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Exploring the effect of a phenomenological teaching-learning sequence on lower secondary school students' views of light polarisation

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Abstract

The wave model of light in general, and the phenomenon of light polarisation in particular, are difficult topics for secondary school students. Prior research has indicated that a model-free phenomenological teaching approach may be fruitful in helping students overcome some of the widespread learning obstacles. These phenomenological approaches are characterised by their departure from abstract and mechanistic models of light, opting instead to prioritise students' observations throughout the exploration of phenomena and experiments, unburdened by mathematical formalism or theoretical

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models. In this paper, we present a three-lessons phenomenological teaching-learning sequence on light polarisation. We evaluated of the teaching concept in classroom practise and analysed ways of thinking about light polarisation among $N = 110$ students (aged 12–14 years) who participated in the intervention using qualitative content analysis of free-text responses. The results provide preliminary empirical evidence that the presented instructional approach can contribute to the development of a qualitative understanding of polarisation among learners in introductory optics.

Keywords: polarisation, optics, phenomena, light

1. Introduction

Studying light polarisation provides students opportunities to understand several related phenomena such as the physics of polarising sunglasses, 3D movies and the stripes on zebras [1–14]. Previous work has used light polarisation to create a framework for inquiry-based learning [15, 16] and presented low-cost experiments for classroom practice [17–22].

Typically, secondary school books introduce students to the polarisation of light using mechanical analogies [23], for instance, making use of the comparison with an oscillating rope, where polarisers correspond to slits or grids (cf figures 1 and 2), while the microscopic explanation of polarisers is usually omitted. Overall, the topic of light polarisation often holds rather peripheral position within school physics curricula, with its educational objective primarily centred around introducing the phenomenon's existence and confirming the transversal character of light waves [23, 24].

However, we believe that presenting light polarisation to learners is valuable, given the diverse array of phenomena it encompasses. In this paper, we therefore present an easy-to-implement teaching-learning sequence that

(i) can directly be connected to a phenomenological approach to optics as those of Udine [17–22] and Erlangen teaching-learning sequence of optics [28–30] which introduces students to topics such as vision and brightness, refraction or image formation (for details, see section 2.2), and
(ii) is aimed at students in early physics education (e.g. pre- or lower secondary school levels).

The design of our teaching-learning sequence was motivated by prior research of the Physics Education Research Group in Udine [17–22] and a pilot study was conducted in Győr, Hungary. It spans three school lessons and is built upon experiment-based materials and activities (for details, see section 3). We evaluated of the teaching concept in the field and investigated how students relate to the concept of polarisation in this new context (cf sections 4–7).

2. Research background

2.1. Physics education research on light polarisation

Physics education research has brought forth a substantial amount of articles focused on student learning about the wave model of light, including the phenomena that can be explained using this model [23, 31–54]: For example, it has been shown that many students lack an elaborate mental model of light, tending to form hybrid models that amalgamate diverse concepts. In particular, numerous (mis-)conceptions of light polarisation apparent among learners have been identified in prior research [23, 31–36]. Some examples are summarised here:

(a) Students often mix up the orientation of electric field oscillation and the direction of propagation. A prevailing misconception arises wherein unpolarised

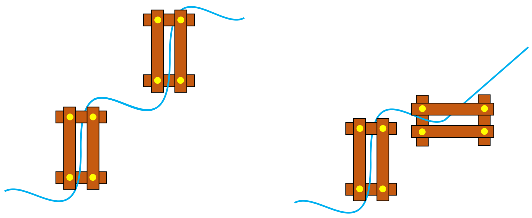

Figure 1. A typical mechanical-analogy-based explanation of the polarisation of light: The oscillating rope and the slits correspond to the light and the polarisers, respectively.

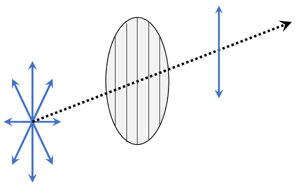

Figure 2. A popular way to present polarisation, for similar figures see e.g. [24–27].

light is erroneously perceived to propagate uniformly in all directions, while polarised light is thought to propagate exclusively in one direction [23, 35]. This misconception is strongly connected to figure 2.

(b) Polarisation is frequently conceptualised as the oscillation of light. Students often visualise light as consisting light rays akin to the undulating motion of a waving rope [23], as depicted in figure 1.

(c) Students often imagine polarisers as slits or gratings where the slits correspond to the transmission axis of the polariser, just like shown in figure 1. These students find it difficult to reconcile the diffraction of light on a grating with the phenomenon of polarisation [23, 31, 32, 34, 35].

