Students' ideas about prismatic images: teaching experiments for an image-based approach

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ABSTRACT

Prismatic refraction is a classic topic in science education. To investigate how undergraduate students think about prismatic dispersion, and to see how they change their thinking when observing dispersed images, five teaching experiments were done and analysed according to the Model of Educational Reconstruction. For projection through a prism, the students used a 'split image projection' conceptualisation. For the view through a prism, this conceptualisation was not fruitful. Based on the observed images, six of seven students changed to a 'diverted image projection' conceptualisation. From a comparison between students' and scientists' ideas, teaching implications are derived for an image-based approach.

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Introduction

Prismatic refraction and dispersion are among the classic topics in science courses. Exploring these topics allows students to understand the formation of a rainbow, to explain colour fringes in lens images, and to handle a spectroscope in astronomy, biology, and chemistry. Along the way, students get to discover the beautiful geometry of colour.

To guide students to the scientists' ideas, teachers need to base their lessons on the students' ideas. Fortunately, there have been many studies on student understanding of prisms (see Appendix 1, Table A1). In the following, we will summarise the main findings of these studies.

When a white slit image is projected through a prism, young learners often think that the prism adds colours (Fehringer, 2013). However, they readily accept that a prism separates white light into its diversely coloured components (Fehringer, 2013). Yet even undergraduate students have difficulty understanding the function of a prism. Even after instruction, only a few of them know that a slit spectrum will change into a normal slit image once the prism is taken out of a spectrograph (Ivanjek, 2012). Students' ray drawings are often based on superficial learning, without an understanding of the physical principles (Mestre, Ross, Brookes, Smith, & Nokes, 2009; Palacios, Cazorla, & Madrid, 1989; Singh & Butler, 1990; Vitharana, 2015). Many students treat refraction and dispersion as separate processes (Singh & Butler, 1990).

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Prismatic inspection, in which an object is viewed through a prism, is especially hard for students to understand. Before instruction, students tend to use a 'holistic image' conceptualisation, whereby the image goes as a whole from the object through the prism to the viewer (Galili, 1996; Galili, Bendall, & Goldberg, 1993; Galili & Hazan, 2000). In their optics lessons, students learn an analytical, 'point-to-point light flux mapping' conceptualisation, whereby bundles of light from each object point are refracted by the prism, apparently coming from a virtual image point. After instruction, students tend to use a hybrid, the so-called 'image projection' conceptualisation, whereby each image point is carried along a single ray from the object point through the prism to the viewer. Typically, students use a mechanistic ray concept, misinterpreting the geometric rays as corporeal entities (Galili, 1996; Galili et al., 1993; Galili & Hazan, 2000).

However, teachers need to realise that their teaching approach might promote such misconceptions: in lessons on prisms, students and teachers typically take rays for granted, unaware of the origin and meaning of the ray model. Visualising rays with narrow light bundles, teachers only contribute to the confusion between model and phenomenon. In a side view of light bundles, students cannot get a direct view of images, see Hahn (2016), Mendoza (2016), or Saeed (2013). It is no wonder, then, why students struggle relating images to rays: such a ray-based approach does not start from the students' holistic viewpoint, but from the scientists' analytic viewpoint.

To guide students from their own viewpoint to the scientists' viewpoint, an image-based approach has recently been proposed (Grusche, 2015a, 2015b, 2016a). In this approach, the observed images form the basis for understanding the ray geometry. First, the students explore how the images change as the setup is varied. This way, they come to understand the imaging process as a progression from an original image to a final image. Afterwards, they use rays as geometric lines that connect images with one another, or with the viewer's eye. Several advantages can be anticipated for such an image-based approach: students understand the imaging process by thinking of whole images; they distinguish between phenomenon and model by seeing images and no light bundles; and they understand the origin and meaning of the ray model by experiencing the modelling process. This image-based approach has been developed with and for high school students, as well as undergraduate students.

Still, the image-based approach needs to be fine-tuned to the students' specific ways of thinking. In previous studies, student understanding of prismatic projection has been investigated only with regard to ray diagrams or abstract slit images (see Appendix 1). Student understanding of prismatic inspection has been investigated only in cases where dispersion is negligible (Galili et al., 1993; Galili & Hazan, 2000). For an image-based approach, we wanted to find out how students think about the dispersion of concrete images.

Recently, we have investigated German 7th graders' ideas (Grusche, 2016b). The teacher had just introduced the students to rays; so we already found an 'image projection' conceptualisation. Regarding prismatic projection, these 7th graders thought that streams or particles of light carry the image to the screen, or 'paint' the image on the screen. During prismatic inspection, they thought that rays carry the whole image to the eye, that rays from the eye reach the object, or that rays from the eye reach the image. Initially, many students thought that the dispersed image was produced by the prism adding colours to the sharp or blurred image. By projecting or looking through colour filters, they came to understand the dispersed image as a superposition of diversely coloured images. Many students initially thought that the dispersed image was caused by light being reflected. Covering various sides of the prism helped students understand that light was being refracted.

For the present study, we turned to German undergraduate students of physics education. Unlike 7th graders, undergraduate students have already learned much about light rays. Still, they are known to think in terms of whole images (Galili, 1996; Galili et al., 1993; Galili & Hazan, 2000). Thus, we had the two-fold goal of finding out (1) how German undergraduate students of physics education initially think about prismatic dispersion, and (2) how they change their initial thinking based on the images they observe in prism experiments.

Theoretical framework and research questions

The Model of Educational Reconstruction

To reach a scientific understanding, students typically need to reconstruct their ideas. To promote that conceptual change, teachers need to reconstruct the scientists' ideas for the students (Duit & Treagust, 2003). The *Model of Educational Reconstruction* provides a theoretical framework for education researchers to relate the scientists' ideas to the students' ideas; the purpose is to design principles, guidelines, and tools for teachers (Duit, Gropengießer, Kattmann, Komorek, & Parchmann, 2012; Kattmann, Duit, Gropengießer, & Komorek, 1996).

The model represents three interdependent and recursive tasks for education researchers: (1) analysing scientists' ideas based on historical and current sources, such as articles in scientific journals and books, (2) analysing students' ideas (and perhaps affective or contextual factors) in empirical studies, and (3) synthesising the students' and scientists' ideas in the design of instruction (Duit et al., 2012). For the first task, we have analysed works on spectroscopy by Newton (1979), Lunazzi (1990), and Bershady (2010), to name just a few. For the second task, we have reviewed national and international studies on student understanding of prisms from the past three decades and performed teaching experiments with 7th graders (see introduction) as well as undergraduate students (for this study). For the third task, we have been designing, testing, and refining an image-based approach to spectroscopy (Grusche, 2015a, 2015b, 2016a), trying to synthesise the students' and scientists' ideas.

For the synthesis to be possible, the ideas of students and scientists need to be analysed and compared at corresponding levels of complexity. From low to high complexity, ideas are categorised as a concept, conception, or conceptualisation (Gropengießer, 2007):

A *concept* (German: 'Begriff') is an elementary idea; it is a thought process that refers to an item or event (such as a ray, or dispersion); it can be represented by a word.

A *conception* (in the narrower sense of 'notion'; German: 'Konzept') is a network of concepts; it is a thought process that refers to an actual situation (such as a spectrum on a projection screen, or a ray diagram); it can be stated in an assertion, cf. Kattmann et al. (1996), and Lewis and Kattmann (2004).

A *conceptualisation* (German: 'Denkfigur') is a thinking pattern; it is a thought process that refers to an aspect of reality (such as the imaging process in spectroscopy); it can be summarised in a principle, cf. Kattmann et al. (1996) and Lewis and Kattmann (2004).

Research questions

In line with our research goal, and within the theoretical framework of the Model of Educational Reconstruction, we posed three research questions:

- Research question 1: Which ray concepts do the students use (without specific intervention)?
- Research question 2: Which conceptions do the students use to relate images to one another, or to rays (before, during, or after image-based prism experiments)?
- Research question 3: Which conceptualisations do the students use to understand prismatically dispersed images (before, during, or after image-based prism experiments)?

