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RESEARCH PAPER

Improving efficiency in optics education with immersive virtual reality

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ABSTRACT. This communication analyzes the potential for immersive virtual reality (IVR) to improve efficiency in optics education. We first critically review the common motivations to use IVR in education. Second, we highlight the two capabilities of IVR that distinguish it from the other visualization technologies that can be used in education: immersion and analysis of the learner's movement. Then, we identify four characteristics of situations in which IVR can efficiently support optics learning: large equipment, operating with distraction, security training, and feedback for motor skills. We illustrate these findings with 11 concrete examples.

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1 Introduction

Virtual reality for education is gaining traction these days because of its distinctive capabilities, such as immersion and presence.[1] Computer-assisted instruction has helped teach new subjects, such as dynamic geometry using tools, such as Geogebra.[2,3] In addition, computer-based training has helped embrace innovative pedagogical approaches, such as flipped classrooms[4] or peer instruction.[5] While this sort of technology and media have indeed proved useful to teaching and learning, the belief that they would inherently improve education has been disproved.[6] It has also been shown that the use of virtual reality to teach sciences does not uniformly yield positive pedagogical outcomes.[7] For example, Makransky et al.[8] show that cognitive overload in virtual reality is detrimental to learning. It is therefore essential to identify the situations in which the risk of cognitive overload is offset by the distinctive affordances of virtual reality in an educational context. An immersive virtual photonics laboratory was developed a few years ago[9] to support photonics education, and we have wondered how to get the best out of it for optics education. This is the motivation for this communication in which we perform a didactical analysis of the affordances of virtual reality in photonics given the current challenges of the optics education community.

1.1 Virtual Reality and the Pitfall of Extraneous Cognitive Workload

There are three types of advanced visualization technologies that can be used to enhance science teaching: augmented reality (AR), desktop virtual reality (DVR), and immersive virtual reality (IVR).[7]

In AR, a digital layer is added to the real world. A good example of this is the HOBIT system[10] wherein students manipulate blocks—optical replicas—that emulate a Michelson

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interferometer. The interference pattern is simulated based on the angles of the optical replica and is displayed on a vertical screen by a first projector. A second projector is placed above the experimental setup and displays textual content, illustrations, and animations over it. Its role is to help students understand physics concepts.

In DVR, a computer-generated virtual world is simulated and displayed on the monitor of the computer. Hayes et al.[11] developed such a virtual optical laboratory in which students explore laser diode characteristics and fiber coupling.

IVR requires the use of a headset to deliver a stereoscopic experience of a virtual environment. Alphanov Technology Center has developed an immersive photonics lab where students can utilize dedicated controllers to align a laser cavity or configure a Michelson interferometer.[7,10] This communication will be focused on IVR.

These results are explained by extraneous cognitive overload in which the diversion of attention toward elements that are peripheral to the core learning objectives hinders students' comprehension. In IVR, extraneous cognitive overload can be due either to the necessary learning of how to interact with the user interface or to the substantial volume of information often presented. Consequently, it is imperative to deploy IVR with care, reserving its application for scenarios where the advantages of IVR outweigh the costs of extraneous cognitive overload.

1.2 Wrong Motivations to Use Virtual Reality in Education

Two persisting myths in education are often hidden behind the motivation to use virtual reality in education. The problem is that these motivations might lead to inefficient use—or even counterproductive use—of IVR in education. In this section, we briefly present those myths and explain why they are wrong.