(d) Frequently, students hold the misconception that polarisers have no impact on light, perceiving them merely as filters that diminish light intensity [23, 32, 35, 36]. This misconception further associates polarisation solely with the reduction in light intensity.

(e) Polarisation is often misconceived as an ensemble of light beams, with students erroneously likening polarisers to optical lenses or attempting to interpret the phenomenon through the frameworks of refraction or reflection in a geometric optics context [23, 36].

(f) Polarisation is an effect of losing magnetic or electric field because they are perpendicular to each other, and the polariser must absorb one of them [23, 34–36], just like indicated in figure 1 where the perpendicular oscillations are always absorbed.

(g) Similarly, students often misunderstand polarisation as the direction in which photons oscillate. In this conception, students imagine that photons oscillate perpendicular to the direction of propagation [23].

Previous research has argued that understanding polarisation would require a well-developed knowledge of electromagnetic waves [23, 34]. While we agree with this view, we believe that an intuitive view of light polarisation can already be achieved through low-cost experiments that are qualitatively interpreted as part of a phenomenological approach to optics.

2.2. *Brief overview of a phenomenological approach to introductory optics: the Udine and Erlangen teaching-learning sequence*

The traditional way of teaching optics is based on abstract models of light (ray, wave or quantum model). However, the model character does often not become obvious to the students [31, 43–48] leading to conceptual mix ups of different ideas in the sense of hybrid mental model as described in section 2.1. The essence of phenomenological educational pathways in optics, such as the Udine [17–22] or Erlangen [28–30] teaching-learning sequences, is that phenomena serve as both, starting point and centre of learning [55–61].

In terms of content, the Erlangen teaching-learning sequence [28–30] begins with the topics of vision and brightness, which form the basis of optical studies. Students observe the phenomena with their own eyes and, consequently, realise that vision is an integral part of optical phenomena. Hence, throughout the teaching-learning sequence, the sender-emission-receiver concept plays a central role (see figure 3 and [28–30, 62]): light is emitted in all directions by an emitting sender, then some light might reach a re-emitting

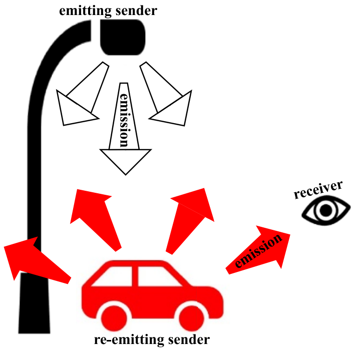

Figure 3. Sender-emission-receiver concept: the light is emitted by a sender (e.g. a lamp). This light is re-emitted by a re-emitting sender (e.g. a red car), from which a part of the scattered/reflected light arrives at the receiver (e.g. a human's eye).

sender, and as a result of scattering and/or reflection, light arrives at the receiver, e.g. our eye. In the course of the Erlangen teaching-learning sequence [28–30], students carry out experiments with self-made optical components such as (liquid) prisms and lenses. All concepts are introduced through the careful investigation of phenomena to uncover the conditions of their appearance. It is essential that light models are almost entirely replaced by the precise observation of images, the optical phenomena themselves. For details of the Erlangen teaching-learning sequence for introductory optics, we refer the reader to [28].

The Udine vertical proposal [17–22] aims all grade of students, where students gradually gain three ways of looking at phenomena: image perspective, light pathway, interpretation process based on the nature of light. The rationale of the Udine phenomenological approach is very similar to that of Erlangen. For details of the Udine proposal for introductory optics, we refer the reader to the website [22] including a collection of teaching-learning materials. The Physics Education Research Group of Udine has also developed extended material on polarisation (we propose the book [17] as the main reference), aimed at higher grade students.

Empirical research has shown that students participating in the Erlangen teaching-learning sequence in introductory optics lessons outperform peers who received traditional (i.e. model-based) optics instruction with regards to conceptual understanding of topics such as vision or image formation [29, 30]. Based on these favourable outcomes, we proceeded to incorporate the Udine teaching-learning proposal on light polarisation [17–22] into the Erlangen teaching-learning sequence [28–30] through additional lessons. A noteworthy innovation in this endeavour is the potential to make polarisation comprehensible to learners without the need for extensive effort in constructing an abstract wave model. Hence, the topic of polarisation will be available for all grade of students because the amount of prior knowledge required is greatly reduced.