Thus, we focused on conceptual aspects, paying only some attention to affective and contextual variables during data analysis.

Methods

Teaching experiment methodology

To get to know students' initial ideas, and to see how these ideas change in response to teaching actions, we applied the *teaching experiment methodology* (Steffe & Thompson, 2000). In a teaching experiment, the researcher acts both as an interviewer and as a teacher. Thus, the researcher can learn about students' ideas, and adapt the teaching during and after a session. Conversely, the subjects act both as interviewees and as students. This way, they have a chance to express their initial ideas, and to adapt them towards scientific ideas. Teaching experiments are meant to build a bridge between the research into students' ideas and the design of teaching guidelines (Steffe & Thompson, 2000).

Being exploratory, a teaching experiment serves to generate hypotheses about students' ideas. Accordingly, the researcher uses 'responsive and intuitive interactions' to 'become the students and attempt to think as they do' (Steffe & Thompson, 2000, p. 278). However, 'one does not embark on the intensive work of a teaching experiment without having major research hypotheses to test' (Steffe & Thompson, 2000, p. 275). Thus, the researcher also uses 'analytic interaction' to test a hypothesis about a student's thinking (Steffe & Thompson, 2000, pp. 280–281).

In line with our research questions, we had five major hypotheses to test:

- Hypothesis 1: The students will use a mechanistic ray concept, mixed with the concept of light waves.
- Hypothesis 2.1: The students will translate the conception of ray dispersion into the conception of mutually shifted images. After all, they probably know from school and media (such as the iconic cover for Pink Floyd's 'The dark side of the moon') that a prism splits up a white ray into differently coloured rays. Accordingly, they may conclude that a white image is split up into differently coloured images.
- Hypothesis 2.2: Students will come to understand a spectrum as the superposition of differently coloured images. After all, students are known to think in terms of whole images. This thinking may form a basis for further insights.

- Hypothesis 2.3: For prismatic inspection, the students will not predict that the perspective in the image depends on colour. Even scientists have only recently discovered this: dispersion transforms the actual viewer into a rainbow-coloured series of virtual viewers. This insight has led scientists to new applications (Grusche, 2014; Lunazzi, 1990), and may help students understand that a dispersive prism provides multiple viewing directions at once.
- Hypothesis 3: The students will use the 'image projection' conceptualisation reported by Galili et al. (1993, 1996) and Galili and Hazan (2000).

Five teaching experiments were performed. Three of them were done with one student each (Anna; Ben; Chris), the other two were done with two students each (David with Edgar; Fabian with Gerd). The seven voluntary subjects were undergraduate students of physics education at the University of Education, Weingarten, although one of them had switched to hygiene technology at the Hochschule Albstadt-Sigmaringen.

Two prism experiments were up for discussion: prismatic projection and prismatic inspection. For *prismatic projection*, the researcher projected a greyscale image through a direct-vision prism, see Figure 1(a). Later, the researcher inserted narrow-band colour filters at the prism, see Figure 1(b,c). This teaching action was intended to mediate the idea that a spectrum is a superposition of differently coloured images. For *prismatic inspection*, the students viewed a white toy car in the foreground and a white matchbox with a colourful logo in the background through a direct-vision prism, see Figure 2(a,b). Again, the researcher inserted colour filters at a later stage, see Figure 2(c–e). This teaching action was designed to convey the idea that the viewing direction depends on colour. In each case, the students were asked to *predict, describe, and explain* their observations. Afterwards, the students were asked to indicate the rays for red and blue light.

None of the students had seen these types of prism experiments before. The researcher explained as little as possible. Thus, the students could express and form their own ideas. The researcher adapted to the students' answers, questions, and suggestions. Hence, the sessions differed in the contents covered. In some cases, the experiments were varied, such as viewing a dispersed projection through a prism, or illuminating the objects using a lamp with a discrete spectrum instead of a continuous one. Still, all students

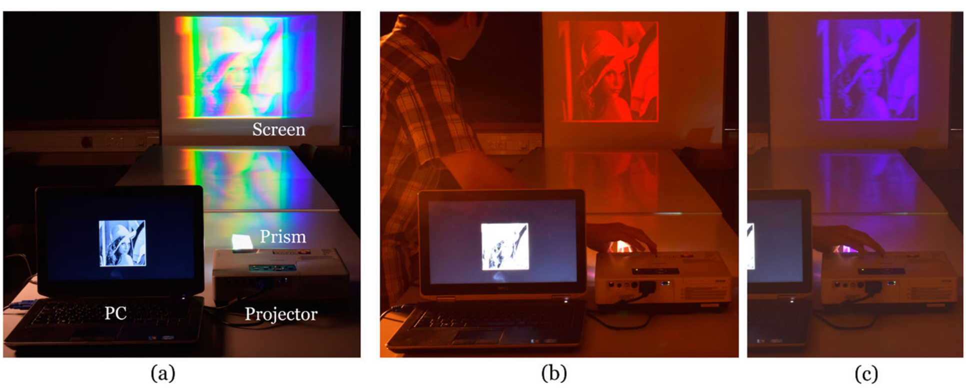

Figure 1. Prismatic projection. (a) Setup, (b) inserting a red filter, and (c) inserting a blue filter.

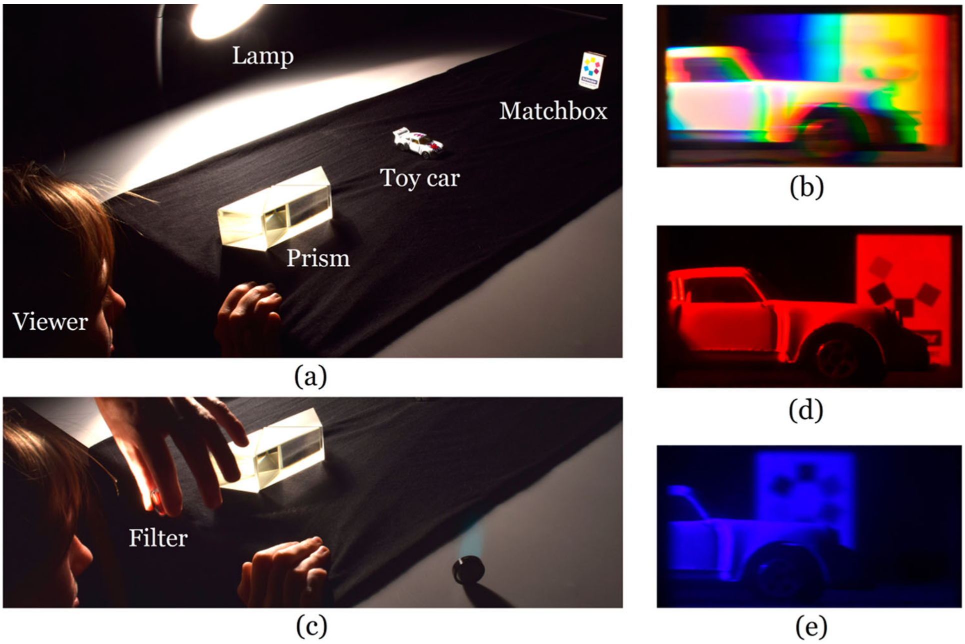

Figure 2. Prismatic inspection. (a) Setup, (b) view through the prism, (c) inserting a colour filter, (d) view through red filter and prism, and (e) view through blue filter and prism.

discussed prismatic inspection. The teaching experiments lasted between 40 and 80 minutes, being videotaped with the students' consent.

Qualitative content analysis

The teaching experiments were evaluated by applying Gropengießer's (2005, 2007) didactics-oriented version of *qualitative content analysis* to the video transcripts, cf. Kattmann et al. (1996), Niebert and Gropengießer (2014), or Riemeier and Gropengießer (2008). The analysis comprised the phases of preparation, interpretation, and generalisation.

The *preparation phase* (Gropengießer, 2007) involved transcribing the video and editing the transcript.

