feher and Meyer (1992), for example, studied children's ideas about colored objects and colored shadows, with particular attention to how these ideas are organized into mental models. Valanides and Angeli (2008) conducted a distributed collaborative investigation regarding the scientific concepts of light, vision, and color with sixth graders. On the other hand, Haagen-Schützenhöfer (2017) focused a study on white light, a crucial element to understand the processes underlying color formation. This author concluded that students often lack an adequate concept of white light even after optics instruction, which causes learning difficulties with respect to color phenomena. Likewise, Martínez-Borreguero et al. (2013) conducted a study with 470 university students and used concept maps to combat the preconceptions found. In addition, within a broader study on geometric optics conducted with trainee teachers, a poor understanding of the concept of dispersion in prisms was detected (Perales Palacios et al., 1989).

The above findings constitute a problem of relevance, especially when the subjects who present preconceptions and low levels of scientific knowledge are pursuing their university studies to become teachers (Kaltakci-Gurel et al., 2016) and must teach these concepts in their future professional practice. Of particular concern is the persistence of these preconceptions in pre-service teachers, both at the Primary and Secondary Education levels, as teachers' understanding and their interests, attitudes and classroom activities greatly influence students' learning (Abd-El-khalick & Lederman, 2000). Perhaps the most troubling aspect of preconceptions, however, is not their existence, but their persistence. In fact, preconceptions should not be seen by teachers as an impediment to learning, but as a necessary starting point to build new scientific knowledge (Furió Más et al., 2006). Teachers must ensure that students build scientific knowledge in which to integrate the ideas with which they come to class, and not the other way around, as is usually the case with much of scientific learning at school (Pozo, 1996). Therefore, one of the key issues is to determine which strategy best helps the student in the process of acquiring academic knowledge.

Learning physics requires bringing concepts and models to the classroom, but also introducing pupils to the development of some specific aspects of scientific work, to ensure satisfactory learning by students (Bravo & Rocha, 2004). Many experts in the field agree that active teaching strategies are of significant help for the improvement of conceptual learning of the different subjects addressed both at university and secondary level (Bostan Sarıoğlan et al., 2021; Martínez-Borreguero et al., 2022; McDermott & Shaffer, 2002; Sokoloff & Thornton, 1997). Active learning methodologies, a product of the last 30 years of educational research, significantly improve the conceptual understanding of physics (Alborch et al., 2015; Laws, 1991), reproducing the scientific process in the classroom and aiding the development of reasoning skills. Therefore, various authors and international organizations have proposed methodologies and strategies to increase student achievement and motivation, always highlighting the use of experimental resources and experimentation in teaching (Pérez Lozada & Falcón, 2009). In this sense, to overcome the barriers associated with traditional teaching, active methodologies emerge that propose to emphasize the role that the student should have in the process of constructing his own knowledge (Alborch et al., 2015). This process considers, fundamentally, the students' starting situation, designing from there a path that helps them to solve the incongruities and contradictions between their beliefs and the scientific knowledge accepted by the experts of the discipline (Benegas et al., 2009). Specifically, education experts suggest relying on active approaches such as constructivism, inquiry, problem-based approaches, context-based learning, or interdisciplinary integration (Millar, 2020; Wood et al., 1995). However, despite indications from experts in the field, the use of active methodologies in the physics classroom is complicated when teachers lack the necessary knowledge to approach such methodologies effectively (Crismond & Adams, 2012). A successful change in the curriculum approach must start with well-trained and willing teachers (Martínez-Borreguero et al., 2022).

One of the didactic tools that can be developed and that can be useful for student learning at different educational levels are hyperrealistic simulations (Martínez-Borreguero, Naranjo-Correa, et al., 2013). For this reason, in the present research hyperrealistic spectral simulations have been developed as an educational resource to help the student to better understand the functioning of light and color as a complement to real observations. The novelty lies in the fact that these simulations provide the user with a more realistic perception of the physical phenomenon being simulated. Hyperrealistic spectral simulations are especially useful for the representation of optical phenomena, since the phenomenon being simulated is the one being seen. In this way, the students identify what they see happening in the simulated model with what they see happening in reality, which prevents problems from arising among students who have a lower capacity for abstraction. We consider it relevant to carry out this type of activities, especially with teachers in training, so that they can increase their levels of teaching self-efficacy, promoting their future professional development.

Considering the above contributions, it is worth noting that initial and lifelong teacher training is part of the change, since educators are the ones who must learn new ways of teaching. Thus, initial teacher training, in the field of science, is a fundamental process in the professional development of future teachers and an interesting area to study and analyze due to its scope and implications (Cofré et al., 2010). For this reason, this work has focused on the development of simulations as didactic tools for teachers in training, with the aim of combating the preconceptions found and promoting an improvement in the teaching of color at all educational stages.

Last, but not least, the present study, while framed within the context of physics education, touches upon the inherently complex nature of color perception—a subject that straddles the lines between physics, biology, and cognitive science. As such, certain terminologies and concepts traditionally accepted within the domain of physics education, such as referring to wavelengths of light as 'colors' of the visible spectrum, may diverge from those used in vision science. We acknowledge that from a vision science standpoint, color is not an intrinsic property of light or objects but rather a perceptual experience located within the observer.

2. Methodology

The research carried out followed a quasi-experimental and quantitative design, with pre-test, post-tests, and distribution of the sample in control and experimental groups. To validate from a didactic point of view the usefulness of the teaching-learning sequences designed, the didactic strategies used in the sessions were considered as an independent variable The dependent variable was the learning achieved by the teachers in training at the end of the didactic intervention.

2.1. Objectives

Several objectives have been formulated according to the variables under study. The first objective of the study was to diagnose the preconceptions that teachers in training have about color and related basic concepts of optics. The second objective of the research was to validate, from an educational point of view, the usefulness of the didactic resources developed.

2.2. Hypotheses

The objectives of the study have served as a basis for formulating the following hypotheses:

Hypothesis 1: Primary and secondary school teacher trainees present preconceptions about basic optics concepts related to light and color.

Hypothesis 2: Hyperrealistic light and color simulations facilitate meaningful, long-term learning in primary school teacher trainees.

2.3. Sample

The study was conducted with the participation of 409 trainee teachers who were selected by non-probabilistic sampling due to the ease of access to them. The 409 participants, future primary and secondary school teachers, were divided into separate groups according to their academic background. Prior to their participation in the study, all participants underwent screening for color vision deficiencies. Individuals diagnosed with any type of color vision deficiency were not included in the study. This measure was implemented to guarantee that the study's results solely represent the impact of the educational interventions, eliminating potential biases arising from differences in color perception abilities among participants.

In this study, the utilization of the subsamples was strategically differentiated to address various phases. Subsamples 1 and 2, comprising students from the Degree in Primary Education and the Master's Degree in Teacher Training in Secondary Education respectively, were primarily involved in the diagnostic phase of the study (Hypothesis 1). Their participation was crucial in identifying and analyzing the persistence of preconceptions about color and optics, despite their formal educational backgrounds.