3. Integrating polarisation into phenomenological approach to optics: a new teaching-learning sequence

By participating in the Erlangen teaching-learning sequence [28–30], students become familiar with the main topics of introductory optics (such as the sender-emission-receiver concept, brightness, light propagation, etc). This enabled us to expand the Erlangen teaching-learning sequence by adding the topic of light polarisation using teaching material adapted from prior work in Udine [17–22], in which the microscopic interpretation of polarisers and the wave model of light are entirely skipped, while the performed experiments and conclusions form the centre of the learning path. The additional teaching-learning sequence on polarisation consists of two parts: The first part comprises two experiment-based lessons (of 45 min each) on the basics of light polarisation, while the second part consists of an additional lesson in which students use light polarisation to explain interesting applications and phenomena. A detailed description of the three lessons is given in the following subsections and an overview of the whole syllabus is given in table 1.

Students are guided through the experiments via prepared worksheets that can be accessed by interested teachers online at [63]. These tutorials are created in a student-centred learning environment, where the role of the teacher is to guide the students. Throughout the educational path described here, the experiments are suggested to be conducted in small student groups (e.g. 2–5 students/group). For these experiments, the only materials required are three linear polarisers (cutted into rectangles, where the longer sides correspond their permitted polarisation direction) and two light filters (light filters are dense materials that only reduce the brightness of light).

3.1. Lesson 1: introduction

The first lesson contains basic experiments in five tasks following the 'worksheet 1' (available at [63]). At the beginning students investigate the change in brightness of light when polarisers are rotated in different situations (the qualitative discovery of the Malus law), for instance, a typical experiment can be seen on the right-hand side of figure 4. An important task is to compare of the behaviour of polarisers and light filters. Finally, after several experiments, students are guided to create an interpretative model of the results. At this point we introduce the *polarisation property* as a very new property of light. The polarisation property is considered to be an internal property of light that is barely perceptible to the human eye [65]. In order to perceive, students need to use a polariser, which is referred to as an *analyser*: a polariser is called an analyser when it is used to determine the polarisation of light. Based on experimental observations, the teacher and students collectively conclude that if the brightness of the light changes while an analyser is rotating, then the light must be polarised. Students also learn that when polarised light is produced using a polariser, the polarisation property corresponds to the direction of polariser, termed as the *polarisation direction*. The polarisation direction of light can always be determined by an analyser, when the light passes through it with maximum brightness; the direction of the analyser aligns with the polarisation direction of light. An exemplary visual representation of polarisation, as utilised in our teaching-learning sequence, is provided in figure 4.

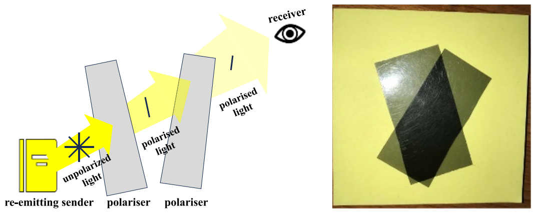

Figure 4. A schematic representation of light polarisation (left) and its experimental implementation (right): the polarisation direction is indicated by a segment inside the yellow arrow representing the light. The yellow sheet of paper is a light emitter, and that light is unpolarised. The unpolarised light can pass through a polariser with arbitrary direction, so this property is indicated by lines in all directions inside the arrow. Light passing through a polariser then becomes polarised, while its brightness is reduced. The second polariser also changes the polarisation direction of light, while its brightness is reduced again.

3.2. Lesson 2: practice the concept of polarisation

In this lesson, a further worksheet ('worksheet 2') [63] guides the learners through five selected experiments. Its purpose is twofold: to give students practice in determining the polarisation direction of light using an analyser; and to tackle a widespread misconception, introduced in section 2.1 (*d*), that it is common to confuse brightness with polarisation and to identify polarisers with light filters. In order to give a better insight into the learning path, we highlight two key experiments.

The first one corresponds to the experimental setup in figure 4: *"Two polarisers are put on the exercise book (which is a re-emitting sender) in the same plane. One of them is slightly rotated relative to the position where the brightness of the transmitted light is at its maximum. An analyser is used to examine the polarisation of the light passing through the polarisers into our eyes. Before doing the experiment, guess which of the polarisers on the exercise book will give the polarisation direction of the light exiting the system.* Students like to believe incorrectly that, polarisation of the light is determined by the relative position of the two polarisers. This confusion between the concept of polarisation and brightness (just

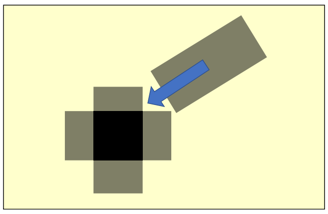

Figure 5. An experiment from lesson 2. What would happen if a third polariser were placed between the two perpendicular polarisers?.

like in misconception *d)* of section 2.1) is perhaps due to the believe of students that polarisation can be inferred from the change in brightness. This exercise helps to lead the fact that polarisation direction is a separate property of light in addition to the brightness.