Transcribing included the following three steps:

(1) *Selecting relevant utterances.* For a first reduction of the material, each video was looked at multiple times to find passages in line with the research goal.
(2) *Documenting the words.* For an authentic representation, the spoken words were transcribed without changing the style or grammar.
(3) *Commenting.* As cues for interpretation, verbal acts ('ah,' 'erm,' etc.) were written down, and non-verbal acts (laughing, looking through a prism, etc.) were described in parentheses. For each second of a pause in speech, a dash '–' was used.

Editing included the following four steps:

(1) *Selecting meaningful passages.* For a second reduction of the material, passages in line with the research questions were highlighted in the transcript and copied into a separate file. Chains of argumentation were preserved, and the beginning and end of each section was specified by the line number from the transcript.
(2) *Deleting redundancies and fillers.* The meaningful utterances were freed from clutter by deleting interruptions (the interviewer's 'yeah,' etc.), fillers (such as 'well, I think that'), direct repetitions, and attempts before the intended statement. Meanwhile, variations in word choice were added in parentheses, as in 'rays (light rays).'
(3) *Formulating autonomous student statements.* To isolate a student's individual statements from the dialogue while including the context, the interviewer's questions were reformulated as part of the student's answers.
(4) *Paraphrasing.* To make a student's statements readable and understandable, grammatical errors were corrected, and missing contextual elements were added based on the interviewer's knowledge about the original situation. Still, the student's choice of words, especially in metaphors and analogies, was preserved. In case of doubt, the video material was revisited.

The *interpretation phase* (Gropengießer, 2007) involved summarising, explicating, and structuring each student's edited statements.

Summarising included the following four steps:

(1) *Classifying the statements.* As a basis for systematic interpretation, statements by a given student were grouped according to *topic*. The broad topics were prismatic projection and inspection, and each stage of a prism experiment was treated as a subordinate topic. Moreover, it was helpful to group the statements according to *kind*, distinguishing between a student's 'prediction,' 'reason for the prediction,' 'observation,' and 'explanation of the observed phenomenon,' following the phases of a teaching experiment. Thus, a table was created, using different lines for different topics, and different columns for different kinds of statements.
(2) *Identifying inconsistencies.* To reveal contradictory ideas, each set of statements was checked for internal consistency: mutually consistent statements were gathered in a paragraph and labelled with a brief title, such as 'background shifted more' versus 'foreground shifted more.' In each paragraph, the line numbers from the transcript were documented.
(3) *Condensing equivalent propositions.* For a third reduction of the material, multiple statements with the same meaning were reformulated as a single statement, indicating variations in parentheses. Still, metaphors and analogies were preserved. Examples were generalised (the 'toy car' being a 'foreground object,' etc.). If an example was significant as such, it was preserved along with its generalised version.
(4) *Sequencing.* If necessary, statements within a titled paragraph were rearranged in a more meaningful sequence. However, each chain of argument was preserved.

Explicating included the following four steps:

(1) *Characterising the student's understanding.* To identify the characteristic features of a student's understanding, the summarised statements were interpreted in light of scientists' ideas. For the present study, this was done by rephrasing each titled paragraph in one or two sentences.
(2) *Interpreting word use.* Language can promote or hinder learning, convey ideas, and hint at the origin of those ideas. Thus, analogies and metaphors were interpreted and crucial words were analysed. In particular, a word search for 'ray' and 'image' was done in the transcript, and the associated verbs were analysed, such as 'go,' 'travel,' or 'hit.'
(3) *Tracing sources of ideas.* To understand whether ideas came from everyday life or from school and media, the sources of central ideas were identified based on reasonable speculation, or based on a student's own mention.
(4) *Identifying problems and interests.* With the design of instruction in mind, inconsistencies and difficulties in student thinking were described, and interests mentioned by a given student were listed.

Structuring included the following two steps:

(1) *Distilling the student's ideas.* To allow for a comparison with scientists' ideas, a student's ideas were inferred from the preceding analysis and formulated at distinct levels of complexity, namely as a concept, conception, or conceptualisation. Each idea was briefly described and given a name.
(2) *Marking the status of the ideas.* To indicate the status of each idea, symbols were placed before each description. For the symbols used in the present study, see Appendix 2.

The interpretation of the students' ideas formed the basis for generalisation.

The *generalisation phase* (Gropengießer, 2007) involved finding categories for students' ideas. *Categorising* was done by looking for similarities and differences across students' ideas. Similar ideas from different students were included in a single category; markedly different ideas were assigned to different categories.

For a reconstruction of *learning pathways*, the students' ideas were chronologically arranged and connected to the teaching actions that occasioned them, cf. Riemeier and Gropengießer (2008). For anonymity, all students' names have been changed in this report.

Results

Foreword

Different students used a given idea on different occasions, and the teacher adapted the teaching actions to each student individually. Thus, we can hardly make any blanket statement about which teaching action promoted which idea. Accordingly, we will present the students' ideas *thematically* rather than chronologically. Still, within each theme, we will specify *when* a given idea was used by a particular student. For an overview of the essential findings, see the discussion.

Students' ray concepts

Throughout the teaching experiments, students used various ray concepts, sometimes interchangeably, see Table 1. Three out of seven students used a geometric ray concept, treating a ray as a line that represents the motion of light. Everybody except Chris used mechanistic ray concepts, imagining a ray as a particle or stream of light. However, most students knew that light particles and light streams were only models. Students found many ways to relate their ray concepts to the concept of light waves, see Table 1.

Conceptions relating rays to prismatic projection

When asked to predict what would be seen in prismatic projection, students did so based on their knowledge of ray dispersion: they used the conception 'split to screen,' see Figure 3(a) and Table 2. For example, Anna knew that a white ray would be split up into coloured rays (supposedly due to *diffraction* at the crystal structure of the prism). She concluded that a ray bundle carrying the greyscale image would be split up into ray bundles carrying differently coloured images to the screen. Similarly, Fabian and Gerd predicted that the image would be fanned out into a series of rainbow-coloured images because each white or grey image point would be separated into its spectral colours. Ben predicted that a prism would deflect light, separating white light into its rainbow colours. When he saw the prismatic image, he immediately recognised that 'in each colour, I still have practically one image, one next to another.'

Chris initially thought that a greyscale image would not be dispersed into colours because the greyscale image was colour-free. The researcher gave him a chance to correct that prediction:

I: But didn't you say that white light consists of all colours?

Chris: Oh, yes, right! That would be possible, but they will be at the borders, primarily.

I: Why only at the borders, why not in the middle?

Table 1. Students' ray concepts.

Category	Definition	Wave-related examples	Other examples
(a) Light particle	A point-like part of light that moves through space	(a) A particle of light that travels along a wave-shaped trajectory (Gerd) (b) A particle of light that can create an elementary wave of light when hitting an object (Edgar)	A particle of light that moves through space, illuminating things and making things visible (Fabian)
(b) Light stream	A narrow stream of light	(a) A line-shaped, immaterial, invisible stream of wave-like radiation that can be stopped by an obstacle (Anna) (b) A narrow bundle of light waves (David)	A line of light that illuminates a point on a surface (Ben)
(c) Light trajectory	A line along the motion of light	(a) A path along which light waves travel (Anna) (b) A line representing the direction in which elementary waves travel (Chris)	(a) A line representing the direction in which particles of light travel (Chris) (b) A line along which an image travels through space (Gerd)

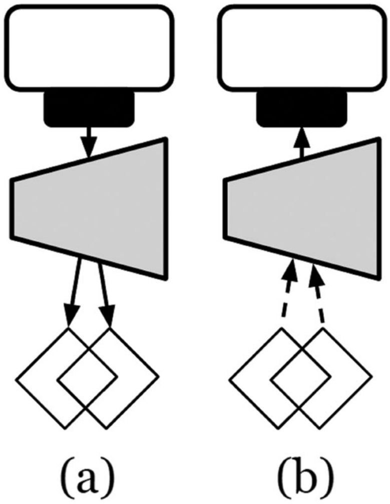

Figure 3. Conceptions relating rays to a projected spectrum. (a) Split to screen and (b) split re-tracing.