Conversely, Subsample 3, which included only primary school teachers in training, played a pivotal role in the assessment phase (Hypothesis 2). This group was specifically engaged in evaluating the effectiveness of the hyperrealistic simulations developed for the study. Subsample 3 was divided into two groups, a Control Group (CG) and an Experimental Group (EG), to facilitate a comparative analysis of the learning outcomes influenced by the traditional teaching methods and the innovative simulation-based approach. This strategic division of subsamples ensured a comprehensive assessment of both the prevailing preconceptions in teacher trainees and the efficacy of the didactic tools designed to address them. Here follows a detailed and precise description of each subsample engaged in the study.

Diagnostic phase:

Subsample 1: On the one hand, several groups of students of the Degree in Primary Education participated, constituting a total of 184 subjects between 21 and 30 years of age. This group of students were in their last year of their university degree to become Primary Education teachers.

Subsample 2: On the other hand, students from the Master's Degree in Teacher Training in Secondary Education with Bachelor's Degrees in Physics, Chemistry, Engineering or Architecture participated in the study. This group consisted of 156 subjects, aged between 24 and 40 years. Our intention in selecting a sample of these characteristics was based on the persistence of preconceptions despite the formal instruction received throughout their years of study (Martínez-Borreguero, Naranjo-Correa, et al., 2013; Uzun et al., 2013).

Validation phase:

Subsample 3: We also worked in subgroups with the group of primary school teachers in training, with the purpose of validating the didactic tools designed, by means of a non-probabilistic sampling due to the ease of access. As an example, this paper presents the results of the intervention developed with 69 students of the Degree in Primary Education, who are studying didactics of experimental sciences to become future teachers. These students were divided into two homogeneous and equivalent working groups in terms of initial knowledge, a Control Group (CG) and an Experimental Group (EG). The CG consisted of 33 students and the EG consisted of 36 students. The same amount of time was used with both the CG and the EG for the teaching of the contents.

2.4. Development of the intervention

In the Control Group, a conventional teaching approach was adopted, where instructors predominantly utilized PowerPoint presentations supplemented with theoretical explanations. These presentations were composed of diagrams and static images, illustrating key scientific principles. However, this method lacked interactive or practical elements, focusing solely on theoretical understanding without hands-on application.

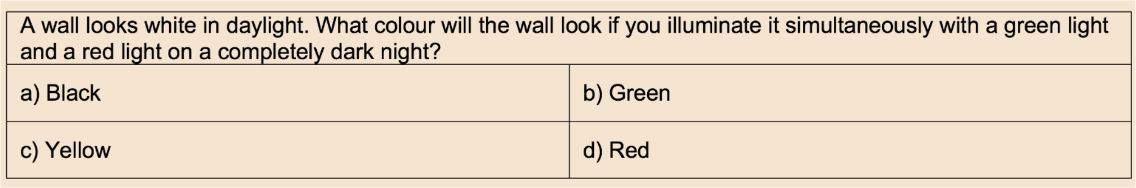
In contrast, the Experimental Group experienced a more innovative approach, engaging with the same scientific topics using hyperrealistic simulations (Martínez-Borreguero et al., 2016; Naranjo-Correa et al., 2017). This dynamic and interactive environment provided a more immersive and engaging learning experience, allowing students to explore and understand the underlying principles through direct experimentation, mirroring real-world scenarios more closely than traditional methods. It should be recalled that the hyperrealistic simulations developed show environments of optical phenomena that reproduce the behavior of real systems with a higher level of reality than those of traditional computer simulations.

2.5. Measuring instrument

A test on basic concepts of optics related to light and color was used as a measuring instrument to analyze the increase in learning achieved by the students after the didactic interventions. This test consisted of closed multiple-choice questions with a single answer, designed based on previous studies (Martínez-Borreguero, Pérez-Rodríguez, et al., 2013; Naranjo-Correa, 2019; Naranjo-Correa et al., 2016) and elaborated considering the distractor theory. The different questions pose a series of situations that provoke in the subjects a reasoning about the optical phenomenon posed, so that each of the possible answers corresponds to a preconception (distractor) or to the desirable correct answer. Among the possible distractors, the best distractor corresponding to the incorrect answer most expected by the population was selected. Given that the participating subjects will be teachers at the primary and secondary academic levels, the optics contents included in the curricula of primary and secondary education were selected.

The test was applied at three separate times. Specifically, once as a pre-test and twice as a post-test. The pre-test was taken at the beginning of the didactic sessions, before starting the teaching of the contents under study in the two groups. The aim of post-test I was to check the effectiveness of the didactic methodology used in each group, as well as to verify the persistence of the preconceptions after the realization of different teaching-learning sequences. Specifically, it was passed to the students after their respective teaching sessions (control and experimental) to know the degree of acquisition of the contents explained according to the different didactic resources used. The purpose of post-test II was to verify whether significant learning had taken place in the students and whether they remembered the contents explained after the passage of time. It was taken by the students of both groups 2 months after post-test I. It should be remembered that the test designed, as it was implemented on an interactive online platform, allowed the questions and their answer options to be displayed randomly, which prevented the post-tests from being answered memoristically.

Figure 1 shows an example question from the questionnaire developed for this purpose. The full questionnaire is available at Appendix A.



A wall looks white in daylight. What colour will the wall look if you illuminate it simultaneously with a green light and a red light on a completely dark night?

a) Black	b) Green
c) Yellow	d) Red

Figure 1. Example question of the questionnaire

Please note that in the present study, some expected answers, such as that "sunlight is made up of all the colors of the visible spectrum", aligns with conventional physics education, while the notion that "color is a property of objects" is identified as a preconception. This perspective stems from physics, where wavelengths of light are often equated with colors. However, from a vision science viewpoint, this approach is somewhat simplistic, as color is a perceptual phenomenon experienced by the observer. For instance, while objects possess an intrinsic spectral reflectance, it is the interaction of this reflectance with light and the human visual system that results in the perception of color. This complexity suggests that what might be deemed a misconception in physics can hold validity in vision science. Therefore, to provide a comprehensive understanding, our study includes the questionnaire with marked correct answers, aiding in interpreting findings about misconceptions in color perception, particularly from a physics teaching perspective. As stated on the *Colour Literacy Project* website (ISCC & AIC, 2020), a joint educational initiative of the Inter-Society Colour Council (ISCC) and the International Colour Association (AIC), "this type of terminology, although not strictly correct, is helpful for communicating ideas about colour in an understandable manner" (ISCC & AIC, 2020). This approach highlights the divergent viewpoints between physics and vision science regarding color perception.

After the intervention, our students are encouraged to further explore the topic of color perception, a complex subject that intersects physics and vision science. This area, although beyond the scope of the current study, offers valuable insights into how color is perceived and conceptualized across different scientific disciplines. Such exploration is especially advantageous for educators, aiding them in understanding the multifaceted nature of color teaching and comprehension, which extends beyond traditional physics education. By engaging with these broader aspects, educators can enrich their perspectives, better addressing intricate questions and potential misconceptions about color in their teaching practices. An excellent comprehensive resource for this endeavor may be found at the already mentioned *Colour Literacy Project*, as it aims to integrate art and science within contemporary color education, offering a website with comprehensive resources on color's artistry, science, and industrial aspects, targeting educators across all levels to correct misconceptions and misinformation (ISCC & AIC, 2020).