The first myth is commonly known as the arousal theory. It posits that the introduction of attention-grabbing elements enhances the learning experience. This belief is reflected in the inclusion of non-informative illustrations in educational materials or the desire to incorporate realistic details into virtual reality scenes. Empirical experiments, however, demonstrated the inefficacy of this theory.[12] Worse, the addition of visually appealing but non-informative information not only fails to enhance learning but also diverts the learner's attention, thereby diminishing the overall learning.[13,14]

The second myth is commonly known as naïve empiricism or hands-on approaches. It suggests that individuals learn more effectively when they do manual activities than when they listen or they read. This belief is often justified by a misinterpretation of Dale's Cone.[15] While it is true that hands-on practice is essential for acquiring motor skills, such as swimming or adjusting an optical setup, not all learning activities require physical manipulation. Cognitive skills and knowledge, such as reading or understanding a Michelson interferometer, require cognitive activity but not necessarily motor activity. The consensus is to advocate for instructional design that integrates both hands and mind, rather than solely relying on a hands-on approach.[16]

Whereas we think that virtual reality has often been advocated for incorrect motivations in education, we maintain that there are valid justifications for its use, which is the reason for this communication.

1.3 Training Challenges in Photonics Education

Optics encounters inherent educational challenges due to the high cost and limited availability of equipment for trainees, the inherent risks associated with handling high-power light sources, and the complexity of the concepts and procedures to be taught. Practical work is fundamental to optics training; however, the expensive and rapidly evolving nature of equipment poses significant obstacles.[17] In initial training programs, acquiring specific apparatus or providing sufficient equipment for simultaneous practice by all students on the same concepts or skills is often a struggle, diminishing training efficiency. In addition, students must acquire skills to work safely with powerful light sources, which requires supervised practice to develop correct habits. Evaluating and certifying individuals for the mastery to operate safely is also difficult, as tragic accidents too frequently remind us. Furthermore, certain optical concepts are known to be complex to grasp,[18,19] and technical training involves mastering complex alignment procedures.

In this paper, we want to investigate cases in which IVR might be an answer to these challenges.

1.4 Research Question

This brings us to our research question: "In which cases might the affordances of immersive virtual reality overcome cognitive overload issues in the teaching of optics?" We will refine this research question after developing the concepts we will use.

2 Important Concepts

In this section, we will describe the concepts that help better define our research question.

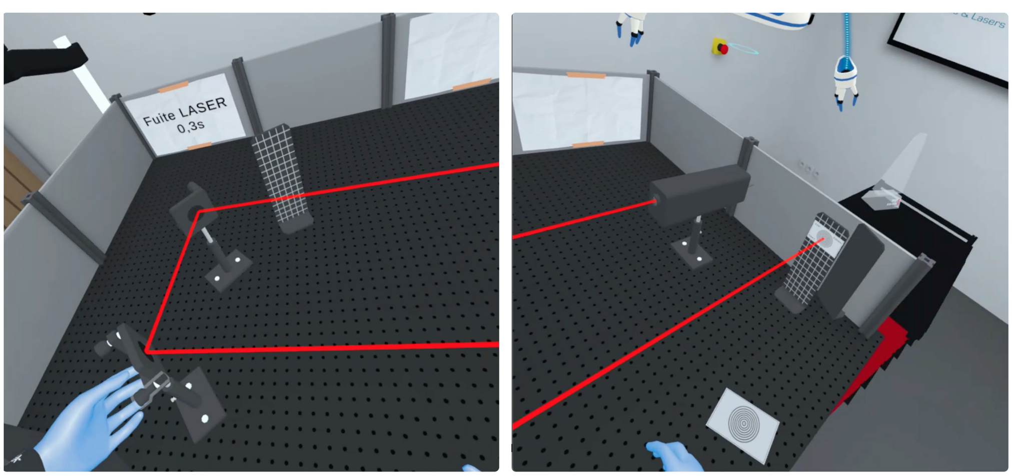
2.1 Two Distinctive Capabilities of Immersive Virtual Reality for Teaching Science

As Clark[6] points out, the motivation to use a specific media such as IVR in education is economic rather than pedagogic. In fact, each medium offers distinct capabilities that can be used to design effective training programs. However, achieving the same pedagogical objectives is always possible with another technology or even without any technology—historically, individuals learned to fly planes before the advent of simulators. According to Clark, the selection of a particular technology is an economic decision, aiming to accomplish pedagogical goals with optimal efficiency. At the level of an educator, this decision is not based only on economics. It can also be based on other constraints, such as the number of available teachers, and the availability of specific equipment or classrooms.