> Chris: Because it could cancel in the middle. I mean, especially in a uniform area, the light will not come back together with the same rays, but the result will be the same.
>
> I: Ah, ok. Because it will be mixed there, again, you mean?
>
> Chris: Yes, I mean, […] if you consider red and blue rays only, they would be shifted by a centimetre, yet it will cancel right away. The greatest effect will be at the top and at the bottom because there will be only one colour, there.

When asked to show the rays for red and blue light, Chris traced the rays backwards from the observed spectrum to the projector, as did Ben. They used the conception 'split re-tracing,' see Figure 3(b) and Table 2.

When relating rays to a projected spectrum, students used two different conceptions to relate rays to the projector: Anna, Fabian, and Gerd used the conception 'shower projector,' whereas Ben and Chris used the conception 'pinhole projector,' see Figure 4 and Table 3. Anna switched to the 'pinhole projector' when she explained the blurry lens image as a superposition of pinhole images. Fabian and Gerd switched to the 'pinhole projector' to treat prismatic inspection analogous to prismatic projection, guided by the teacher.

Conceptions relating images in prismatic projection

Even before filters were inserted, all students had realised that a projected spectrum was a rainbow-coloured series of images, using the conception 'image series,' see Figure 5(a) and Table 4.

Table 2. Conceptions relating rays to a projected spectrum.

Category	Definition
(a) Split to screen	With each white ray being split up into rainbow-coloured rays, a greyscale image is separated into a rainbow-coloured series of images.
(b) Split re-tracing	For a given point in the spectrum, the ray can be traced backwards through the prism to the projector.

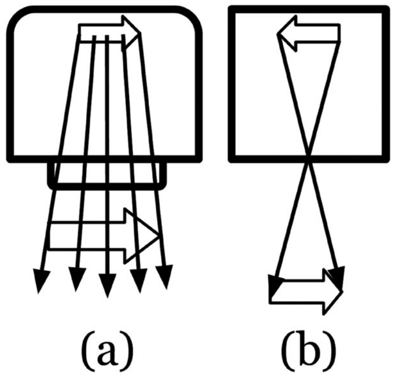

Figure 4. Conceptions relating rays to the image from the projector. (a) Shower projector and (b) pinhole projector.

Table 3. Conceptions relating rays to the image from the projector.

Category	Definition
(a) Shower projector	The rays go through a circular projector aperture, side by side, analogous to water from a shower.
(b) Pinhole projector	The rays intersect at a point-like projector aperture, as in a pinhole camera.

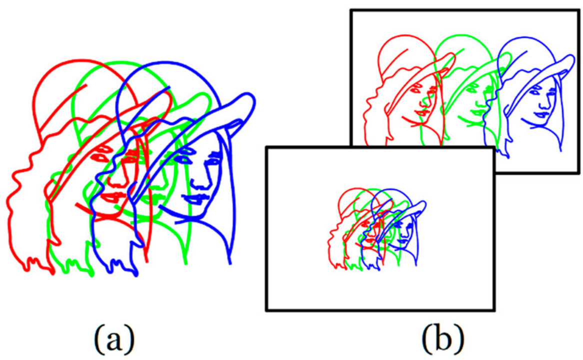

Figure 5. Conceptions relating images in prismatic projection. (a) Image series and (b) distance-dependent displacement.

To predict how the image would change if the screen was moved towards or away from the prism, Chris, Fabian, and Gerd used 'split to screen' to form the conception 'distance-dependent displacement,' see Figure 5(b) and Table 4.

Table 4. Conceptions relating images in prismatic projection.

Category	Definition
(a) Image series	The spectrum is a series of differently coloured images.
(b) Distance-dependent displacement	The larger the distance between prism and screen, the larger the displacement among the images within the spectrum.

Conceptions relating rays to prismatic inspection

When asked to predict what would be seen in prismatic inspection, all students except Ben and Chris used the conception 'split to eye,' see Figure 6(a). For example, Edgar said: 'Those rays that are wandering from the car in the direction of my eye are separated by the prism into the spectral colours.' He concluded: 'The car will be strongly – What do you call that painting style? Expressionism! […] –, […] completely shifted.'

When the students realised that further predictions were difficult, they changed to other conceptions. For an overview of these conceptions, see Figure 6(b–f) and Table 5.

Overall, students followed similar learning pathways, see Figure 7. The students' steps along the learning pathways, and the teaching actions that promoted them, are described in Tables A2–A8, see Appendix 2. Generally, inserting colour filters was crucial. Before that, students used the conceptions 'split to eye,' 'split to object,' or 'split to images.' After colour filtering, they realised that the viewing direction depends on colour. For example, Edgar shouted: 'Ah, parallactic shift!' Thus, all students except David formed some of the more advanced conceptions, namely 'eye to images,' 'views onto object,' and 'di- & converge.'

In many cases, students traced rays from the eye to the prism or from the prism to the object, but they knew that light went the other way around.

When relating rays to a virtual spectrum, students used two different conceptions to relate rays to the eye, see Figure 8 and Table 6. David, Edgar, Fabian, Gerd, and Anna

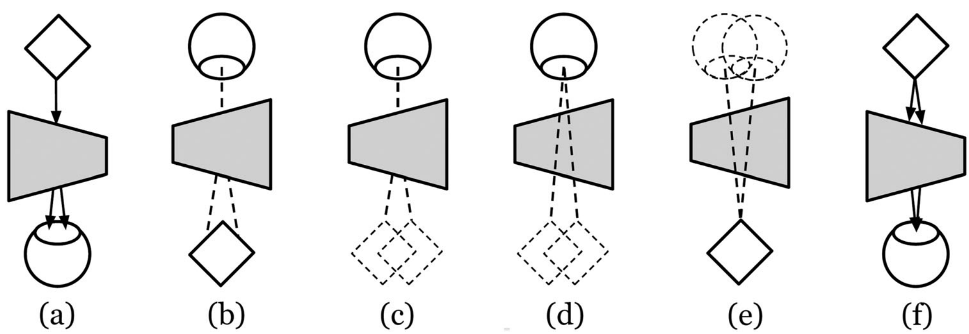

Figure 6. Conceptions relating rays to a virtual spectrum. (a) Split to eye, (b) split to object, (c) split to images, (d) eye to images, (e) views onto object, and (f) di- & converge.

Table 5. Conceptions relating rays to a virtual spectrum.

Category	Definition
(a) Split to eye	A given ray from an object point is separated by the prism towards the eye.
(b) Split to object	A given line of sight is separated by the prism, reaching diverse object points.
(c) Split to images	A given line of sight is separated by the prism, reaching diversely coloured images of a certain object point.
(d) Eye to images	Differently coloured lines of sight go to the images of a given object point along different directions.
(e) Views onto object	Differently coloured lines of sight go to a given object point along different directions.
(f) Di- & converge	Differently coloured rays leave a given object point along diverse directions to be diversely deflected towards the pupil.

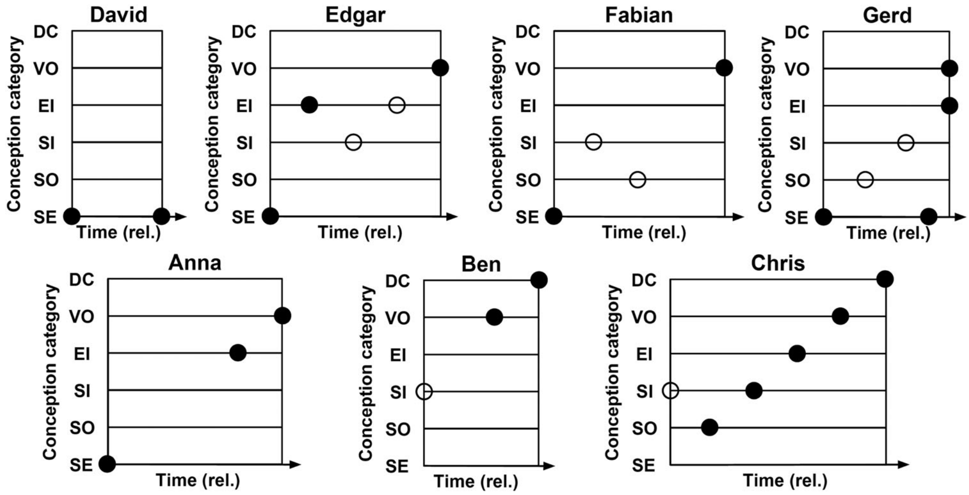

Figure 7. Learning pathways involving rays for a virtual spectrum. SE – split to eye, SO – split to object, SI – split to images, EI – eye to images, VO – views onto object, DC – di- & converge. Black circles represent explicit cases; empty circles represent implicit cases.