The second key experiment is based on the experimental task sketched in figure 5. There are two perpendicular polarisers in the same plane. It is observed that no light passes through this system. Before carrying out the experiment, the question is posed as to what would happen if a third polariser were placed between the two pre-positioned polarisers, as shown in the picture (figure 5)? In our experience, students tend to forget that the inserted polariser can change the polarisation of light, and therefore light can pass through the system (misconception (*d*) of section 2.1).

3.3. *Lesson 3: applications*

In this lesson students are introduced to some applications and biological curiosities related to polarisation as shown in table 1. The first experiment is a demonstration of the Brewster angle. The teacher shines a lamp on a tub of water and the students individually observe the surface of the water through an analyser. The distance between the students and the tub is preset, the surface of the water can be seen close to the Brewster angle ($\sim$53° relative to the vertical). When the students rotate their own analysers in front of their eyes, the brightness of the reflected light changes, sometimes it is almost completely absorbed. Full absorption only occurs when the direction of the analyser is vertical, hence the reflected light is horizontally polarised, however, the lamp emits unpolarised light. The Brewster angle is followed by a presentation on polarised sunglasses, which can be used to filter out distracting reflected light when driving or fishing. Photographs taken using linearly polarising filters to filter out reflections will also be shown.

The lesson continues with biological curiosities [1–14] extended with fascinating videos and photos adapted from [1–14]. In 2016, Hungarian scientists received the prestigious Ig Nobel prize for physics for the funniest research of the year. Their awarded publication was entitled *'discovering why white-haired horses are the most horsefly-proof horses, and for discovering why dragonflies are fatally attracted to black tombstones'* [64]. In this research [3, 8] they tried to find out why certain surfaces attract aquatic insects. It was revealed that the key to the solution lies in the polarisation pattern of the reflected light, which is barely perceptible to the human eye, but visible to various polarotactic aquatic insects. These insects search their aquatic habitats by following horizontally polarised light sources. Humanity have modified their optical environment, so animals are receiving more and more false and often deadly signals. Light reflections from artificial surfaces, such as solar panels [5], asphalt roads [7], windows, cars [9], basically all shiny objects, represent ecological traps for billions of polarotactic aquatic animals on a daily basis, because they reflect light similarly polarised as water surfaces. This is how a seemingly harmless tombstone becomes a weapon of mass destruction and a graveyard for thousands of insects. The connection of polarised light and vision of insects is an interesting discipline [1]. In this lesson an evolutionary advantage of stripes of zebras is also shown: bloodsuckers also follow (reflected) polarised light to find their prey, but due to its stripes a zebra attracts much less biting horseflies than a shiny black horse [2]. This gift from nature can be put to practical use, with small white lines painted on the solar panels to help keep them clean by saving many insects [5].

Table 1. The teaching-learning syllabus of light polarisation.

Lesson	Topics	Details	Material and work forms	Learning goal
#1	The introduction of polarisation direction of light.	In order to learn qualitatively about the Malus law, students carry out five experimental exercises. Students create an interpretative model to explain what they have experienced with polarisers. The teacher introduces the concepts of polarisation property, polarisation direction and analyser.	Students work in small groups (2–5 person each). Each group has at least three polarisers and two light filters. 'Worksheet 1' [63] is used.	Students recognise a new phenomenon, light polarisation.
#2	Distinction of brightness and polarisation.	Students carry out five experimental exercises to interpret the phenomena (e.g. see figure 5). Students try to interpret basic experiments with the new concept of polarisation.	Students work in small groups (2–5 person each). Each group has at least three polarisers and two light filters. 'Worksheet 2' [63] is used.	The students use the concept of polarisation direction to explain the change in brightness.
#3	The Brewster angle. Sunglasses and polariser filters on cameras. Polarised light pollution. Zebras and solar panels: the advantage of strippes.	Demonstration of the Brewster angle. The teacher shines a lamp on a tub of water while the students watch the surface of the water through an analyser. Then students recognise polarising sunglasses and linearly polarising filters on cameras. The lesson ends with a presentation on polarised light pollution, zebra stripes and solar panels based on the literature [1–14, 64].	A lamp and a tub of water are used to demonstrate the Brewster angle. Each student has a piece of analyser. The distance is preset so that the students can see the surface of the water close to the Brewster angle. The teacher gives a presentation about interesting biological phenomena related to polarisation.	Students recognise that nature is full of patterns of polarisation and some technological applications are also shown.