2.6. Validation of the Evaluation Instrument

To establish the validity of the questionnaire, a first draft of the designed test was given to a group of expert teachers, with the aim of checking whether the questions included were adapted to the level of the participating subjects, or whether their formulation was appropriate for the research. Specifically, following the guidelines of other studies (C. S.

Ding & Hershberger, 2002), a concordance test was conducted among experts, who were provided with eight assessment criteria on which they had to mark their degree of agreement (scored as 1) or disagreement (scored as 0). The degree of agreement is calculated as the result of the number of total agreements divided by the sum of the number of total agreements plus the total disagreements. The value obtained in this study was 0.91, which indicates a degree of agreement classifiable as very good according to the literature (C. S. Ding & Hershberger, 2002).

Furthermore, several psychometric tests were conducted to highlight the reliability of the instrument within the study, following the recommendations of various authors (L. Ding et al., 2006; McColgan et al., 2017; Melo Niño et al., 2016). Statistical tests focused on the assessment of the test items were performed, such as the difficulty index, discrimination indexes, point biserial coefficient, Ferguson's Delta, and Kuder-Richardson's 20 coefficient, using the formulas specified in previous studies. Table 1 shows the values obtained and the values recommended in the literature (L. Ding & Beichner, 2009) of the calculated indices. As can be seen in Table 1, all values are within the recommended range. Based on this, the test presents an adequate degree of reliability and validity, constituting a reliable evaluation instrument, with an adequate level of difficulty and discriminatory power. Likewise, the designed items compose a measurement instrument with a great usefulness from a didactic point of view. Specifically, they can allow us an improvement in the teaching-learning of basic concepts of optics at different academic levels from the initial diagnosis of the preconceptions, with the purpose of carrying out an implementation of didactic sequences and the development of didactic materials (Naranjo-Correa et al., 2017) that allow a conceptual change in students and a meaningful and lasting learning of the concepts involved (Duit & Treagust, 2003).

Table 1. Psychometric analysis of the Evaluation Instrument

Coefficient	**Obtained Value**	**Recommended Value**
Mean difficulty index (P)	0.49	[0.30 – 0.90]
Mean discrimination index 1	0.36	≥ 0.30
Mean discrimination index 2	0.72	≥ 0.50
Mean point-biserial coefficient (r)	0.32	≥ 0.20
Ferguson's Delta (δ)	0.91	≥ 0.90
KR-20	0.72	≥ 0.60

2.7. Simulations used with the experimental group

A more detailed understanding of the principles behind the developed simulations and the simulation of spectral distributions for various light sources and object reflectance can be found in previous research (Naranjo-Correa et al., 2019; Naranjo-Correa & Martínez-Borreguero, 2023; Wahler, 2013).

To enhance the realism of the color simulations, a virtual environment was modeled based on an actual lighting booth. These booths, essential for precise color evaluation, simulate standardized lighting conditions to assess color appearance and metamerism without environmental interference (Marcus, 2012). Typically, they are outfitted with a range of light sources to mimic different conditions, such as daylight with D50 or D65 illuminants. The simulation overcomes the high cost and technical limitations of real booths by allowing the emulation of any light type, from incandescent to LED, and the visualization of objects, including those of atypically large sizes or altered appearances. For instance, Figure 2 demonstrates the capability of the simulated booth, showcasing apples under different illuminants, illustrating the booth's versatility and educational value in teaching color concepts.

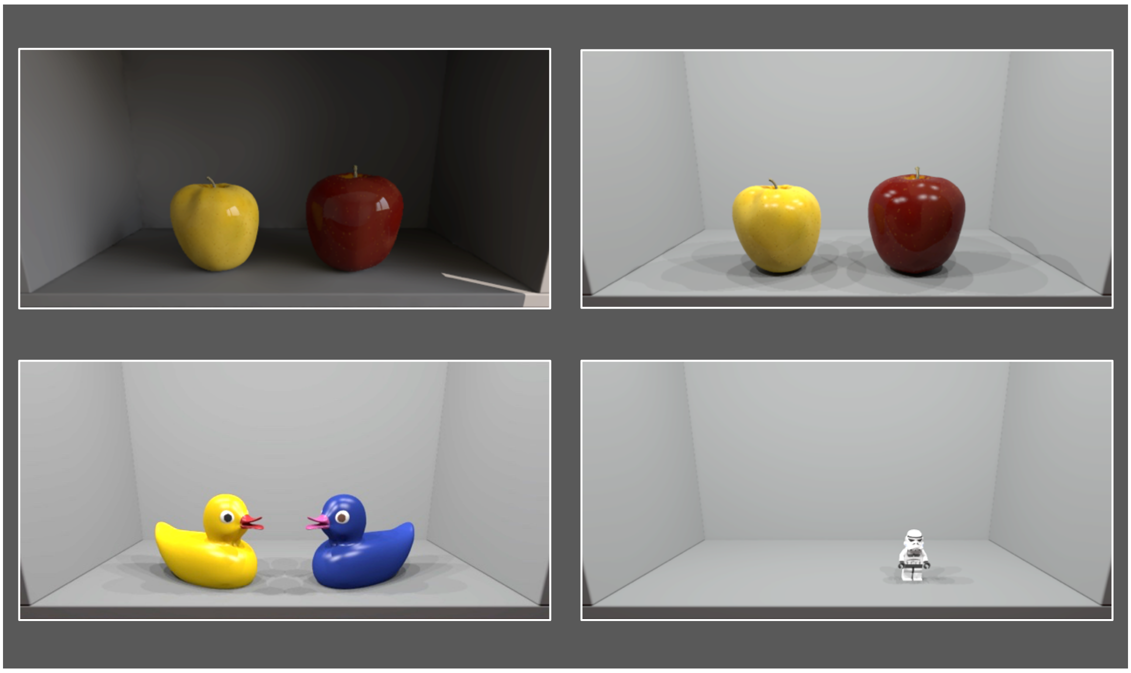


Figure 2.- Simulation of various objects in the illumination booth

Simulations were conducted with variously colored objects under differing illuminants to demonstrate the effect of light-object interactions on color perception. This exercise aimed to address and correct common preconceptions by visually representing how different lighting conditions alter the perceived color of objects (Eaton et al., 1986; Feher & Meyer, 1992; Martínez-Borreguero, Pérez-Rodríguez, et al., 2013; Mota & Lopes Dos Santos, 2014).. For instance, the depicted simulations in Figure 3 include a pair of metameric rubber ducks illuminated by three distinct light sources: a cold white fluorescent tube, the CIE standard illuminant D65, and a high-pressure sodium lamp, showcasing the changes perceived under each type of lighting.