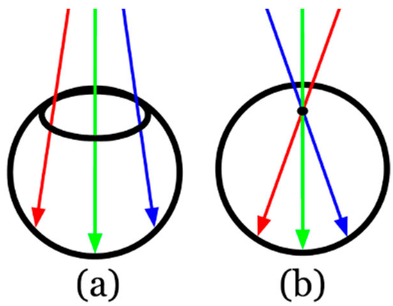

Figure 8. Conceptions relating rays to the spectrum on the retina. (a) Bowl eye and (b) pinhole eye.

Table 6. Conceptions relating rays to the spectrum on the retina.

Category	Definition
(a) Bowl eye	All or some of the component rays go through a circular pupil, side by side, analogous to a spray of water going through the opening of a bowl.
(b) Pinhole eye	The component rays intersect at a point-like pupil, as in a pinhole camera.

used the conception 'bowl eye.' For example, Anna said: 'This is the receiver, instead of the projection screen: my eye.' In contrast, Ben and Chris used the conception 'pinhole eye.' For instance, Ben talked about the 'pupil point.' Fabian and Gerd switched to the 'pinhole eye' in connection with 'split to object' and 'split to images.'

Within the conception 'bowl eye,' there were notable variations. For example, Gerd and Anna imagined entire monochromatic images travelling along the separated rays, ignoring that the eye produces an inverted image. Edgar, instead, remembered that the retinal image is inverted with respect to the virtual image. He drew red and blue rays based on the inverted sequence of colour fringes on the retina, without considering entire monochromatic images.

Conceptions relating images in prismatic inspection

Students used numerous conceptions to relate images in prismatic inspection. For an overview of these conceptions, see Figure 9 and Table 7.

Using the conception 'image series' (Figure 9(a)), all students understood a spectrum as a series of differently coloured images. Four of seven students used this conception to predict the prismatic image. David, Edgar, and Ben formed it afterwards to predict what would be seen through filters.

The conception 'magnification' (Figure 9(a)) was conveyed by David and Edgar before they looked through the prism.

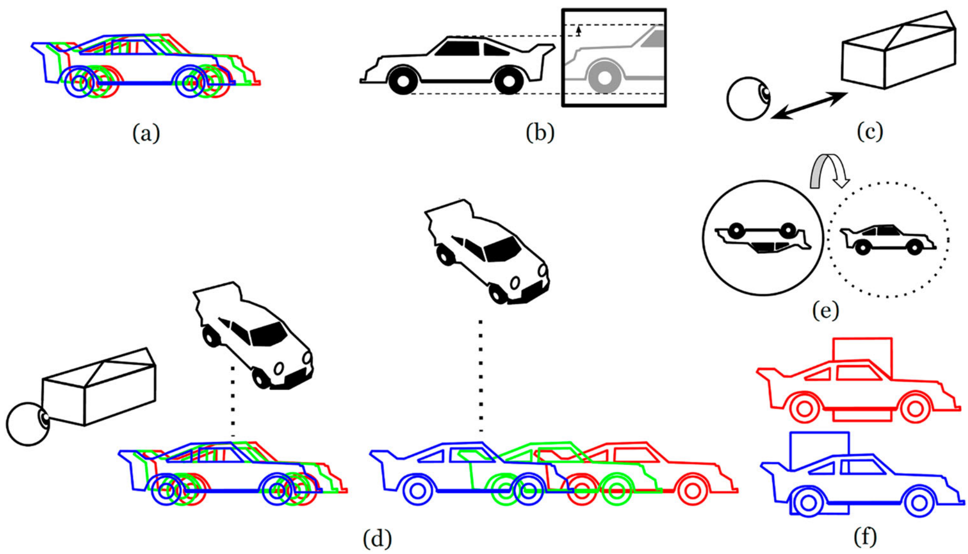

Figure 9. Conceptions relating images in prismatic inspection. (a) Image series and (b) magnification, (c) prism-to-eye distance irrelevant, (d) object-to-prism distance crucial, (e) inverted image and (f) relative shift.

Table 7. Conceptions relating images in prismatic inspection.

Category	Definition
(a) Image series	The spectrum is a series of sharp, differently coloured images.
(b) Magnification	The prism makes the object appear larger or smaller.
(c) Prism-to-eye distance irrelevant	The distance between the prism and eye does not affect how wide the spectrum is (in relation to a given object).
(d) Object-to-prism distance crucial	The further a given object is away from the prism, the wider is the spectrum (in relation to that object).
(e) Inverted image	The brain flips the retinal image.
(f) Relative shift	The lateral offset between the foreground image and background image depends on colour.

The conception 'prism-to-eye distance irrelevant' (Figure 9(a)) was expressed by one student during his predictions: Chris reasoned that looking at the white object through the prism would be equivalent to looking at a coloured object without the prism.

The conception 'object-to-prism distance crucial' (Figure 9(d)) was used by five of seven students. Two of them formed it even before the experiment: Edgar said it was intuitive, Chris talked about visual rays being dispersed across the object.

The conception 'inverted image' (Figure 9(e)) was uttered by David, Edgar, Fabian, and Gerd during their discussion of the imaging process.

The conception 'relative shift' (Figure 9(f)) was expressed by all students while looking through the filters. Gerd and Chris formed this conception even before that, based on the above-mentioned conception 'object-to-prism distance crucial.'

All above-mentioned conceptions are adequate to some degree, see discussion. However, we also found some conceptions that were not in agreement with experimental facts, see Table 8. All of these misconceptions, except 'common shift,' were expressed in the prediction phase. After their observations, the students corrected these misconceptions.

Conceptualisations of prismatic spectrum formation

All students used only one ray to map an object point to its image point, and many students thought of rays as carrying the image. Thus, they used an 'image projection' conceptualisation. For prismatic spectra, we identified two versions: '*split* image projection,' and '*diverted* image projection,' see Figure 10 and Table 9.

'*Split* image projection' was used both for prismatic projection and inspection, giving rise to the above-mentioned conceptions 'split to screen,' 'split re-tracing,' 'split to eye,' 'split to object,' and 'split to images.' '*Diverted* image projection' was developed only for prismatic inspection, emerging from the above-mentioned conceptions 'eye to images,' 'views onto object,' and 'di- and converge.' For the change from 'split image projection' to 'diverted image projection,' looking through the prism with colour filters was crucial.

Table 8. Misconceptions relating images in prismatic inspection.

Category	Definition	Possible source of the misconception
(a) Colour-dependent width	The width of a single-coloured image within the spectrum depends considerably on its colour.	Seeing that the blue end of the prismatic spectrum is considerably longer than the red end.
(b) Common shift	When switching filters, the foreground and background are shifted together, such that the foreground always covers the same part of the background.	Assuming that background and foreground are represented in a unified image. The offset varies only slightly with colour.
(c) Object-to-prism distance irrelevant	The distance between the prism and a given object does not affect how wide the spectrum is (in relation to that object).	Focusing on the constant image displacement on the retina while ignoring the change in image size.
(d) Same colour sequence	The colour sequence is the same in prismatic inspection as in prismatic projection.	Treating the prism and the colour sequence as a unit. Ignoring that the brain inverts what is projected onto the retina.
(e) Prism-to-eye distance crucial	The further the eye is away from the prism, the wider is the spectrum (in relation to a given object).	Treating the object as a projector and the eye as a screen.