4. Research question

Light polarisation has shown to pose striking obstacles to students, therefore, as a first attempt, we aimed at an exploration of the views of polarisation apparent among students who participated in the teaching-learning sequence described in this article. Hence, we posed the following research question: *what views about light polarisation can be found among students who are introduced to light polarisation following our teaching-learning sequence?*

5. Methods

5.1. Study design and sample

In order to contribute to the clarification of our research question, we conducted a pilot study to evaluate our teaching-learning sequence. This evaluation study was carried out in the field, involving three different classes from a high school in Győr. The students participated in the teaching-learning path described in this article during their regular physics lessons. The final total sample was $N = 110$ lower secondary school students (aged 12–14).

5.2. Data collection

To survey students' thinking about polarisation after instruction, an open-ended question was asked: *'How would you describe the meaning of "light polarisation" or what do you think "light polarisation" is? Write full sentences.'* Student responses were collected in paper-and-pencil format. We refrained from collecting the responses prior to the intervention since the study participants had not received any instruction on light polarisation before.

5.3. Data analysis

All student responses were analysed using qualitative content analysis according to [66]. Categories were formed inductively based on the data and are presented in table 2 along with coding rules and anchor examples. Equitable treatment was afforded to all categories throughout the coding process: Instances of the identical category recurring within a participant's transcript were excluded from coding, given their lack of contribution to new insights into the participant's views as has been argued in earlier physics education research on students' mental models (e.g. see [67, 68]). Frequency analysis was used to quantify the occurrence of each individual category.

6. Findings: students' views of light polarisation

The coding rules, anchor examples and occurrence frequencies can be seen in table 2. The website [63] provides all student responses in the original Hungarian version via the document 'Categorisation', while we provide translated student quotations in this article.

Categories C3 and C4 together are included in the misconception (*e*) in section 2.1, and category C5 corresponds to the misconception (*d*). Category C6 often appears as an accompaniment to other categories (C5, C7, C8, C9). The most common case is that students argue in this category together with categories C7 and C8. An example: '*Both light beams and polarisers have properties. If the light beam passes through a polariser with vertical direction, we "know" that it will not be able to pass through a polariser with horizontal direction. We humans cannot see polarisation, which is why we created polarisers, so that we can observe this process. Bugs, unlike us, can see this phenomenon.* (C6 + C8)'

The responses in category C9 often appeared with category C8. None of the responses in this category identified the direction of light with its direction of propagation, so we cannot identify this category with the misconception (*a*) from section 2.1 (confusing the polarisation direction with the direction of propagation). Some of the responses in this category is a very new way of thinking about polarisation and can be considered the appropriate way of expressing polarisation when the direction of light is referred to as the internal property that is barely perceptible to the naked eye. To illustrate this, we refer to an interesting answer: '*Light polarisation is not visible to the naked eye, while the brightness is. Light polarisation means the direction of light and the light deflected because of this. Some animal, such as insects, can see it.*'. In this response, categories

Table 2. Students' ideas about light polarisation. All of the answers can be reached though the website [63].

Answer category	Coding rules	Anchor example	Frequency
(C1) Incomprehensible or no answer.	An answer is assigned to this category if it cannot be understood.	—	24 (21.8%)
(C2) Polarisation is a property of an object (not light).	An answer is included in this category if it assigns the polarisation property to the object instead of the light.	*'Polarised: water/monitor. Unpolarised: brick. It is invisible to humans. There are animals that sense this and lay their eggs in the polarised areas.'*	1 (0.9%)
(C3) Refraction.	An answer is assigned to this category, when a student tries to interpret polarisation with refraction or says that the polariser changes the trajectory of the light. These students often argue that the brightness is reduced due to the polariser's refraction of light which cannot reach our eyes.	*'Diverting the path of light.'*	3 (2.7%)
(C4) Reflection.	This category is very similar to the previous one except that refraction is replaced by reflection. These students often argue that the brightness is reduced due to the polariser's partial reflection of light.	*'It absorbs light, no light is reflected/less light is reflected.'*	3 (2.7%)
(C5) Confusion with brightness/polarisers identified as light filters.	An answer is assigned to this category, when a student identified the concept of brightness with the concept polarisation or polarisers with light filters, just like in the misconception (*d*) in section 2.1.	*'A polariser filter is a filter that can filter light.'*	21 (19.1%)
(C6) Phenomenological description.	When a student tries to illustrate ideas through experimental examples, instead of describing the concept of polarisation, the answer is assigned to this category.	*'The light, which is passed through a polariser, becomes polarised, which means that if it falls on another polariser which is perpendicular to the first one, the light is absorbed. If the second polariser is not perfectly perpendicular, the brightness is reduced, and the second polariser determines the polarisation of the light.'*	19 (17.3%)
(C7) A property of light.	An answer is assigned to this category, when a student only says that this is a new property of light which is different from the previously learned ones, without mentioning that the new property cannot be seen by naked eye.	*'Light polarisation means that light has a special polarisation property, so it can be absorbed by polarisers.'*	17 (15.5%)