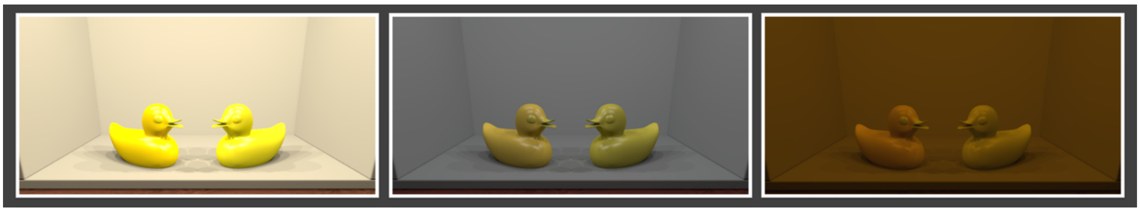


Figure 3.- Simulation of a pair of metameric rubber ducks under three different illuminants.

Figure 4 shows a beach ball in which, under a D65 illuminant, three distinct colors are perceived (left). If we change the illuminants appropriately, we can see how certain colors are no longer perceived. Of course, in the real world, objects reflect a broad spectrum of wavelengths, not just the narrow band of their perceived color, and when illuminated by light of a different color the object would still be visible, its appearance influenced by the object's reflective properties and the spectral power distribution of the light. Indeed, such a situation would typically occur with objects and light sources that reflect or emit a wide range of wavelengths, unlike the more constrained examples of laser beams or objects reflecting light in a very narrow wavelength range used in Figure 4. They are, however, pedagogically valuable, providing an exaggerated effect within a controlled environment to enhance students' conceptual understanding. These initial simplifications should be considered as a steppingstone, helping students to first grasp foundational concepts before advancing to the nuanced realities of color perception and object illumination.

Figure 4.- A beach ball under daylight (left) and under six different illuminants (right).

2.8.Limitations

The study's limitations include its reliance on non-probabilistic sampling, limiting the generalizability of results to all teacher trainees. Long-term retention of knowledge post-intervention remains to be evaluated, presenting an area for future research. Additionally, implementing the hyperrealistic simulations-based methodology on a broader scale is challenging due to the diversity in teaching styles, environments, and the requirement of specific technological resources. Furthermore, the focus on color and optics within physics education may restrict the applicability of findings to other scientific disciplines.

Moreover, it should be considered that what is regarded as a misconception in one scientific field may not be categorized as such in another. For instance, while the physics-centric view in education may label the belief that color is a property of objects as a misconception, this statement finds validity when considering color from the perspective of an observer's perception in vision science. This study thus underscores the importance of context when evaluating preconceptions and invites a broader discussion on the teaching of color that encompasses multiple scientific disciplines.

Last, while integrating simulations with real-world observations offers valuable insights, this approach was not within the intended scope of the study, as the primary focus was on diagnosing preconceptions in color and optics and validating the educational utility of the developed didactic resources.

3. Results

3.1. Results obtained after the analysis of preconceptions.

Table 2 shows the descriptive statistics of the scores obtained in the test by the teachers in training at the primary education level and by the teachers in training at the secondary education level.

Table 2. Descriptive statistics of the scores obtained in the test by the teachers in training

Group	N	Mean	Std. Error Mean	Std. Deviation
Primary school teachers in training (G1)	184	4.28	0.10	1.36
Secondary school teachers in training (G2)	156	5.74	0.18	1.35

As shown in Table 2, G1 obtains a mean of 4.28 points out of 10, with a standard deviation of 1.36. Conversely, G2 obtains a mean of 5.74 points out of 10, with a standard deviation of 1.35. In global terms, it is observed that both prospective primary and secondary teachers present low scores. This denotes the presence of preconceptions in these groups with respect to the subject under study.

Regardless of the better results obtained by G2, the low scores obtained in general by both groups are worrying from a didactic point of view. These professionals will have to teach soon at the primary and secondary academic levels these basic contents of optics, which they clearly do not master. This is especially serious in G2, since these are students who come from degrees with a strong scientific background (such as physics, chemistry, engineering, or architecture). In the case of G1, most of its members (more than 75%) come from a social science or humanities baccalaureate and have received practically no instruction in science during their last years of training.

By way of example, some of the preconceptions found in both groups are presented in detail. Thus, most subjects in both groups answered correctly that sunlight is made up of all the colors of the visible spectrum. However, there are statistically significant differences in the percentage of correct answers (96% in G2 versus 74% in G1). On the other hand, it should be noted that there is a 15 % of primary school teachers in training who present the preconception that sunlight is only formed by the color yellow, which already appears in the literature reviewed (Feher & Meyer, 1992; Haagen-Schützenhöfer, 2017).

On the other hand, 33% of teachers in training manifest the preconception that the sun only emits yellow, red, or orange light, compared to 11% in future secondary education teachers in science fields. This preconception is related to that obtained in the previous analysis and appears reflected in several studies (Feher & Meyer, 1992; Maurício et al., 2017).

Regarding the test questions referring to additive or subtractive color mixing (Hecht, 2016; Nassau, 1997), it should be noted that there are multiple preconceptions about these concepts already described in the literature (Eaton et al., 1984, 1986; Martínez-Borreguero, Pérez-Rodríguez, et al., 2013). Thus, for example, when asked about the mixing of light colors (additive mixing), it is observed that there are differences between the percentage of correct answers of primary school teachers in training and those of secondary school teachers in scientific specialties. Likewise, in both groups there are subjects with the same preconceptions. Table 3 shows, by way of summary, the most frequently found preconceptions in subsamples 1 and 2.

Table 3.- Percentages of the results obtained in the test by teachers in training

Answers	Primary school teachers	Secondary School Teachers (Technology / Physics & Chemistry)
Right Answer in all questions	13.8 %	29.1 %
Preconception 1 The perceived color is the mixture of the color emitted by the object plus the color of the light that illuminates it.	40.9 %	33.8 %
Preconception 2 Color is a property of objects.	20.4 %	15.9 %
Preconception 3 The object will always be seen in the color of the light that illuminates it.	12.4 %	11.3 %
Preconception 4 The color of the illuminant fills the space around the objects, so that an object of the same color as the illuminant will not be seen due to lack of contrast.	4.1 %	3.3 %
Other	8.4 %	6.6 %

3.2. Results obtained after didactic interventions

The results of the Control Group and the Experimental Group from subsample 3 are presented after analyzing how the scores have evolved in each case over time, to estimate whether the change has been significant and thus evaluate the validity of the didactic interventions conducted in each group.

Table 4 shows the descriptive statistics for the Control Group.

Table 4. Statistics of paired samples from the Control Group

		Mean	**N**	**Std. Deviation**	**Std. Error Mean**	**Cohen's d**
Pre-test vs Post-test I	Pre-test	4.54	33	1.14	0.20	1.72
	Post-test I	7.26	33	1.93	0.34	
Pre-test vs Post-test II	Pre-test	4.54	33	1.14	0.20	1.10
	Post-test II	5.84	33	1.22	0.21	
Post-test I vs Post-test II	Post-test I	7.26	33	1.93	0.34	-0.88
	Post-test II	5.84	33	1.22	0.21	

As shown in Table 4, the CG obtained a lower average score in post-test II than in post-test I, with a mean difference between the two post-tests of 1.42 points. To further analyze these differences, several Student's t-tests for paired samples were performed to estimate the evolution between pre-test, post-test I and post-test II within each of the groups. Table 5 shows the paired samples t-test for the comparison of the means between the three tests in the CG.