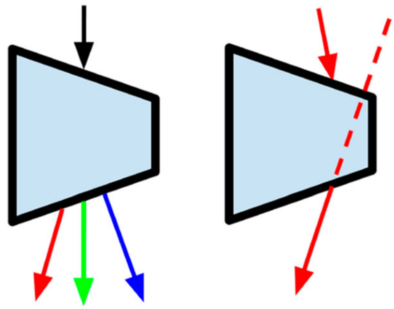

Figure 10. Conceptualisations of prismatic spectrum formation. (a) Split image projection and (b) diverted image projection.

Discussion

Broad answers to the research questions

Overall, the students in our teaching experiments used three ray concepts, thinking of rays as particles of light, streams of light, or paths of light.

Most students started with the conception that a ray is split up towards the screen or eye. During the prism experiments, students confirmed or developed many image-related conceptions. These served as a basis for continually restructuring the ray-related conceptions of prismatic inspection. Although students initially used some false conceptions about prismatic inspection, they corrected these misconceptions based on observation. Moreover, some students treated the projector as a kind of shower and the eye as a kind of bowl. If specifically guided by the teacher, they later modelled the projector and eye in analogy to a pinhole camera.

Initially, students used a 'split image projection' conceptualisation, whereby a white ray is split up into differently coloured rays. This conceptualisation was useful for prismatic projection, but failed during prismatic inspection. Once the students looked through the prism with colour filters, they saw that the viewing direction depends on colour. Thus, all students except one changed to a 'diverted image projection' conceptualisation, whereby a single-coloured ray enters and exits the prism at colour-dependent angles.

Table 9. Conceptualisations of prismatic spectrum formation.

		Affiliated conceptions	
Category	Definition	Prismatic projection	Prismatic inspection
(a) Split image projection	A prism splits a composite ray into its component rays, thus splitting the original image into differently coloured images.	(a) Split to screen (b) Split re-tracing	(a) Split to eye (b) Split to object (c) Split to images
(b) Diverted image projection	A prism diverts each component ray according to colour, such that an object is viewed from a colour-dependent direction, and an image of the object is seen in a colour-dependent direction.	Not found	(a) Eye to images (b) Views onto object (c) Di- & converge

Evaluation of the hypotheses

Hypothesis 1 was largely confirmed: Six of seven students used a mechanistic ray concept, thinking of rays as particles or streams of light. Some students mixed the ray concept with a wave concept, thinking that a particle of light moved like a wave or caused a wave, or that a stream of light comprised waves. Only three out of seven students used a geometric ray concept, thinking of rays as lines that represent the motion of light or images.

Hypothesis 2.1 was largely confirmed: all students knew that a ray of white light would be split up into differently coloured rays. Four out of seven students used that knowledge to predict a series of differently coloured images.

Hypothesis 2.2 was confirmed: before filters were used, all students understood a spectrum as a series of mutually shifted images. They used that conception to predict and explain many phenomena based on images, and to refine their understanding of the ray geometry in prismatic inspection.

Hypothesis 2.3 was mostly confirmed: only three out of seven students predicted a colour-dependent perspective. However, through observation, six of seven students came to understand the virtual spectrum as a superposition of multiple perspectives, forming the conception 'views onto object.'

Hypothesis 3 was confirmed: all students used the 'image projection' conceptualisation reported by Galili et al. (1993, 1996) and Galili and Hazan (2000). For prismatic dispersion, we specified two versions: '*split* image projection' and '*diverted* image projection.' During prismatic inspection, all students except one made a conceptual change from 'split image projection' to 'diverted image projection.'

Validity

To ensure the validity of our findings, we have taken the measures proposed by Gropengießer (2007). For *selection validity*, we have interviewed regular students. For *procedural validity*, we have (1) created a trustworthy atmosphere during the teaching experiments, (2) used multiple ways to probe a student's idea (such as speech, drawings, and experimental activities), so-called *internal methodological triangulation*, (3) proceeded stepwise in our qualitative content analysis (as outlined in the methods section), (4) documented all steps in separate files, (5) supported our interpretations with arguments (as part of explication), and (6) checked the coding for the learning pathways against a colleague's coding. Where the coding differed, we reached consensus through discussion, cf. Niebert and Gropengießer (2014), or Riemeier and Gropengießer (2008). For *correlative validity*, cf. Niebert and Gropengießer (2014), we have checked our interpretations against previous studies on students' ideas and our preliminary analysis of scientists' ideas, see the following section 'Students' ideas from a scientific viewpoint.'

In addition, we have discussed our interpretations of students' conceptions with most of the students themselves: Anna, Chris, Fabian, and Edgar confirmed that their words have been interpreted correctly.

Our sample size was small, as is typical of teaching experiments; cf. Steffe and Thompson (2000, p. 275), who did a study with 6 students, and Riemeier and Gropengießer (2008), who had 15 students. Our sample was large enough to fulfil the criterion of theoretical saturation: displaying *intraindividual variability* and *intersubjective* *uniformity* (Gropengießer, 2007, p. 149), our students used a wide range of conceptions along similar learning pathways. Thus, it is unlikely that further teaching experiments with undergraduate students would yield new categories of conceptions. Still, our results are not definitive, and students' individual ideas will differ considerably within a given conception.

Students' ideas from a scientific viewpoint

It is beyond the scope of this article to look at all students' ideas from a scientist's viewpoint. Still, the reader may be interested in some essentials.

The students' concept 'light trajectory' is the only scientifically adequate ray concept, at least from a modern standpoint. From a historical standpoint, the students' concept 'light particle' is scientifically adequate, as well: it corresponds to Isaac Newton's definition of the light ray (1979, pp. 1–2). When students traced rays from the projected spectrum to the prism, from the eye to the prism, or from the prism to the object, they intuitively applied the optical principle of reversibility (Newton, 1979, p. 5).

The students' conception 'shower projector' is scientifically inadequate. Still, for prismatic projection, it is as fruitful as the scientifically adequate 'pinhole projector.' The 'shower projector' ceases to be applicable only when the ray geometry within the projector becomes relevant, for example when treating the eye as a reverse projector.

At first sight, the 'bowl eye' appears incorrect. However, even from a scientific viewpoint, differently coloured rays do pass through the pupil side by side, and their colour range is indeed limited by the pupil size, see Figure 11(a). Still, these rays are not the only ones relevant for the spectrum on the retina, see Figure 11(b): a full range of

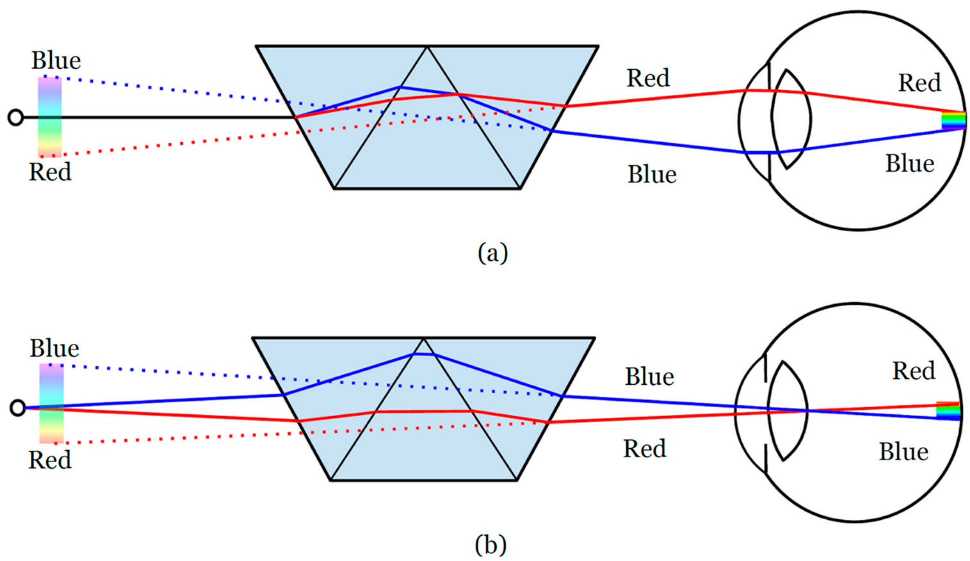

Figure 11. Two scientifically adequate ways of relating rays to a virtual spectrum. The rays between the prism and eye can be extended backwards to the virtual spectrum, as indicated by the dotted lines. (a) A single composite ray is split up by the prism. (b) Multiple component rays diverge from each object point, being diverted by the prism according to colour.

differently coloured rays may always pass through a point at the eye lens, corresponding to the students' conception 'pinhole eye.'

