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2014 Phys. Educ. 49 671

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# Teaching optical phenomena with Tracker

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## Abstract

Since the invention and dissemination of domestic laser pointers, observing optical phenomena is a relatively easy task. Any student can buy a laser and experience at home, in a qualitative way, the reflection, refraction and even diffraction phenomena of light. However, quantitative experiments need instruments of high precision that have a relatively complex setup. Fortunately, nowadays it is possible to analyse optical phenomena in a simple and quantitative way using the freeware video analysis software 'Tracker'. In this paper, we show the advantages of video-based experimental activities for teaching concepts in optics. We intend to show: (a) how easy the study of such phenomena can be, even at home, because only simple materials are needed, and Tracker provides the necessary measuring instruments; and (b) how we can use Tracker to improve students' understanding of some optical concepts. We give examples using video modelling to study the laws of reflection, Snell's laws, focal distances in lenses and mirrors, and diffraction phenomena, which we hope will motivate teachers to implement it in their own classes and schools.

 Online supplementary data available from [stacks.iop.org/PhysED/49/671/mmedia](http://stacks.iop.org/PhysED/49/671/mmedia)

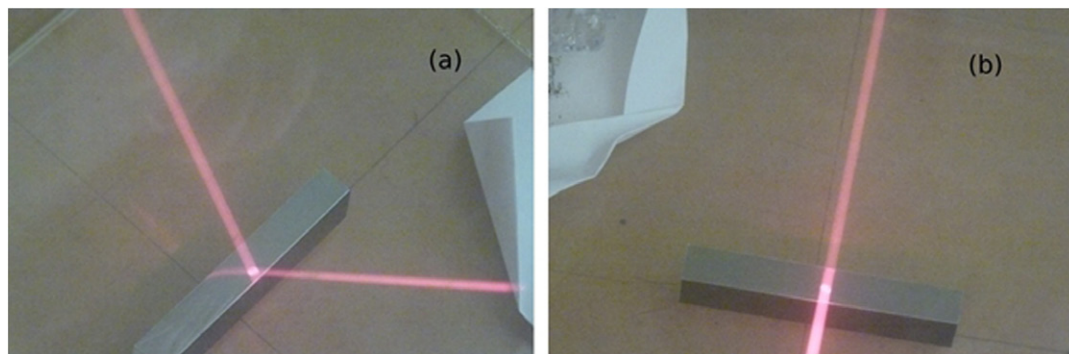
## 1. Introduction

Nowadays, video modelling can be used as a tool for teaching and learning several topics in physics. Most of these topics are related to kinematics and motion phenomena in general. This generally does not include other topics in physics such as optics, considered a 'static' field.

In order to promote a better understanding of concepts and laws in optics, teachers usually carry out practical activities in optical school laboratories to study these topics, where students

can manipulate adequate scientific equipment. However, for safety reasons, students usually do not have free access to these laboratories, so there is limited time for executing the experimental work. Despite the simplicity of most basic optics experiments, students often show some difficulties concerning the basic concepts and the interpretation of optical phenomena.

The video recording of a real experiment, also called video-based experimental activity (VBEA), is a very close approach to reality, and has one great advantage for students: the



**Figure 1.** Incident and reflected beams on a flat mirror, in different perspectives: (a) side view and (b) top (aligned) view.

experiment can be seen (and consequently analysed) at any time, as many times as they want, and results discussed online with their friends over the internet.

Teachers can record a video or take a photo of one particular experimental detail, which they distribute to their students, or they can ask students to build their own video recordings, to engage students in the interactive learning environment and to extend the teaching process out of the class.

'Tracker' [1, 2] is free video analysis software that has a large number of tools suitable for video and image analysis [3]. Therefore, teachers must define adequate classroom strategies to explore videos, so that they can be used as a demonstration, an exploration or a problem issue, or as a VBEA.

In the following, we shall give real examples of how to use videos and images for teaching basic optics. Videos were recorded with a photo camera at  $30\text{frames s}^{-1}$ , and analysed with the open source software Tracker.

## 2. Laws of reflection

The laws of reflection state that (i) the *incident* and *reflected* rays, and the reflecting surface *normal axis* are *within the same plane*, and (ii) the angle of incidence *is equal to* the angle of reflection. Usually, law (i) is given to students without any proof, as if it is quite an obvious assumption; but it is not!