Table 5. Paired samples test of the Control Group

	Paired Differences					**t**	**df**	**Sig. (2-tailed)**
	Mean	**Std. Deviation**	**Std. Error Mean**	**95 % Confidence Interval of the Difference**				
				Lower	**Upper**			
Pre – Post I	-2.72	2.34	0.41	-3.55	-1.89	-6.68	32	< 0.001
Pre – Post II	-1.30	1.13	0.20	-1.70	-0.90	-8.36	32	< 0.001
Post I – Post II	1.42	2.23	0.39	0.63	2.21	3.65	32	< 0.001

Table 5 shows that the significance obtained is less than 0.05 in the three pairs analyzed, which indicates statistically significant differences between the average scores obtained by the CG in the three evaluation instruments. Based on these results, we can affirm that the implementation of the didactic methodology carried out in the CG has been effective, but only in the short term. Although the CG students significantly improve their initial scores immediately after the didactic intervention, this increase in scores is not maintained over time, as there is a significant decrease between post-test I and post-test II.

Additionally, Table 6 presents the descriptive statistics for the EG.

Table 6. Statistics of paired samples from the Experimental Group

		Mean	**N**	**Std. Deviation**	**Std. Error Mean**	**Cohen's d**
Pre-test vs Post-test I	Pre-test	4.27	36	1.14	0.19	2.65
	Post-test I	7.12	36	1.01	0.17	
Pre-test vs Post-test II	Pre-test	4.27	36	1.14	0.19	2.03
	Post-test II	6.83	36	1.36	0.23	
Post-test I vs Post-test II	Post-test I	7.12	36	1.01	0.17	0.24
	Post-test II	6.83	36	1.36	0.23	

As can be seen in Table 6, the EG students significantly improve their scores after the interventions. In addition, these students obtain a similar average score in post-test I and post-test II, obtaining only a difference in scores of 0.29 points.

To assess for the existence of statistically significant differences between means, a t-test for paired samples was applied for the comparison of means between the three tests in the EG. Table 7 shows the results obtained.

Table 7. Paired samples test of the Experimental Group

	Paired Differences					**t**	**df**	**Sig. (2-tailed)**
	Mean	**Std. Deviation**	**Std. Error Mean**	**95 % Confidence Interval of the Difference**				
				Lower	**Lower**			
Pre – Post I	-2.85	1.59	0.27	-3.39	-2.31	-1.07	35	< 0.001
Pre – Post II	-2.56	1.91	0.32	-3.21	-1.91	-8.03	35	< 0.001
Post I – Post II	0.29	1.67	0.28	-0.27	0.86	1.05	35	0.301

Table 7 shows that there are statistically significant differences between pre-test vs. post-test I, and between pre-test vs. post-test II. However, the significance between post-test I and post-test II is greater than the 0.05 reference value (Sig. = 0.301), thus finding no statistically significant differences in the EG between the scores obtained in post-test I and the scores obtained in post-test II. Based on these results, we can affirm that the implementation of the didactic methodology carried out in the EG has been effective beyond the short term. The students in the EG significantly improve their initial scores after the didactic intervention, and this increase in scores does not decrease significantly with the passage of time.

Based on the results obtained in the inferential statistical analysis in both the CG and the EG, we can indicate that the students in the CG control group seem to have forgotten the concepts worked on over time, with the resurgence of preconceptions about them like those obtained in the pre-test. This suggests that the CG had a more rote learning of the contents worked on in the didactic sessions. On the other hand, the students in the EG continued to remember the concepts after the passage of time, which indicates that they had a more meaningful learning of the concepts as opposed to the CG. Therefore, we can accept Hypothesis 2 formulated in the research (Hyperrealistic simulations on light and color facilitate meaningful and long-term learning in primary education teachers in training).

4. Conclusions

The progressive decrease in the number of students in scientific disciplines and the alarming scientific illiteracy observed in society require the implementation of novel resources and educational tools to teach and disseminate science. In this sense, the results obtained show that practical activities prove to be an effective tool for the promotion of scientific-experimental education of teachers (Pérez Lozada & Falcón, 2009) and their learning levels. The students participating in the study have significantly improved their level of knowledge after the interventions. However, it is verified that the practical interventions make it easier for learning to last over time. Specifically, in the comparative analysis between groups according to the didactic methodology used, it can be concluded that, in short-term learning, students who use hyperrealistic simulations for learning basic optics concepts obtain similar average scores to students who follow a more traditional didactic intervention. However, with respect to long-term learning, it was found that there are statistically significant differences in the learning variable of the student who follows a didactic intervention based on the use of hyperrealistic simulations versus the student who follows a more traditional didactic intervention. Specifically, the differences found are in favor of the EG, which used the didactic tools designed. Therefore, it can be concluded that the hyperrealistic simulations have facilitated meaningful long-term learning in the teacher trainees and the preconceptions that were initially encountered have been effectively combated with the intervention developed. Conversely, students who used a more traditional methodology have forgotten over time the contents learned, and some of the preconceptions found at the beginning of the research have resurfaced in them. Based on these results, it is concluded that it is necessary to develop physics learning strategies that are consistent with this orientation, which implies considering the preconceptions presented by the students (Grizalez et al., 2002). It is increasingly evident that purely expository classes are routine and demotivating for students.

Finally, it should be noted that it is not so easy to change the methodological tradition of teachers. Doing so requires a great deal of effort, both institutional and individual. We believe that incorporating a mixed teaching system during initial teacher training could help students to gradually overcome this certain attitude of rejection. Teacher training plays a crucial role in ensuring that professional practice goes beyond the mere transmission of knowledge. It should also focus on guiding and accompanying the learning process. This will generate an encouraging environment for students to construct their own meanings.

Future work stemming from this study will focus on enhancing learning outcomes through advanced simulations that bridge the gap between theoretical knowledge and real-world color perception. Integrating simulations with real-world investigations could enhance learning outcomes. The combination of virtual and hands-on experiences allows students to see the practical application of theoretical knowledge, providing a more holistic understanding of concepts. This may include augmented and virtual reality technologies to create immersive and customizable learning experiences, blending simulations with hands-on activities, and extending applications to interdisciplinary contexts. Longitudinal studies are also proposed to assess the long-term retention of knowledge, alongside empirical validation of these methods' impact on educational efficacy and test scores. Additionally, the integration of these simulation tools into teacher training programs will be explored to improve pedagogical approaches for teaching color theory.