All of the students' conceptions relating rays to a virtual spectrum can be used in a scientifically adequate manner. However, students tend to get some details wrong (see Table 10).

Both versions of the 'image projection' conceptualisation have been used by scientists such as Newton (1979) and Lunazzi (1990). 'Split image projection' seems especially useful for prismatic projection, whereas 'diverted image projection' seems more useful for prismatic inspection. Ultimately, however, the two conceptualisations represent two sides of the same coin, as exemplified in Figure 11. Overall, spectroscopists seem to prefer the 'image projection' conceptualisation over the 'point-to-point light flux mapping' conceptualisation, at least for virtual spectra.

Interestingly, the students' learning pathways run roughly parallel to the sequence of presentation in Newton's lectures (see Figure 12). In his manuscript 'Optica,' Part II (Shapiro, 2010), the order is the following: in lecture 12, he uses 'di- & converge' and 'eye to images' in Figure II, 41 (Shapiro, 2010, p. 550). Then, he uses 'eye to images' in

Table 10. Using conceptions about rays for virtual spectra.

Category	Scientifically adequate use	Students' typical errors
Split to eye	Predicting the virtual spectrum by extending the separated rays backwards, even if only one of the rays goes through the pupil.	Tracing the separated rays forward to obtain the real spectrum on the retina, concluding that the colour range of the virtual spectrum is determined by the pupil size. Treating the object as a projector and the eye as a screen.
Split to object	Predicting the colour-dependent perspectives.	Confusing 'split to object' with 'split to images'.
Split to images	Predicting the effect of distance variations.	Assuming that the colour sequence is the same as in prismatic projection.
Eye to images	Predicting the mutual tilt among the images, or modelling light paths between prism and eye.	Assuming that the images lie on a straight line (instead of an arc around the prism), thus predicting the wrong perspective for each colour.
Views onto object	Predicting the colour-dependent perspectives, or modelling light paths between object and prism.	Assuming that the colour sequence of the virtual eyes is the same as in prismatic projection.
Di- & converge	Combining 'Eye to images' and 'Views onto object'.	Confusing the colours.

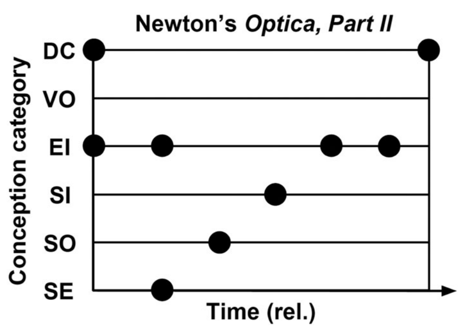

Figure 12. Newton's lecturing involving rays for a virtual spectrum. SE – split to eye, SO – split to object, SI – split to images, EI – eye to images, VO – views onto object, DC – di- & converge.

Figure II, 44 (p. 554), which he explains (p. 555) with 'split to eye.' In Figure II, 47 (p. 557) and the accompanying text (pp. 557–559), he uses 'split to object,' and 'split to images.' In Figure II, 48 (p. 558), he uses 'eye to images.' In lecture 13, he uses 'eye to images' in Figure II, 49 (p. 562). Then, in Figure II, 52 (p. 568), he uses 'di- & converge.' However, the conception 'views onto object' is not represented in Newton's works. It is expressed only in recent scientific work (Grusche, 2014; Lunazzi, 1990).

Some implications for teaching

With many students using a ray concept akin to Newton's, teachers can contrast this historical ray concept with the modern ray concept. Moreover, many students intuitively apply the principle of reversibility. Teachers can use this principle to discuss geometric versus mechanistic ray concepts.

Faced with the phenomena in prismatic inspection, most students progress from the 'split image projection' conceptualisation to the 'diverted image projection' conceptualisation. Typically, their starting point is the conception 'split to eye,' and their endpoint is 'views onto object' or 'di- and converge.' From a scientist's perspective, there would be a shortcut: instead of a single composite ray being split up, you might consider multiple diverging composite rays being split up. From a teacher's perspective, however, it would be worthwhile to join the students on their longer learning pathways. In this way, they can use their observations and activities to test and adjust their conceptions.

Teachers may guide students along their learning pathways. For example, the teacher may support the students' simpler and more fruitful conceptions of the 'pinhole projector' or the 'pinhole eye' by placing a pinhole in front of the projector or the eye. In prismatic inspection, observing diverse perspectives through various colour filters is key to rethinking the relevant rays. Thus, teachers may need to tell students to look for an apparent shift among the background and foreground, and to step back from the prism for the shift to be greater. For a better understanding of prismatic inspection, teachers may tell students to treat the eye as a reverse projector, rather than as a screen. Moreover, teachers should counter students' typical misconceptions with experimental evidence and point out typical errors. Finally, teachers may support the students by demonstrating how to relate rays to the observed images. Much confusion about image inversion can be avoided by telling the students that they need not trace the rays forward from the pupil to the retina, but that they can extend them backwards from the pupil towards the virtual image.

Conclusion

To characterise undergraduate students' ideas about image formation with a dispersive prism, we analysed teaching experiments according to the Model of Educational Reconstruction. Most of our students used a mechanistic ray concept, similar to Isaac Newton. With many students intuitively using the principle of reversibility, teachers have an opportunity to contrast Newton's mechanistic ray concept with the geometric ray concept.

For prismatic projection and prismatic inspection, most students predicted a colourful series of images, based on their knowledge that a composite ray is split up into its component rays. In prismatic inspection, however, the students became frustrated with this '*split* image projection' conceptualisation. Based on the virtual images they observed, most students started to consider component rays diverging from the object and converging to the eye. Thus, they made a conceptual change to the '*diverted* image projection' conceptualisation. Both versions of the 'image projection' conceptualisation have been used by Newton and are still used by scientists today. For prismatic projection, it is enough to think of 'split image projection'; for prismatic inspection, it may be more useful to think of 'diverted image projection.'

Overall, there are many parallels between students' and scientists' ideas about prismatic projection and inspection. Even the students' learning pathways were parallel to the evolution of Newton's research on the subject. Still, the teacher needs to be aware of typical errors within the students' conceptions. Having time to explore the phenomena is essential for students to note and correct these errors. By carefully observing the prismatic images, students can refine their understanding of the ray geometry, especially in prismatic inspection. This way, an image-based approach to prismatic images will allow students to reconstruct their ideas towards a scientific understanding.

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Appendix 1. Previous studies

Table A1. Studies on student understanding of prisms.

Reference	Sample	Prism-related tasks
Palacios et al. (1989)	44 2nd-year science trainee teachers	Express prior knowledge about optical prisms, dispersion, refraction (Written test)
Singh and Butler (1990)	41 students from school (ages 15–17) and 1st-year undergraduate physics	Complete ray diagrams for prisms, potentially with total reflection or dispersion (Written questionnaire)
Galili et al. (1993)	13 prospective elementary teachers	Explain prismatic double image of a pencil using rays (Individual demonstration interview)
Galili and Hazan (2000)	166 students. Pre-instruction group: 9th grade (64 students). Post-instruction group: 10th grade (3 classes) and prospective technology teachers (1 class)	Explain prismatic double image of an object using rays, answer questions about white light and colour (Written questionnaire)
Mestre et al. (2009)	48 undergraduate engineering majors in a physics course	Complete a ray diagram using the law of refraction (Written test after lecture)
Ivanjek (2012)	Undergraduate physics students (9 interviewees; 778 students for one written question, 442 students for a different written question)	Predict phenomena for variations of a basic prism spectrograph (Individual demonstration interview or written question, after course)
Fehringer (2013)	10 school students (ages 14–15)	Complete diagrams for red, blue and white light beams through a prism; explain projected slit spectrum and filters (Teaching interview)
Vitharana (2015)	212 8th graders	Complete diagram for a white ray entering a prism (Written test after instruction)

Appendix 2. Learning pathways

The status of students' ideas is indicated as follows:

• Used and not abandoned
? Associated with doubts
∇ Initially adopted, but later abandoned

Predictions are represented in future tense; observations are represented in present tense.