In fact, we have to be inventive in the way we show this to students. In particular, two perspectives should be observed: one from above the incident and reflected beams (to show their projection is a straight line), and another from

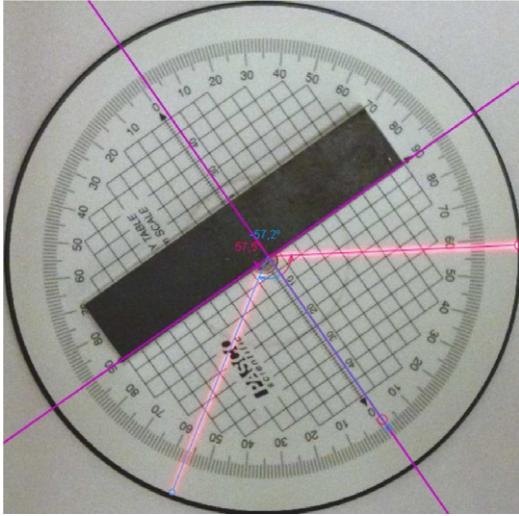
the side to make them observe that they are in the same plane as the mirror normal axis. The best way to show this properly is in a real experiment with a mirror and a light source (see figures 1(a) and (b)). As an alternative, we present one video recorded in a lateral perspective, which is available for download from [stacks.iop.org/PhysED/49/671/mmedia](http://stacks.iop.org/PhysED/49/671/mmedia) [4].

To understand law (ii), students must collect data from incident and reflected light beams. Figure 2 shows a mirror on top of a Hartl disc, and two red laser beams: one corresponding to the incident light and the other to the reflected light. This figure was taken from the video available at [stacks.iop.org/PhysED/49/671/mmedia](http://stacks.iop.org/PhysED/49/671/mmedia) [5], in which the incident beam is fixed while the Hartl disc is rotating.

To analyse the video and collect experimental data, students have to position the origin of the local referential frame at the ray's incident point, and align one of the referential axes with the mirror's surface while the other axis points in the normal direction (perpendicular to the mirror plane). Then they only have to use the *protractor* tool (either from the Hartl disc, or from Tracker) to measure the angle of the incident and reflected rays against the normal axis.

As the incident angle changes through the video, students can measure the incident and reflected angles for different frames (they may have to readjust the referential frame at each measurement). This will allow them to realize that the incident and reflected angles are equal within an experimental error.

In fact, these measurements are a great opportunity for students to manipulate and understand



**Figure 2.** Analysis of one frame of the video with Tracker. The local referential and protractor tools are visualized: the red protractor measures the incident angle while the blue protractor measures the reflected angle.

the abstract concept of the normal axis and its usability in optics. Instead of a plane mirror, students could study the laws of reflection with a circular mirror (figure 3) and realize why the angles, in optics, are measured against the normal axis at each point of the mirror instead of a unique normal surface axis.

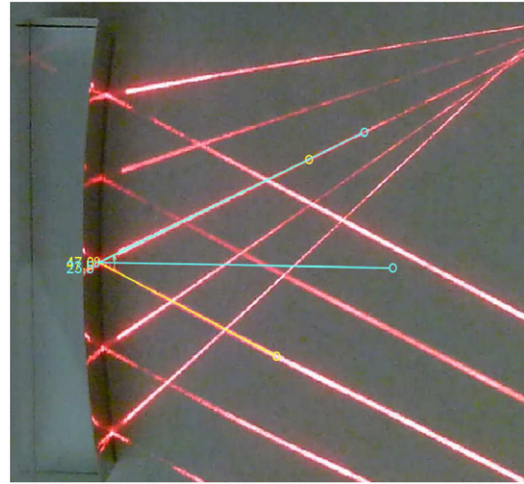
The proposed VBEA has several advantages for students and teachers: (1) manipulation of concepts such as normal axis, incident and reflected rays, incident and reflection angles; (2) use of the protractor as a tool to measure incident and reflection angles, (3) to understand the need for a reference frame (normal axis), (4) to learn the laws of reflection from a ‘hands on’ point of view, and (5) to be used in class as an experimental activity, or out of class as a homework assignment.

All these advantages relate to the use of VBEAs to promote a substantial learning of abstract concepts normally confined to schematic images in books.

### 3. Snell’s law

The refraction phenomenon is more complex and less intuitive than reflection, and will be better understood if students see what happens with a light ray at the interface of two transparent media.

