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HOBIT: Hybrid Optical Bench for Innovative Teaching

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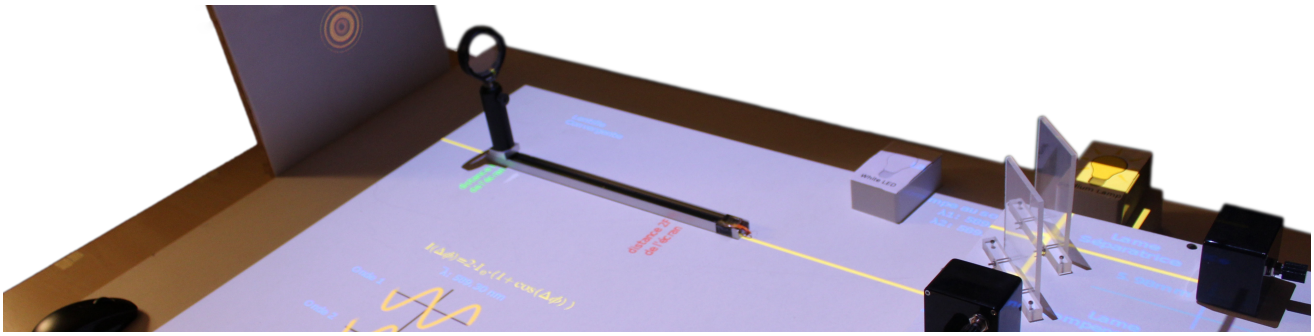


Figure 1. Simulation and augmentation of a Michelson interferometer experiment. Physical and digital content are merged in a unique environment.

ABSTRACT
Practical work in optics allows supporting the construction of knowledge, in particular when the concept to be learned remains diffuse. To overcome the limitations of the current experimental setups, we have designed a hybrid system that combines physical interaction and numerical simulation. This system relies on 3D-printed replicas of optical elements, which are augmented with pedagogical information. In this paper, we focus on the well-known Michelson interferometer experiment, widely studied in undergraduate programs of Science. A 3-months user study with 101 students and 6 teachers showed that, beyond the practical aspects offered by this system, such an approach enhances the technical and scientific learning compared to a standard Michelson interferometer experiment.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g., HCI): User Interfaces; K.3.1. Computers and Education: Computer Uses in Education

Author Keywords
Education and Training; Optics; Augmented Reality; Simulation; Michelson interferometer

Authors' version

INTRODUCTION
In optics, many concepts and phenomena are difficult to perceive and understand. This is particularly true with wave optics where phenomena may appear as counterintuitive [14]. Hence, universities and schools generally reinforce theoretical courses with physical experiments where students manipulate the concepts to be learned. The integration of laboratory activities into the classroom is an essential part of science education [19] since it allows students to observe, test hypotheses, and apply their understanding of the physical world [2, 16]. Furthermore, the observation, testing and experimentation found in experimental physics have a positive impact on the students' motivation [25, 26].

However, current experimental setups suffer from several limitations, as reported by the optics teachers with whom we have worked (see *Evaluation* section). First, from a practical point of view, setting up and maintaining optics experiments may be time consuming (in particular in the case of wave optics). The required material is generally expensive and fragile. This limits the number of experiments that can be run. Experiments can be dangerous too, in particular as soon as laser sources are used. These observations were also reported in the literature [15, 22, 4].

Second, from a pedagogical point of view, the teachers as well as other prior work [27] reported that traditional experiments were not always sufficient for transmitting knowledge. Students often have difficulties to develop an understanding of the complexity and ambiguity of empirical work. They may also fail to acquire the skills needed to calibrate and troubleshoot

setups used to make observations, whereas this learning is the main objective of practical works [17].