Table A2. David's learning pathway involving rays for a virtual spectrum.

Teaching action	Individual student's conception	Conception category
Task: Predict what will be seen in prismatic inspection.	• *Separated rays*. Being refracted at the prism, white rays from the illuminated object will be separated according to wavelength, giving rise to diverse colours.	Split to eye
Experiment: Prismatic inspection without filters.	? *Modifying edges*. The light is latently modified upon hitting the edges of the object. ? *Revealing prism*. The prism reveals those parts of the object that have modified the light. ∇ *Absorbing edges*. The prismatic colours arise from light absorption at the edges of the object. • *Selected rays*. From each separated ray, a select colour enters the eye.	Split to eye

Table A3. Edgar's learning pathway involving rays for a virtual spectrum.

Teaching action	Individual student's conception	Conception category
Experiment: Prismatic inspection without filters.	• *Separated components*. A white ray headed for the viewer will be separated into its coloured components upon refraction at both sides of the prism, resulting in a colourful image. ∇ *Image-like ray sequence*. The colour sequence for the rays exiting the prism is the same as for the virtual spectrum. • *Inverted ray sequence*. The colour sequence for the rays exiting the prism is inverted with respect to the virtual spectrum because the brain inverts the image. • *Displaced arrival*. Next to each other, the separated rays go through the pupil to the retina.	Split to eye
Task: Predict what will happen if the object is put further away.	∇ *Narrowing with distance*. The further the object is away from the prism, the smaller will be the colour fringes because the angle between the coloured rays will be smaller.	Eye to images
	• *Widening with distance*. The further the object is away from the prism, the wider its spectrum will be.	Split to images
Experiment: Prismatic inspection with filters.	• *Perspectival shift*. The background image is shifted by the same distance as the foreground image, but the background appears to shift more due to perspective.	Eye to images
	• *Parallax simulation*. The perspectival shift is similar to the parallactic shift observed when switching between both eyes while viewing objects at different distances.	Views onto object

Table A4. Fabian's learning pathway involving rays for a virtual spectrum.

Teaching action		Individual student's conception	Conception category
Task: Predict what will be seen in prismatic inspection.	∇	*Normal view*. Viewed through a prism, an object will appear normal because the differently coloured images will hardly be shifted on their way from the prism to the eye.	Split to eye
	∇	*Narrow colour fringes*. The object will appear to have narrow colour fringes because its differently coloured images will be shifted only slightly on their way from the prism to the retina.	
	∇	*Object-to-prism distance irrelevant*. The distance from the object to the prism will be irrelevant because the image is not fanned out until it reaches the prism.	
Hint: Treat the eye analogous to a projector.	∇	*Same colour sequence*. The colour sequence will be the same as for projection, because image inversion does not matter.	Split to images
	•	*Shift-based colour flip*. The colour sequence is flipped between projection and inspection because the differently coloured images are mutually shifted within the projected spectrum, but not within the inspected object.	Split to object
Experiment: Prismatic inspection with filters.	•	*Switching eyes*. The apparent jumping when switching filters can be imitated by switching between one's eyes.	Views onto object

Table A5. Gerd's learning pathway involving rays for a virtual spectrum.

Teaching action		Individual student's conception	Conception category
Task: Predict what will be seen in prismatic inspection.	•	*Refracted image*. Going from the object through the prism, the image will be refracted into a spectrum that reaches the retina.	Split to eye
	∇	*Object-to-prism distance irrelevant*. The spectrum will be the same for any distance between the object and the prism, because the image is not refracted before reaching the prism.	
Hint: Treat the eye analogous to a projector.	•	*Greyscale image synthesis*. Looking at a projected spectrum through a prism, one will see a greyscale image, because the eye is the reverse of a projector.	Split to object
	•	*Greyscale image analysis*. Looking at a greyscale image through a prism, one will see a spectrum as the counterpart to greyscale image synthesis.	Split to images
	∇	*Same colour sequence*. With the eye instead of the projector and the seen spectrum instead of the projected spectrum, the colour sequence will be the same.	
	•	*Object-to-prism distance crucial*. The distance from the object to the prism will be crucial for the spectrum during inspection, because it will correspond to the distance from the prism to the screen during projection.	
Experiment: Prismatic inspection with filters.	•	*Distance-dependent refraction*. For a given colour, the object-to-prism distance affects the direction into which the image is refracted onto the retina.	Split to eye
	•	*Colour-dependent perspective*. The object is seen from a colour-dependent viewing direction because the apparent position of an object beyond the prism depends on colour.	Eye to images + Views onto object

Table A6. Anna's learning pathway involving rays for a virtual spectrum.

Teaching action	Individual student's conception	Conception category
Task: Predict what will be seen in prismatic inspection.	• *Received bundles*. A ray bundle carrying the image from the object will be split up by the prism into ray bundles carrying differently coloured images to the eye. • *Eye-screen analogy*. The eye is analogous to a projection screen.	Split to eye
Experiment: Prismatic inspection with filters.	• *Shifting viewing directions*. The perspective will be colour-dependent because one will need to view each image from a different direction to see the object through the centre of the prism.	Eye to images
	• *Parallax analogy*. The variation in perspective will be similar to viewing an object from different directions.	Views onto object

Table A7. Ben's learning pathway involving rays for a virtual spectrum.

Teaching action	Individual student's conception	Conception category
Task: Predict what will be seen in prismatic inspection.	∇ *Same colour sequence*. One will see the same colour sequence as in prismatic projection. • *Reverse colour sequence*. The colour sequence is reversed, compared to prismatic projection.	Split to images
Experiment: Prismatic inspection with filters.	• *Colour-dependent viewing direction*. Due to the prism, the viewing direction towards the objects varies according to colour. • *Parallax analogy*. One can simulate the colour-dependent offset by moving one's head sideways. • *Colour-dependent pre-viewpoint*. The colour-dependent viewing direction towards a given object point defines a colour-dependent, preliminary viewpoint on the front of the prism.	Views onto object
	• *Colour-dependent ray arrival*. Out of many differently coloured rays that go from a given object point to a given point on the prism, only one gets through the point-like eye pupil. • *Colour-dependent ray direction*. Differently coloured rays that leave a given object point in different directions are deflected by the prism into the eye.	Di- & converge

Table A8. Chris' learning pathway involving rays for a virtual spectrum.

Teaching action	Individual student's conception	Conception category
Task: Predict what will be seen in prismatic inspection.	• *Image-object analogy*. Prismatic inspection is similar to prismatic projection because an object is similar to an image.	Split to images
	• *Differently refracted visual rays*. The further an object is away from the prism, the larger will be the separation between differently refracted visual rays as they reach the object.	Split to object
	• *Distance-dependent effect*. The greater the distance between prism and object, the greater will be the shift among the diverse colours of light, resulting in a greater colour effect.	Split to images
	• *Prism-to-eye distance irrelevant*. The distance between the prism and the eye will not affect the apparent colouring of the object, because the object and prism are equivalent to a correspondingly coloured object.	Eye to images
Experiment: Prismatic inspection with filters.	• *Apparent starting point*. A ray appears to start at the shifted image, but it proceeds from the object itself. • *Backward ray-tracing*. One can trace a ray backwards from the eye straight through the prism towards the image, but at the prism, it is refracted towards the object.	Eye to images + Views onto object = Di- & converge