The classical classroom experiments of refraction with a glass prism or water are very



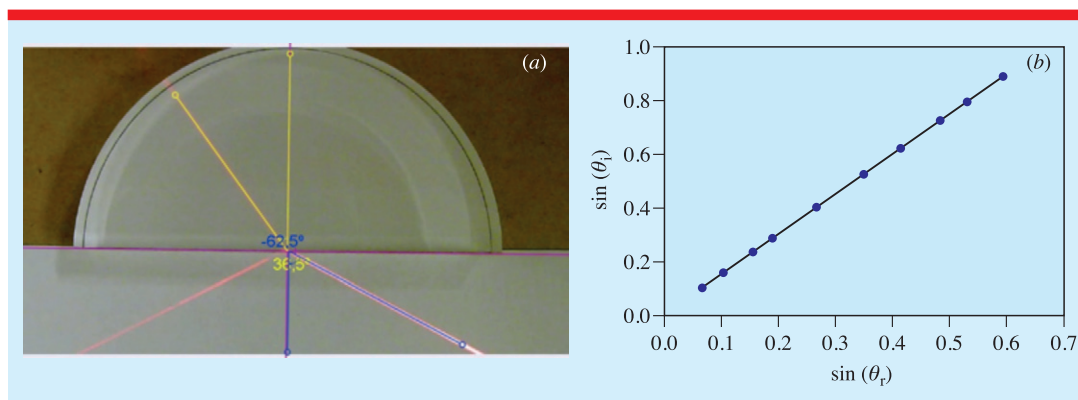
**Figure 3.** Measurement of the reflection angle of a light ray on a curvilinear mirror.

important to allow the discussion of this phenomenon, and once again the video analysis can be a good complement to it. By recording a video of the refraction phenomenon within a transparent medium, students can use Tracker to analyse it, in a similar way to that described above. In this VBEA, we have used a semi-circular transparent body that is fixed in relation to the video camera, while a red laser beam is directed onto the body at different incident angles (figure 4(a)).

The incident ray is refracted at the flat interface between the body and air. We can observe that the incident angle ( $\theta_i$ ) is bigger than the refraction (or transmitted) angle ( $\theta_t$ ). Using the *protractor* tool from Tracker, students can measure these angles for several frames. From Snell’s law,

$$n_{\text{air}} \sin \theta_i = n_{\text{body}} \sin \theta_t, \quad (1)$$

and by considering  $n_{\text{air}} \approx 1$  the refraction index of the body can be easily obtained. The use of two protractors (one for the incident angle, and another for the transmitted angle) is strongly suggested in order to simplify the measurements. Depending on the video frame rate, we can control the quantity of data to collect by adjusting the number of frames to visualize in the ‘step size’ button. This procedure is useful to reduce the time taken collecting data, and is particularly important in the context of the classroom. For the video we have used in our VBEA (frame rate of  $220 \text{ frames s}^{-1}$ ), we suggest a ‘step size’



**Figure 4.** Tracker's analysis of a VBEA. (a) A video frame analysis, where a semi-circular body is crossed by a laser beam. The incident angle (at the bottom right) is larger than the transmitted angle (at the top left); (b) plot of  $\sin(\theta_i)$  as a function of  $\sin(\theta_r)$ , allowing the calculation of the refraction index of the semi-circular body by linear fitting. The video is available from [stacks.iop.org/PhysED/49/671/mmedia](https://stacks.iop.org/PhysED/49/671/mmedia).

parameter in Tracker software of about 10—this reduces the overall time acquisition for students to less than 5 min, which is comparable to a real classical experiment.

A statistical treatment of data (linear fit and corresponding standard deviation) can be done from a graphical representation of  $\sin \theta_i$  versus  $\sin \theta_r$  (figure 4(b)). The value obtained for  $n_{\text{body}}$  (in the case of our study,  $1.488 \pm 0.004$ ) can be compared to those listed in reference books for acrylic and glass materials, and be used to identify the possible composition of the optical body.

Students can also study the total reflection of light, by providing them with a video where the incident angle (measured from the transparent body) increases until no light is transmitted, and we can only see the incident and reflected light rays at the flat body–air interface (figures 5(a) and (b)).