IVR applications have higher production costs and impose more constraints compared to DVR applications. Therefore, in this section, we aim to underscore the distinctive capabilities of IVR over other forms of virtual worlds.

2.4.1 *Immersion*

What sets IVR apart from other forms of virtual worlds is its immersivity.[1] The stereoscopic 3D visual representations induce a sense of genuine presence in the virtual environment. Users can turn their heads or bodies and receive information from all directions, akin to a pilot in a cockpit. This immersive capability is useful when learners need to acquire skills for operating in scenarios where information emanates from diverse spatial locations. An example in optics is when a learner must learn to align a laser beam by acting on a mirror while simultaneously monitoring a screen in the distance as shown in Fig. 1.



(a) (b)

Fig. 1 Two screenshots of a learner in the Immersive Photonics Lab taken within less than a second. (a) The learner is looking at her left hand to grab the screw on the mirror and (b) the learner is looking at the target on her right.

Furthermore, immersivity is particularly valuable when individuals need to acquire proficiency in working within noisy environments. In this way, it is possible to control the level and to gradually introduce these external disturbances during the learning process. Under these conditions, students gradually learn to integrate and free themselves from these disturbances, focusing on the relevant elements.

2.4.2 *Analysis of the learner's movements*

Depending on the IVR system, users can interact with the virtual world using their bare hands, controllers, or gloves. This capability enables the application to provide feedback based on the learner's movements. This is not the case in the other virtual worlds. Some AR set-ups such as the HOBIT[10] comprise a camera (or even a set of 3D cameras) that records the movements of objects but not of the learner. In DVR, the learner interacts with the mouse or the keyboard of the computer, hence this technology cannot give feedback on the learner's movements.

The analysis of the learner's movements is a feature that is used in the Immersive Photonics Lab[9] application to detect if the learner's hand has crossed the virtual laser beam. Hence, the learner gets immediate feedback—the controller vibrates, and the virtual hand turns red as shown in Fig. 2—which is important for security training.

2.2 Three Different Types of Knowledge

A more detailed analysis of the knowledge to be taught is essential to determine in which cases IVR is a promising technology for enhancing optics teaching. PISA framework distinguishes three types of knowledge in science: conceptual, procedural, and epistemological knowledge.[20]

Conceptual knowledge relates to the comprehension of concepts, definitions, and laws in physics. Examples may include understanding the concept of wavelength, understanding how an interference pattern is modified when the diffractive object is moved, or grasping the concept of a virtual object in geometrical optics.

Procedural knowledge ranges from basic procedures such as measuring a wavelength with a diffracting set-up to more general procedures such as how to test a model. It is useful for our purpose to distinguish motor skills and cognitive skills. Assembling a laser without putting one's hand in the beam involves motor and cognitive skills, whereas predicting the size of the image of a given object through an optical set-up is a purely cognitive skill.

Epistemological knowledge refers to knowledge about how science works, and for example, the role played by experimentation in building new knowledge.