References

Abd-El-khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of nature of science: A critical review of the literature. In *International Journal of Science Education* (Vol. 22, Issue 7, pp. 665–701). https://doi.org/10.1080/095006900500044044

Alborch, A., Pandiella, S., & Benegas, J. (2015). Aprendizaje activo en óptica (Programa ALOP). Relato de una experiencia en la escuela secundaria. *Anuario Digital de Investigación Educativa*, *26*, 1–16.

Anderson, C. W., & Smith, E. L. (1984). Children's preconceptions and content-area textbooks. *Comprehension Instruction: Perspectives and Suggestions*, 187–201.

Andersson, B., & Kärrqvist, C. (1983). How Swedish pupils, aged 12-15 years, understand light and its properties. *European Journal of Science Education*, *5*(4), 387–402. https://doi.org/10.1080/0140528830050403

Aydin, S. (2012). Remediation of misconceptions about geometric optics using conceptual change texts. *Journal of Education Research and Behavioral Sciences*, *1*(1), 1–12. http://www.apexjournal.org

Bendall, S., Goldberg, F. M., & Galili, I. (1993). Prospective elementary teachers' prior knowledge about light. *Journal of Research in Science Teaching*, *30*(9), 1169–1187.

Benegas, J. C., Villegas, M. P., Pérez de Landazábal, M. C., & Otero, J. (2009). Conocimiento conceptual de física básica en ingresantes a carreras de ciencias e ingeniería en cinco universidades de España, Argentina y Chile. *Revista Iberoamericana de Física*, *5*(1), 35–43.

Bleicher, R. E., & Lindgren, J. (2005). Success in Science Learning and Preservice Science Teaching Self-Efficacy. In *Source: Journal of Science Teacher Education* (Vol. 16, Issue 3).

Bostan Sarıoğlan, A., Şen, R., & Altaş, R. (2021). What do secondary school students think about experimental practices in science lessons taught in distance education? *Journal of Educational Technology and Online Learning*, *4*(2), 193–214. https://doi.org/10.31681/jetol.907470

Bravo, B., & Rocha, A. (2004). Learning about light and color in the second stage of the general basic education. *Journal of Science Education*, *5*(1), 43–46.

Bruner, J. S. (Jerome S. (1996). *The culture of education*. Harvard University Press.

Busquets, T., Silva, M., & Larrosa, P. (2016). Reflections on the Teaching-Learning of the Natural Sciences: New perspectives and challenges. *Estudios Pedagógicos (Valdivia)*, *42*(Special), 117–135.

Ceuppens, S., Deprez, J., Dehaene, W., & De Cock, M. (2018). Tackling misconceptions in geometrical optics. *Physics Education*, *53*(4), 45020. https://doi.org/10.1088/1361-6552/aac604

Cofré, H., Camacho, J., Galaz, A., Jiménez, J., Santibáñez, D., & Vergara, C. (2010). La educación científica en Chile: debilidades de la enseñanza y futuros desafíos de la educación de profesores de ciencia. *Estudios Pedagógicos (Valdivia)*, *36*(2), 279–293.

Colin, P., Chauvet, F., & Viennot, L. (2002). Reading images in optics: Students' difficulties and teachers views. *International Journal of Science Education*, *24*(3), 313–332. https://doi.org/10.1080/09500690110078923

Colin, P., & Viennot, L. (2001). Using two models in optics: Students' difficulties and suggestions for teaching. *American Journal of Physics*, *69*(S1), S36–S44.

Costa, L. S. O., Barros, V. F. A., Lopes, M. C. R., & Marques, L. P. (2015). La formación docente y la educación de jóvenes y adultos: Análisis de la práctica pedagógica para la enseñanza de ciencias. *Formacion Universitaria*, *8*(1), 3–12. https://doi.org/10.4067/S0718-50062015000100002

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, *101*(4), 738–797. https://doi.org/10.1002/j.2168-9830.2012.tb01127.x

Dávila-Acedo, M. A. (2017). The emotions and their causes in the learning of Physics and Chemistry, in the students of Secondary Education. *Revista Eureka Sobre Enseñanza y Divulgación de Las Ciencias*, *14*(3), 570–586.

Ding, C. S., & Hershberger, S. L. (2002). Assessing content validity and content equivalence using structural equation modeling. *Structural Equation Modeling*, *9*(2), 283–297. https://doi.org/10.1207/S15328007SEM0902_7

Ding, L., & Beichner, R. (2009). Approaches to data analysis of multiple-choice questions. *Physical Review Special Topics-Physics Education Research*, *5*(2), 20103. https://doi.org/10.1103/PhysRevSTPER.5.020103

Ding, L., Chabay, R., Sherwood, B., & Beichner, R. (2006). Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment.

Physical Review Special Topics-Physics Education Research, *2*(1), 10105. https://doi.org/10.1103/PhysRevSTPER.2.010105

Disessa, A. A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science*, *28*(6), 843–900. https://doi.org/10.1207/s15516709cog2806_1

Driver, R., Guesne, E., & Tiberghien, A. (1985). *Children's ideas in science* (R. Driver, E. Guesne, & A. Tiberghien, Eds.). Open University Press.

Duit, R., Schecker, H., Höttecke, D., & Niedderer, H. (2014). Teaching Physics. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of Research on Science Education, Volume II* (pp. 434–456).

Duit, R., & Treagust, D. F. (1998). Learning in Science: From Behaviourism Towards Social Constructivism and Beyond. In B. J. Fraser & K. G. Tobin (Eds.), *International Handbook of Science Education* (pp. 3–25). Kluwer.

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education*, *25*(6), 671–688. https://doi.org/10.1080/09500690305016

Eaton, J. F., Anderson, C. W., & Smith, E. L. (1984). Students' misconceptions interfere with science learning: Case studies of fifth-grade students. *The Elementary School Journal*, *84*(4), 365–379. https://doi.org/10.1086/461370

Eaton, J. F., Sheldon, T. H., & Anderson, C. W. (1986). *Light: A Teaching Module*. The Institute for Research on Teaching.

Favale, F., & Bondani, M. (2014). Misconceptions about optics: An effect of misleading explanations? *Proceedings of SPIE*, *9289*, 92891A. https://doi.org/10.1117/12.2070520

Feher, E., & Meyer, K. R. (1992). Children's conceptions of color. *Journal of Research in Science Teaching*, *29*(5), 505–520. https://doi.org/10.1002/tea.3660290506

Furió Más, C., Solbes Matarredona Jaime, & Carrascosa Alís, J. (2006). Las ideas alternativas sobre conceptos científicos: Tres décadas de investigación. *Alambique: Didáctica de Las Ciencias Experimentales*, *48*, 64–77.

Galili, I., Bendall, S., & Goldberg, F. M. (1993). The effects of prior knowledge and instruction on understanding image formation. *Journal of Research in Science Teaching*, *30*(3), 271–301.