This will allow teachers to introduce the concept of *critical angle*,  $\theta_c$ , and students can measure it with the protractor tool (figure 5(b)). In this case, Snell's law can be rewritten as

$$n_{\text{body}} \sin \theta_i = n_{\text{air}} \sin \theta_t \quad (2)$$

becomes, for  $n_{\text{air}} \approx 1$  and  $\theta_t = 90^\circ$ ,

$$n_{\text{body}} \sin \theta_c = 1. \quad (3)$$

Therefore, students can determine  $n_{\text{body}}$  and compare this value to the one previously calculated.

It is important to have a high number of frames per seconds in the video, because this will improve the accuracy of the critical angle's measurement.

Students can also study experimentally the dependence of the refraction index with the frequency of light (figure 5(c)). In our VBEA, the critical angles for red and green light are slightly different as depicted in figures 5(b) and (c), which implies that the refraction index for green light ( $n = 1.53$ ) is higher than that for red light ( $n = 1.49$ ).

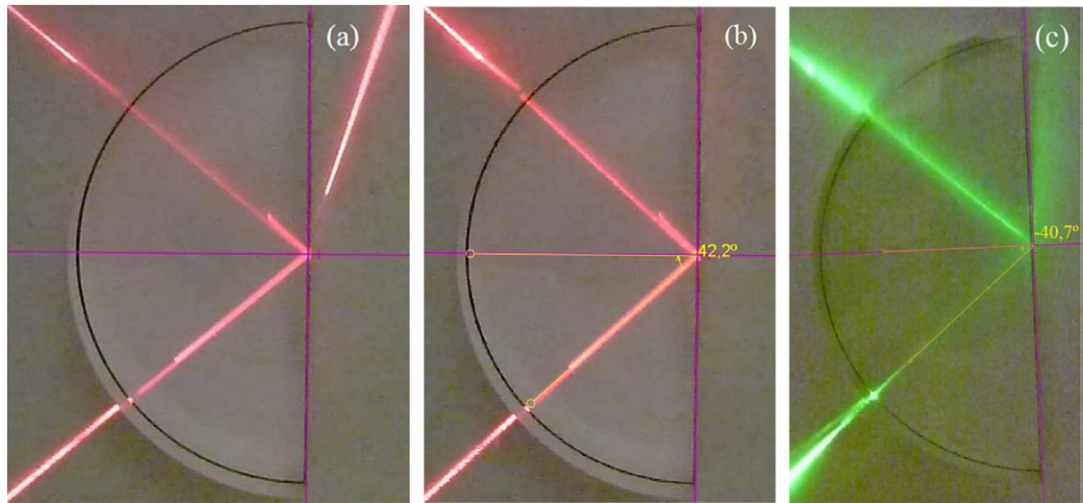
#### 4. Focal distances in lenses and mirrors

Lenses and mirrors are optical components used for the construction of images. To understand how these components work, students need to manipulate them, make observations and make some measurements to determine physical quantities.

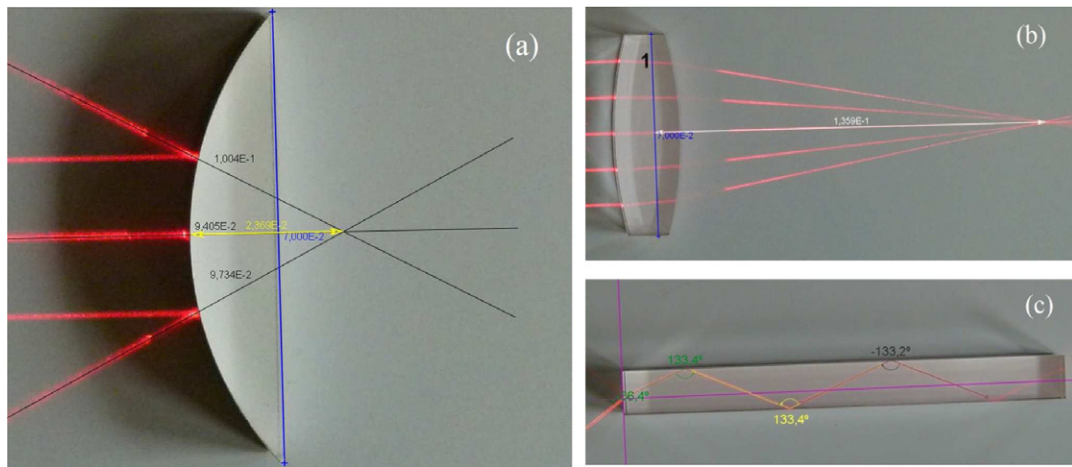
Experiments with lenses and mirrors are innumerable, but they all have in common the fact they are motionless, need procedural skills to be executed and can only be done in a laboratory with light sources. We can try to make them feasible without losing too much of the realistic context by providing students (it is better if they do it on their own) with photos or videos of experimental setups that they can work with outside the classroom.