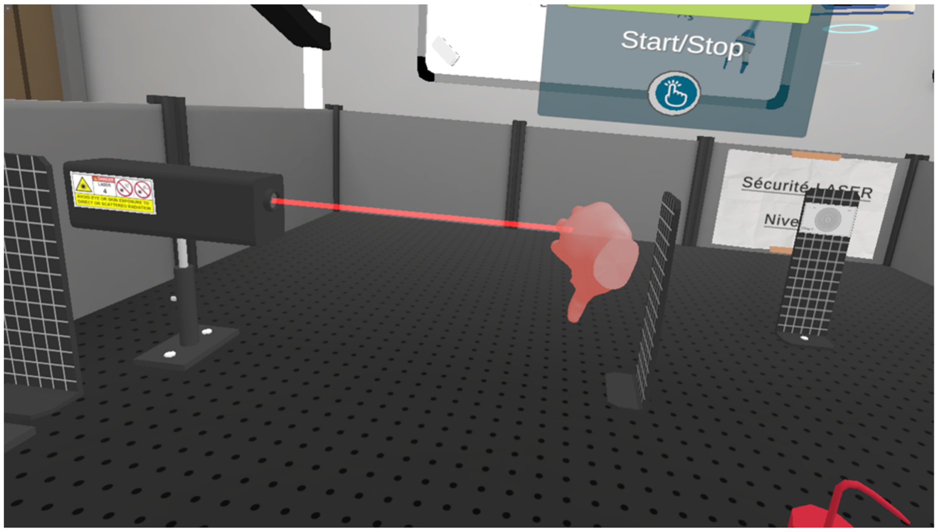


Fig. 2 Screenshot of the Immersive Photonics Lab with the right virtual hand of the learner turning red because it has crossed the laser beam.

3 Results

In this section, we address two research questions: RQ1: "Which knowledge to be taught in optics education can be efficiently supported by IVR?" and RQ2: "What are the scenarios in optics education in which IVR might enhance efficiency?"

We answer these questions through an "*a-priori* didactical analysis" aiming to highlight affordances in pedagogical situations.[21]

3.1 RQ1: Which Knowledge to Be Taught in Optics Education Can Be Efficiently Supported by IVR?

As recalled in Sec. 1,[7,8,12–14] the literature in education highlights the detrimental impact of cognitive overload on learning, particularly in IVR. It is therefore important to identify the distinctive capabilities of IVR as a teaching technology, the use of which can justify taking the risk of a cognitive overload. Following the analysis of J. Martin-Guttiérrez et al.,[1] we identified two distinctive capabilities (immersion or analysis of the body movement) that can make a difference over other technologies. These two capabilities can be particularly useful to help teach procedural knowledge as defined in PISA framework. This leads us to conclude that IVR has clear advantages over other technologies to teach procedural knowledge over conceptual or epistemic knowledge.

In this section, we illustrate this conclusion with four concrete examples. The first two are examples of conceptual knowledge teaching for which IVR might seem relevant but is not because it does not make use of the two distinctive capabilities we have identified: immersivity and analysis of body movements. The last two examples exemplify how these two distinctive capabilities of IVR can be useful in teaching procedural knowledge.

Example 1: Discriminating rings movements when translating a mirror of a Michelson interferometer. Students often struggle to discriminate between rings moving in and rings moving out on the interference pattern of a Michelson interferometer when approaching or moving away from the optical contact. One can think that using an IVR simulation can be useful because students can move the mirror in the virtual world without the risk of changing any other settings. Plus, the pattern on the virtual screen would probably have a better signal-to-noise ratio than in real life. But here, there is no added value of the distinctive capabilities of IVR: discriminating between two pattern movements happens only on one screen (no need for immersion) and there are no motor skills involved in this learning (no need for the analysis of the learner's movements). Therefore, there is no reason to use IVR to teach how to discriminate between rings moving in or out rather than DVR or another technology.

Example 2: Creating a mental representation of the interference figure of two correlated punctual light sources (Young's holes or Michelson interferometer). Students often struggle to predict the interference pattern that they will see as they move the screen in space. It might seem appealing to help them with a 3D representation of the interference figure. But here there is no need for immersion since there is no added value of a 360 deg video over an animation on a desktop computer screen. There are also no motor skills involved for which analysis of the learner's movements would be useful. In this case, interactivity in IVR can even be detrimental to learning. Imagine for example how difficult it is to place a screen at a given angle and keep it in IVR. It would be easier on a computer on which you can precisely set the angles. Nevertheless, it would be interesting to analyze the relevance of IVR in cases where the physical concepts involved require 3D visualization (such as anisotropic optics) and where the ability to move within the material allows observation of various effects from different perspectives. This could perhaps temper this statement.

On the other hand, IVR's distinctive capabilities are promising for skill training, and we present two examples below.