Galili, I., & Hazan, A. (2000). Learners' knowledge in optics: interpretation, structure and analysis. *International Journal of Science Education*, *22*(1), 57–88. https://doi.org/10.1080/095006900290000

Ghafarpour, H., & Moinzadeh, A. (2020). A dynamic systems analysis of classrooms: teacher experience and student motivation. *Learning Environments Research*, *23*(1), 101–116. https://doi.org/10.1007/s10984-019-09293-y

Gil-Llinás, J., Suero-López, M. I., Pérez-Rodríguez, Á. L., & Solano-Macías, F. (2003). Misconceptions in optics: their persistence at university level. *Journal of Science Education*, *4*(1), 17.

Goldberg, F. M., & McDermott, L. C. (1986). Student difficulties in understanding image formation by a plane mirror. *The Physics Teacher*, *24*(8), 472–481.

Grizalez, M. A., Bermeo, D., Agudelo, J. M., & Sánchez, N. (2002). Preconceptos y conceptos erróneos acerca de las leyes del movimiento y sus aplicaciones en docentes de educación media que enseñan física en el departamento del Caquetá. *Revista Colombiana de Física*, *34*(2), 529–531.

Guesne, E. (1985). Light. In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science* (pp. 10–32). Open University Press.

Haagen-Schützenhöfer, C. (2017). Students' conceptions on white light and implications for teaching and learning about colour. *Physics Education*, *52*(4), aa6d9c. https://doi.org/10.1088/1361-6552/aa6d9c

Hecht, E. (2016). *Optics* (5th ed.).

Heywood, D. (2005). Primary Trainee Teachers' Learning and Teaching About Light: Some pedagogic implications for initial teacher training. *International Journal of Science Education*, *27*(12), 1447–1475. https://doi.org/10.1080/09500690500153741

ISCC, & AIC. (2020). *Colour Literacy Project*. Https://Colourliteracy.Org/.

Kaltakci-Gurel, D., Eryilmaz, A., & McDermott, L. C. (2016). Identifying pre-service physics teachers' misconceptions and conceptual difficulties about geometrical optics. *European Journal of Physics*, *37*(4), 45705. https://doi.org/10.1088/0143-0807/37/4/045705

Langley, D., Ronen, M., & Eylon, B. S. (1997). Light Propagation and Visual Patterns: Preinstruction Learners' Conceptions. *Journal of Research in Science Teaching*, *34*(4), 399–424. https://doi.org/10.1002/(SICI)1098-2736(199704)34:4<399::AID-TEA8>3.0.CO;2-M

Laws, P. W. (1991). Calculus-based physics without lectures. *Physics Today*, *44*(12), 24–31. https://doi.org/10.1063/1.881276

Marcus, R. T. (2012). Color and light. In V. Koleske, Josep (Ed.), *Paint and Coating Testing Manual* (15th ed., pp. 535–557). ASTM.

Martínez-Borreguero, G., Naranjo-Correa, F. L., & Mateos-Núñez, M. (2022). Development of STEM Instructional Resources for Teaching Optics to Teachers-in-Training: Influence on Learning and Teacher Self-Efficacy. *Education Sciences*, *12*(3). https://doi.org/10.3390/educsci12030186

Martínez-Borreguero, G., Naranjo-Correa, F. L., Pérez-Rodríguez, Á. L., & Suero-López, M. I. (2016). Development of hyperrealistic simulations to teach concepts about colors. *Color Research and Application*, *41*(3), 330–332. https://doi.org/10.1002/col.22013

Martínez-Borreguero, G., Naranjo-Correa, F. L., Pérez-Rodríguez, Á. L., Suero-López, M. I., & Pardo-Fernández, P. J. (2013). Use of computer generated hyper-realistic images on optics teaching: The case study of an optical system formed by two opposed parabolic mirrors. *Journal of Science Education*, *14*(1), 25–29.

Martínez-Borreguero, G., Pérez-Rodríguez, Á. L., Suero-López, M. I., & Pardo-Fernández, P. J. (2013). Detection of misconceptions about colour and an experimentally tested proposal to combat them. *International Journal of Science Education*, *35*(8), 1299–1324. https://doi.org/10.1080/09500693.2013.770936

Maurício, P., Valente, B., & Chagas, I. (2017). A Teaching-Learning Sequence of Colour Informed by History and Philosophy of Science. *International Journal of Science and Mathematics Education*, *15*(7), 1177–1194. https://doi.org/10.1007/s10763-016-9736-8

McColgan, M. W., Finn, R. A., Broder, D. L., & Hassel, G. E. (2017). Assessing students' conceptual knowledge of electricity and magnetism. *Physical Review Physics Education Research*, *13*(2), 20121. https://doi.org/10.1103/PhysRevPhysEducRes.13.020121

McDermott, L. C., & Shaffer, P. S. (2002). *Tutorials in introductory physics*. Prentice Hall.

Mellado Jiménez, V., Borrachero Cortés, A. B., Brígido Mero, M., Melo Niño, L. V., Dávila Acedo, M. A., Cañada-Cañada, F., Conde Núñez, M. del C., Costillo Borrego, E., Cubero Juánez, J., Esteban Gallego, R., Martínez-Borreguero, G., & Sánchez Martín, J. (2014). Emotions in Science teaching. *Enseñanza de Las Ciencias*, *32*(3), 11–36. https://doi.org/10.5565/rev/ensciencias.1478

Melo Niño, L. V., Sánchez, R., Cañada-Cañada, F., & Martínez-Borreguero, G. (2016). Learning difficulties on Archimedes' Principle in the floating context. *Revista Brasileira de Ensino de Física*, *38*(4), e4401. https://doi.org/10.1590/1806-9126-RBEF-2016-0077

Millar, V. (2020). Trends, Issues and Possibilities for an Interdisciplinary STEM Curriculum. *Science and Education*, *29*(4), 929–948. https://doi.org/10.1007/s11191-020-00144-4

Mota, A. R., & Lopes Dos Santos, J. M. B. (2014). Addition table of colours: Additive and subtractive mixtures described using a single reasoning model. *Physics Education*, *49*(1), 61–66. https://doi.org/10.1088/0031-9120/49/1/61

Naranjo-Correa, F. L. (2019). *Luz y Color: Desarrollo de herramientas didácticas para mejorar su enseñanza en docentes en formación* [Universidad de Extremadura]. https://www.educacion.gob.es/teseo/mostrarRef.do?ref=1745880

Naranjo-Correa, F. L., & Martínez-Borreguero, G. (2023). Educational simulations of spectral color dispersion in negative index prisms. *Color Research and Application*. https://doi.org/10.1002/col.22898

Naranjo-Correa, F. L., Martínez-Borreguero, G., Pérez-Rodríguez, Á. L., Pardo-Fernández, P. J., & Suero-López, M. I. (2017). Teaching rainbows with simulations: revisiting Minnaert's lab experiment. *Applied Optics*, *56*(19), G54–G69. https://doi.org/10.1364/AO.56.000G69

Naranjo-Correa, F. L., Martínez-Borreguero, G., Pérez-Rodríguez, Á. L., Suero-López, M. I., & Pardo-Fernández, P. J. (2016). A new online tool to detect color misconceptions. *Color Research and Application*, *41*(3), 325–329. https://doi.org/10.1002/col.22017

Naranjo-Correa, F. L., Martínez-Borreguero, G., Pérez-Rodríguez, A., Pardo-Fernández, P. J., & Suero-López, M. I. (2019). Spectral simulations for the teaching of metamer colour pairs at various educational levels. *Optica Pura y Aplicada*, *52*(1). https://doi.org/10.7149/OPA.52.1.51009

Nassau, K. (1997). *Color for science, art and technology* (Vol. 1). Elsevier.