Figure 6 gives some examples of lenses and mirrors that can be worked on by students as





**Figure 5.** Tracker's analysis of a video frame from the VBEA, where we can see that (a) the incident angle (on the left) is smaller than the transmitted angle (on the right); (b) the measurement of the critical angle; (c) the critical angle for a green light in the same transparent medium. The videos are available from [stacks.iop.org/PhysED/49/671/mmedia](https://stacks.iop.org/PhysED/49/671/mmedia).

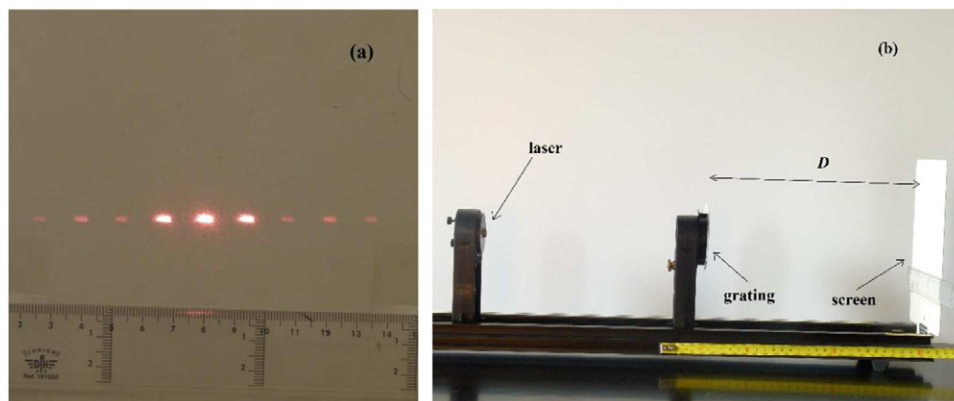


**Figure 6.** (a) Determination of the virtual focus point of a convex mirror. (b) Calculation of the focal distance of a convergent lens. (c) Trajectory of light inside a transparent optical medium with total reflection (optical fibre simulation).

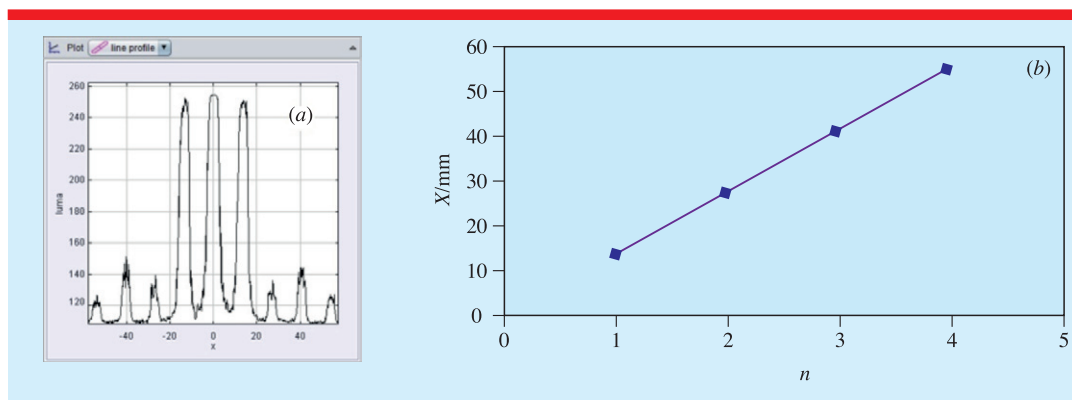
homework assignments, to observe convergent and divergent light rays, determine focal distances or simply explore changes in the direction of light when passing throughout a transparent medium.

Teachers can also use other configurations, namely association of lenses and/or mirrors, to produce photos or videos where students can explore physical quantities and study the functioning of optical instruments (e.g. schemes for image

construction in microscopes or telescopes). We find that videos have more advantages than photos, because, as in the case of the laws of reflection in mirrors, students can see the invariance of the optical laws during transient phenomena, and what is not invariant such as the changing of focus position (figure 2(b)), which is always represented in the optical axis of a mirror or lens, therefore helping to fix some of the misconceptions of the students.