Example 3: Learning how to align an optical compressor. Aligning an optical compressor is a complex procedure for which a step-by-step tutorial with a simulation seems promising. The process of aligning an optical compressor involves handling substantial equipment, and accessing elements situated at various locations across the entire optical table while simultaneously monitoring a screen. This advocates for the immersivity capability of IVR. In this case, we can hypothesize that the transfer from what has been learned in the simulation would be faster with IVR than with DVR.

Example 4: Learning how to transport safely a laser beam. Here, the difficulty is to learn how to move to grab objects or to act on them without putting one's hand in the laser beam. To achieve this pedagogical goal, it is useful to track the learners' hand movements to give them instant feedback when their virtual hands cross the beam. In this situation, the analysis of the learner's movement is important, and there is a potential superiority of IVR over other technologies for efficient training.

From this first analysis, we infer that immersive VR might exhibit superiority over other educational technologies when procedural knowledge is involved. More specifically, this advantage is evident when the procedure involves a large piece of equipment, the need to learn how to operate in the presence of distraction, the need to manipulate safely, and/or the need to learn motor skills.

3.2 RQ2: What Are the Scenarios in Optics Education in which IVR Might Increase Efficiency?

In this section, we present four scenarios and seven examples that our analysis has identified as relevant for using IVR in optics education.

3.3.1 *Remote training*

The first scenario in which IVR adds value to optical training is remote training and we will exemplify it with two user-cases.

Example 5: Customer training. The first user case involves a French company that distributes lasers all over the world, particularly in Asia. Maintenance operations, troubleshooting, and repairs on these lasers are occasionally required. Traditionally, knowledge transfer from the company to customers involves sending a trainer to Asia for a week. However, the company can use IVR reality by emulating the laser in it, providing customers with headsets, and remotely guiding them through maintenance operations. In this scenario, IVR proves superior to DVR because the expert can watch in real-time how the customer reproduces the procedure and give immediate feedback on their movements.

Example 6: Remote photonics laboratory works. The second user case involves a university that teaches photonics to students enrolled in sandwich courses. To facilitate the regular practice of photonics, each student could be equipped with an IVR headset for home assignments. The instructor would record a set-up demonstration that students could watch in IVR. Students could reproduce the operations in IVR when they have time for it and save the final scene to send it to the instructor. Subsequently, the instructor could review the scene, assess the set-up, and assign grades, considering the safety score recorded during the student's operation. IVR proves beneficial in this context as the instructor can demonstrate hand gestures, such as "following the holes on an optical table to align two elements" or "pre-align the two arms of a Michelson, ensuring, with the help of a graduated ruler, so that the distances between each mirror and the beam splitter are approximately identical," which are tasks particularly challenging to achieve in DVR. Moreover, this scenario incorporates the analysis of learners' movements to provide students and instructors with feedback on safety, including proximity to the laser beam and the controlled handling of the laser beam.

3.3.2 *Pre-training when equipment is inaccessible or fragile*

Here, we describe two examples in which IVR is used for pre-training learners when some equipment is either inaccessible or fragile.

Example 7: Training operators on a large facility. This example involves a research center operating a high-power laser within a very large facility. They need to train operators, but it is complicated to pause the line. To pre-train the operators and minimize the downtime of the line, they could emulate the equipment in IVR and use a step-by-step training scenario. The learners could go through the application at their pace, and, upon completion of the final training sequence, be tested within the application. If needed, they would have the opportunity to rehearse the application until they successfully passed the test. Once all learners have completed this pretraining phase, they can pursue their learning in real life with an instructor for a short period.

In addition, learners could also rehearse rare procedures in IVR before executing them in real life. This scenario involves large equipment and security training and is therefore well suited for IVR.

Example 8: New photonics program. This example involves a university that wants to open a new program in photonics. However, they need to train students on costly equipment to obtain accreditation. With the aid of IVR, they could pre-train students at university through simulation and purchase only a few hours of training at an external center on the actual equipment to fulfil the opening criteria. This scenario is relevant for IVR if the equipment is large, and/or if there are security issues in how the students move while operating the equipment.