Osborne, J. F., Black, P., Meadows, J., & Smith, M. (1993). Young children's (7-11) ideas about light and their development. *International Journal of Science Education*, *15*(1), 83–93. https://doi.org/10.1080/0950069930150107

Osborne, J. F., Driver, R., & Simon, S. (1998). Attitudes to Science: Issues and Concerns. *School Science Review*, *79*(288), 27–33.

Perales Palacios, F. J., Nievas Cazorla, F., & Cervantes Madrid, A. (1989). Misconceptions on geometric optics and their association with relevant educational variables. *International Journal of Science Education*, *11*(3), 273–286. https://doi.org/10.1080/0950069890110304

Pérez Lozada, E., & Falcón, N. (2009). Diseño de prototipos experimentales orientados al aprendizaje de la óptica. *Revista Eureka Sobre Enseñanza y Divulgación de Las Ciencias*, *6*(3), 452–465. http://fisica.facyt.uc.edu.ve/showfisica

Pesa de Danón, M. A. (1999). Concepciones y preconcepciones referidas a la formación de imágenes. *Revista de Enseñanza de La Física*, *12*(1), 13–46.

Pesa de Danón, M. A., & Colombo de Cudmani, L. (1998). ¿Qué ideas tienen los estudiantes respecto a la visión? *Revista Educación y Pedagogía*, *10*(21), 15–33.

Pesa de Danón, M. A., Colombo de Cudmani, L., & Bravo, S. (1995). Formas de razonamientos asociadas a los sistemas preconceptuales sobre naturaleza y propagación de la luz: Resultados de una experiencia piloto. *Caderno Brasileiro de Ensino de Física*, *12*(1), 17–31.

Pozo, J. I. (1996). Las ideas del alumnado sobre la ciencia: de dónde vienen, a dónde van... y mientras tanto qué hacemos con ellas. *Alambique: Didáctica de Las Ciencias Experimentales*, *7*, 18–26.

Sokoloff, D. R., & Thornton, R. K. (1997). Using interactive lecture demonstrations to create an active learning environment. *The Physics Teacher*, *35*(6), 340–347. https://doi.org/10.1119/1.2344715

Titsworth, S., Quinlan, M. M., & Mazer, J. P. (2010). Emotion in teaching and learning: Development and validation of the classroom emotions scale. *Communication Education*, *59*(4), 431–452. https://doi.org/10.1080/03634521003746156

Tural, G. (2015). Cross-Grade Comparison of Students' Conceptual Understanding with Lenses in Geometric Optics. *Science Education International*, *26*(3), 325–343.

Uzun, S., Alev, N., & Karal, I. S. (2013). A cross-age study of an understanding of light and sight concepts in physics. *Science Education International*, *24*(2), 129–149.

Valanides, N., & Angeli, C. (2008). Distributed cognition in a sixth-grade classroom: An attempt to overcome alternative conceptions about light and color. *Journal of Research on Technology in Education*, *40*(3), 309–336. https://doi.org/10.1080/15391523.2008.10782510

van Zee, E. H., Hammer, D., Bell, M., Roy, P., & Peter, J. (2005). Learning and teaching science as inquiry: A case study of elementary school teachers' investigations of light. *Science Education*, *89*(6), 1007–1042. https://doi.org/10.1002/sce.20084

Viennot, L., & de Hosson, C. (2012). Beyond a Dichotomic Approach, The Case of Colour Phenomena. *International Journal of Science Education*, *34*(9), 1315–1336. https://doi.org/10.1080/09500693.2012.679034

Vosniadou, S. (2008). Conceptual change in learning and instruction: The framework theory approach. In *International Handbook of Research on Conceptual Change* (pp. 11–30).

Vosniadou, S. (2019). The Development of Students' Understanding of Science. *Frontiers in Education*, *4*. https://doi.org/10.3389/feduc.2019.00032

Wahler, R. I. (2013). *Spectral Rendering with POV-Ray*. http://www.lilysoft.org/CGI/SR/Spectral Render.htm

Witt, P. L., Wheeless, L. R., & Allen, M. (2004). A meta-analytical review of the relationship between teacher immediacy and student learning. In *Communication Monographs* (Vol. 71, Issue 2, pp. 184–207). https://doi.org/10.1080/036452042000228054

Wood, T., Cobb, P., & Yackel, E. (1995). Reflections on Learning and Teaching Mathematics in Elementary School. In L. P. Steffe & J. Gale (Eds.), *Constructivism in Education* (pp. 419–440). Routledge.

Appendix A – Questionnaire

Expected answer (within the physics education framework) is underlined.

1. Sunlight is composed of…

a) Only the yellow color
b) Only the blue color
c) Only the green color
d) <u>All the colors of the visible spectrum</u>

2. On a blank piece of paper you print a magenta circle. If you print a yellow line over the circle, what color will the line look like?

a) White
b) Yellow
c) Red
d) Black

3. A wall looks white in daylight. What color will the wall look if you illuminate it at the same time with a green light and a red light on a very dark night?

a) Black
b) Green
c) Yellow
d) Red

4. A wall looks white in daylight. What color will the wall look if you illuminate it at the same time with a red light and a blue light on a very dark night?

a) Magenta
b) Blue
c) Red
d) Black

5. On a blank piece of paper you print a cyan circle. If you print a magenta line over the circle, what color will the line look like?

a) Blue
b) Magenta
c) White
d) Black

6. A wall looks white in daylight. What color will the wall look if you illuminate it at the same time with a yellow light and a blue light on a very dark night?

a) Yellow
b) Blue
c) White
d) Black

7. At noon, a ball looks magenta in the sunlight. On a very dark night you illuminate it with red light. What color will the ball look like?

a) Magenta
b) Red
c) Pink
d) Black

8. At noon, a ball looks red in the sunlight. On a very dark night you illuminate it with green light. What color will the ball look like?

a) Red
b) Green
c) Yellow

d) Black

9. At noon, a ball looks green in the sunlight. On a very dark night you illuminate it with green light. What color will the ball look like?

a) Green
b) It cannot be seen
c) Magenta
d) Black

10. At noon, an eggplant looks magenta in the sunlight. On a very dark night you illuminate it with red light. What color will the eggplant look like?

a) Magenta
b) Red
c) Pink
d) Black

11. The White Horse of St. James gallops at night illuminated only by a red spotlight. What color does the White Horse of St. James look like?

a) White
b) Pink
c) Red
d) It cannot be seen

12. Choose the correct option

a) Color is a property of objects
b) Color is not a property of objects

13. The sun only emits yellow, red or orange light

a) True
b) False