**Figure 7.** (a) Diffraction pattern obtained from a diffraction grating of unknown separation value ( $d$ ). (b) Experimental setup showing the diffraction grating at a distance  $D$  from the screen, and a red laser beam of wavelength  $\lambda = 633$  nm.



**Figure 8.** (a) Brightness of the diffraction pattern (in Luma units) as a function of the distance  $X$  from the central spot of the pattern. (b) Plot of  $X$  as a function of  $n$ , for a grating of separation  $d$  between slits, at a distance  $D = 1000$  mm from the screen. The laser wavelength was  $\lambda = 633$  nm.

### 5. Diffraction phenomena

Optical diffraction is another phenomenon that can be studied by image analysis with Tracker software. Figure 7(a) shows a diffraction pattern obtained from a diffraction grating crossed by a red laser beam of wavelength  $\lambda = 633$  nm. The grating has an unknown slit separation  $d$  and is located at a length  $D$  from the screen (see figure 7(b)).

It is expected that the distances  $X$  between the central and the two-sided laser spots on the screen are related to the laser wavelength  $\lambda$  by [6]

$$X \approx n \frac{\lambda D}{d}, \quad (4)$$

where  $n$  is an integer corresponding to the order of the spot in the diffraction pattern (in this model we assume that  $D$  is much higher than the slit width).

For each image at a distance  $D$ , we can measure  $X$  with Tracker's measuring tool *line profile* (figure 8(a)), plot  $X$  as a function of  $n$  (figure 8(b)), and obtain  $d$  from a linear fit to the experimental results.

The results obtained for different values of  $D$  are shown in table 1.

As a classroom strategy, we can give as much information as we want to the students (relevant and/or irrelevant to the problem), either in a worksheet or appearing inside the photo of the experimental setup, such as the wavelength of the

**Table 1.** Experimental measures of the separation between slits of a diffraction grating, for different distances  $D$  from the screen.

$D$ (mm)	$350 \pm 5$	$500 \pm 5$	$700 \pm 5$	$850 \pm 5$	$1000 \pm 5$
$d$ ( $\mu\text{m}$ )	$41.8 \pm 1.8$	$46.4 \pm 0.8$	$47.0 \pm 0.4$	$46.8 \pm 0.5$	$46.8 \pm 0.3$
	$\bar{d} = 46 \pm 2 \mu\text{m}$				

light, the distance  $D$  for each diffraction pattern and/or the temperature (figure 7(b)), and ask students to find the distance between slits. They can carry out the video-based experiment in the classroom/laboratory or as a homework assignment, using Tracker as a tool to analyse the diffraction patterns.

## 6. Conclusion

It is usually assumed that video analysis is only engaged with mechanics, in particular kinematics. The new tools incorporated in recent video analysis software such as Tracker enlarges the scientific fields where this software can be used as a teaching and learning tool.

There are several didactic advantages in using VBEAs for teaching concepts in physics: (1) the videos can be freely distributed on the web and explored with students within the classroom, or as a homework assignment to improve students' understanding of specific content; (2) the teachers can engage their students by requesting them to execute simple experiments including the filming; (3) the students can carry out the analysis of the experiments at any time, as many times as they want; and (4) the students apply and associate physical concepts in real situations.

In the context of optics, videos and photos can be used to measure incident, reflected and refraction angles, to build graphs and obtain relations between these angles, and ultimately to determine the refractive index of optical media. Therefore students can study the laws of optics and consolidate content taught in the classroom, such as lenses or diffraction phenomena. VBEAs present a large didactic potential for teaching basic optics in high schools with an interactive methodology.

Work is in progress to study the impact of Tracker software for teaching physics with videos in motivating and interactive environments. Results of the respective gains of students' learning will be published elsewhere.

## Acknowledgments

MR and PSC are grateful to Fundação para a Ciência e a Tecnologia for funding project PTDC/CTM/099415/2008, and to Ciência Viva – Agência Nacional para a Cultura Científica e Tecnológica for funding Project Escolher Ciência – da Escola à Universidade PEC259.

Received 23 May 2014, in final form 24 June 2014,

accepted for publication 22 July 2014

doi:10.1088/0031-9120/49/6/671

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