3.3.3 *Step-by-step tutorials for complex procedures*

Example 9: Setting up a Michelson interferometer. The procedure of setting up a Michelson interferometer is complex because of the numerous degrees of freedom of the set-up and the need for a conceptual understanding of the links between one's actions and the modifications on the interference pattern. Usually, the first sessions on the Michelson interferometer are a nightmare for instructors who have to spend a lot of time with each couple of learners. In this scenario, the learner starts in IVR with a step-by-step tutorial with a lot of scaffolding. The tutorial is designed progressively, with single degrees of freedom in the early levels and, in the final stage, allowing manipulation of all screws. Within $\sim$1.5 h, each student acquires the fundamentals of the Michelson interferometer setup and is prepared to work with an actual interferometer. The use of IVR in this context is also justified during the initial setup of the interferometer. To ensure that the lengths of each arm are approximately the same, students should use a graduated ruler to measure these distances while positioned above the interferometer. Without touching the various elements (mirrors, beam splitter, and compensator), one must estimate these distances, minimizing parallax effects as much as possible. The advantage of IVR over DVR in this context comes, for example, from the necessity to learn to manipulate a screw while simultaneously observing a screen in a different direction or when the learner needs to move around in 3D space to find the right angle for observing or measuring a physical quantity.

3.3.4 *Security training and evaluation*

The issue of security holds great significance in photonics, necessitating the training and evaluation of individuals to ensure safe operations.

Example 10: Learn to analyze the security of a work environment including high-power light sources.

Teaching people by having them visit faulty and non-faulty locations can be time-consuming and costly. This approach can be implemented in both DVR and IVR. Our analysis indicates that IVR outperforms DVR only when additional environmental distractions (such as noises and people approaching to talk) are desired (immersion), or when evaluating how the learner behaves—for instance, how they pick up a pencil from the floor without putting themselves at risk (security—analyzing the learner's movement).

Example 11: Improving skills to operate safely. In this last example, a company aims to improve safety by improving the skills of each of its operators. These operators are all certified and therefore convinced that they operate safely. The company organizes a tournament where each operator has a series of assemblies to build in the IVR. They receive a score based on how safely they have operated. Tips are provided after each assembly, and operators can follow a tutorial to enhance their skills before the next one. This scenario capitalizes on the capability to measure the learner's movements in IVR.

4 Conclusion, Discussion, and Perspective

In this communication, we have identified two capabilities of IVR that may be useful to enhance the efficiency of optics education: immersion and the ability to analyze the learner's movement. Through multiple examples, we have demonstrated how these two criteria help identify the pedagogical goals for which IVR is the most appropriate technology along with showcasing user cases where IVR could enhance optical training efficiency. These two criteria play a crucial role in selecting situations where IVR holds a distinct advantage over other virtual environments, such as DVR.

However, it is essential to acknowledge the potential risk of extraneous cognitive load when using IVR. It is therefore important to minimize it by different means. In this communication, we have not addressed the many ways to minimize cognitive load in IVR either in the design phase (avoiding complex interactions or avoiding ultra-realistic graphics) or in the teaching phase (providing students with extra time in the IVR previous to teaching to get used to the environment and its interactions). Minimizing cognitive load should be a serious consideration to maximize the potential efficiency of these applications.

In addition, we have not delved into the limitations of IVR in terms of precision in movement recording. Currently, this, coupled with the absence of haptic feedback, poses a constraint on training for precise movements. Nevertheless, it is worth noting that technology is evolving rapidly, and these limitations may be addressed shortly.

The next step would be to measure the efficiency of some of the scenarios that we presented in this communication to see if (1) learners actually learn by using them and (2) if learning is indeed more efficient (cost, time, ...) with this technology than without or with another technology.