(Continued.)

Table 2. (Continued.)

Answer category	Coding rules	Anchor example	Frequency
(C8) An intrinsic property of light that cannot be seen by naked eye.	It is very similar to the category (C7) extended by that our naked eye cannot perceive the polarisation of light and often said that we have to use an analyser to detect it. Such responses are generally correct and consistent with our approach (see section 3.2).)	*'It is an internal property of light, invisible to us, which determines the direction in which the light can pass through a polariser.'*	32 (29.1%)
(C9) The direction of light.	An answer is included in this category, when a student says that polarisation is the direction of light, without identifying what does this direction mean.	*'That the polariser does not refract but absorbs most of the light and changes the direction of the light.'*	7 (6.4%)

C3, C8 and C9 appeared, and the only mistake is the idea that the light is deflected and not absorbed due to its polarisation direction.

7. Discussion

Various misconceptions documented in the literature (bullet-points (*a*), (*b*), (*c*), (*f*) and (*g*) from section 2.1) did not appear at all. The categories C3 and C4 (which correspond to the misconception (*e*) from section 2.1) appeared very rarely. These are perhaps because students do not struggle with any abstract idea of light (light ray, electromagnetic wave and quantum model) within the model-free phenomenological approach. An exception arises in the confusion between brightness and polarisation and between light filters and polarisers (category C5 or misconception (*d*) from section 2.1), because a light filter is very similar to a polariser at the first sight.

Category C6 indicates that students try to explain light polarisation by describing experiments which is an obvious solution in a phenomenological approach. High frequencies of responses in categories C6 and C8 indicate a developed view of polarisation that is in accordance with the representation provided in the teaching-learning sequence. This positive outcome may stem from the structured educational path developed in Udine [17–22], involving students actively in the learning process [69].

Another interesting finding is the emergence of new types of arguments (C7–C9), suggesting that the presented teaching-learning sequence has an impact on students' understanding. In category C9, students argue about polarisation as the direction of light without linking this direction with the direction of propagation making category C9 different from (*a*) from section 2.1. The responses of C9 are quite well-formed and can be accepted as a way of thinking about polarisation. This type of argument has also been appeared in a previous study about quantum mechanics, where the polarisation state of photons was identified with the direction of photons [70].

The results are promising, suggesting that the misconceptions in section 2.1 may largely result from several presumable reasons that could be investigated in the future. For instance, hybrid light models are stemmed from abstract representations. We believe that light polarisation requires a well-thought-out learning path with an appropriate amount of time, the phenomenon is difficult to understand if it is kept in a peripheral position only containing a short demonstration and explanation. Our proposed alternative might assist students in refining their interpretive frameworks, enabling them to focus on a more accurate interpretation of the light polarisation.

This study has several limitations: More empirical data is required because we only asked one question with a free-text. The learning difficulties and misconceptions have to be investigated, and a comparison with traditional approaches is required.

8. Conclusion

In this paper we presented a new educational proposal on introducing light polarisation via the phenomenological approach in introductory optics classes. The first results are encouraging. We categorised the students' thinking about polarisation, and some previously revealed misconceptions appeared rarely or not even at all. An exception is the confusion between polarisers and light filters and between polarisation direction and light intensity. A further result is that new ideas have emerged, which has not been revealed in the literature before.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://fiztan.phd.elte.hu/letolt/polarizacio/index.html.

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Ethical statement

The study was conducted in accordance with IOP Publishing's Ethical policy. Authors acknowledge that the research was conducted anonymously, that consent was obtained from all participants, and that all participants are informed about the publication of the results of this study.

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