Code and Data Availability

Data sharing is not applicable to this article, as no new data were created or analyzed.

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References

1. J. Martín-Gutiérrez et al., "Virtual technologies: trends in education," *EURASIA J. Math. Sci. Technol. Educ.* **13**(2), 469–486 (2017).
2. Y. A. Wassie and G. A. Zergaw, "Capabilities and contributions of the dynamic Math Software, GeoGebra: a review," *North Am. GeoGebra J.* **7**(1), 68–86 (2018).
3. J. Darricarrère and E. Bruillard, "Utilisation des TIC par des professeurs de mathématiques de collège: discours et représentations," *Bull. Soc. Enseign. Neuchâtel. Sci.* **39** (2010).
4. P. Strelan, A. Osborn, and E. Palmer, "The flipped classroom: a meta-analysis of effects on student performance across disciplines and education levels," *Educ. Res. Rev.* **30**, 100314 (2020).
5. E. Mazur, "Peer instruction: getting students to think in class," *AIP Conf. Proc.* **399**, 981–988 (1997).
6. R. E. Clark, "Media will never influence learning," *Educ. Technol. Res. Dev.* **42**(2), 21–29 (1994).
7. H. Matovu et al., "Immersive virtual reality for science learning: design, implementation, and evaluation," *Stud. Sci. Educ.* **59**(2), 205–244 (2023).
8. G. Makransky, T. S. Terkildsen, and R. E. Mayer, "Adding immersive virtual reality to a science lab simulation causes more presence but less learning," *Learn. Instr.* **60**, 225–236 (2019).
9. L. Lescieux and A. Loulier, "ALPhANOV: immersive photonics lab - photonics training accessible to anyone, anywhere, anytime!" *Proc. SPIE* **11716**, 1171603 (2021).
10. D. Furió et al., "HOBIT: hybrid optical bench for innovative teaching," in *Proc. 2017 CHI Conf. Hum. Factors in Comput. Syst.*, ACM, Denver, Colorado, pp. 949–959 (2017).
11. D. Hayes et al., "Virtual-reality-based educational laboratories in fiber optic engineering," *Proc. SPIE* **9289**, 928921 (2014).
12. R. C. Clark and R. E. Mayer, *E-Learning and the Science of Instruction*, Wiley (2011).
13. R. E. Mayer et al., "Increased interestingness of extraneous details in a multimedia science presentation leads to decreased learning," *J. Exp. Psychol. Appl.* **14**(4), 329–339 (2008).

14. R. E. Mayer, J. Heiser, and S. Lonn, “Cognitive constraints on multimedia learning: when presenting more material results in less understanding,” *J. Educ. Psychol.* **93**(1), 187–198 (2001).
15. D. P. Subramony et al., “The mythical retention chart and the corruption of dale’s cone of experience,” *Educ. Technol.* **54**(6), 6–16 (2014).
16. E. Sassi and M. Vicentini, “Aims and strategies of laboratory work,” in *Connecting Research in Physics Education with Teacher Education, ICPE Book*, M. Vicentini and E. Sassi (2008).
17. W. R. Woodward, “Meeting evolving technology education challenges in photonics and optics,” *Proc. SPIE* **8481**, 848108 (2012.
18. K. M. Cvenic et al., “Development and validation of the conceptual survey on wave optics,” *Phys. Rev. Phys. Educ. Res.* **18**(1), 010103 (2022).
19. J. Uwamahoro et al., “Physics students’ conceptual understanding of geometric optics: revisited analysis,” *J. Sci. Educ. Technol.* **30**(5), 706–718 (2021).
20. J. Osborne, “Defining a knowledge base for reasoning in science: the role of procedural and epistemic knowledge,” in *Reconceptualizing STEM Education*, R. A. Duschl and A. S. Bismack, Eds., Routledge (2016).
21. H. Sollervall, “Validating affordances as an instrument for design and *a priori* analysis of didactical situations in mathematics,” *Int. J. Math. Teach. Learn.* (2015).

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