All these issues prompt to upgrade traditional optics experiments by i) overcoming the practical limitations of the current experimental setups and ii) providing pedagogical supports aiming to help the understanding of the studied phenomena. To this end, we propose HOBIT, an interactive system which stands for Hybrid Optical Bench for Innovative Teaching. Our goal is to let students operate as if they were working with a real optics experiment, but where the observed phenomenon comes from a numerical simulation. Beyond the simulation, this system allows augmenting the experiment with co-located pedagogical supports (see Figure 1).

In a first step, we focused on the Michelson interferometer, which is used in numerous applications (e.g. Fourier Transform Spectroscopy, Laser Interferometer Gravitational-Wave Observatory, and so on). Consequently, the Michelson interferometer (Figure 2) is one of the most popular optics experiments. It is based upon the division of a light wave into two beams that reflects on two separate plane mirrors before merging back into a combined beam whose projection can be observed on a projection screen. By slightly modifying the axial position or the orientation of the mirrors, one can observe resulting interference patterns—fringes or rings—on the screen (See Figure 5(a)). Various experiments can be performed with a Michelson interferometer, such as the measurement of wavelengths (e.g. Helium-Neon Laser), precise distance, or refractive indexes of transparent materials. Therefore, it is fundamental that, during lab work sessions, students familiarize themselves with the setup adjustments. They also need to translate their theoretical background into practice and understand causal effects of their direct manipulations on optical interferences phenomena.

Our contributions for this work are

- the design of a new interactive system that simulates and augments a Michelson interferometer
- a study that assesses the pedagogical relevance of the proposed approach in an ecological situation.

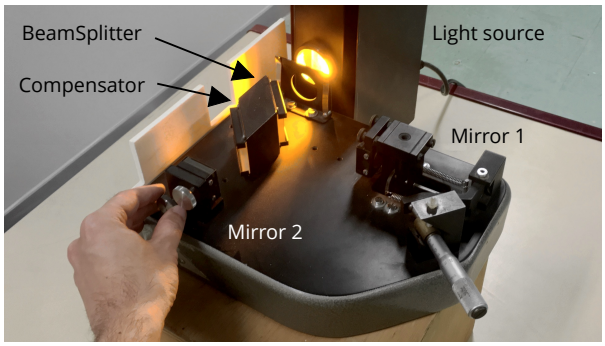


Figure 2. A picture of a standard Michelson interferometer where a user is moving the orientation of one of the mirrors. The interference pattern is projected on a screen located on the left of the interferometer (not visible in this image).

RELATED WORK

Due to the abstract nature of the studied concepts, optics is one of the fields where many works were conducted to improve educational approaches and tools. Many authors emphasize the importance of Hands-on learning experience, as we do in our approach. This is notably the case of the workshop carried out by Takayama et al. [24]. During two hours, basic optics concepts (e.g. polarization and wavelength) were introduced to high school students who performed the experiments themselves, guided by two experts. Despite direct manipulations, such traditional experiments may suffer from a disconnection between the theoretical concepts to learn and the actual handling, since students can not observe the phenomena and the underlying theoretical concepts at the same time.

Beyond standard experiments, authors have explored alternative technologies to improve the teaching of physics (and optics) concepts. For example, Rodrigues and Carvalho [20] developed video-based experimental activities. Real experiments were recorded and students had to answer questions by watching and analyzing the videos. Such multimedia systems have interesting advantages over traditional experiments. Beyond cost and safety considerations, videos can be freely distributed on the web, making possible to spread them to a large number of students that can work with them at any time, and as many times they want. On the other hand, physical investigations are not possible with such intangible approaches. This can maintain misconceptions [29]. To overcome this, our work supports physical interaction.

In past few years, new approaches based on Virtual Reality (VR) have emerged with the popularization of the related technologies. These approaches rely on the immersion of users in an interactive virtual environment. Related with optics education, Hayes et al. [11] developed a VR educational module that implements a virtual laboratory with realistic models of optical devices. In this virtual lab, students can set up and perform an optical experiment, e.g. dealing with laser diode characteristics and fiber coupling. The module was composed of three levels with a short quiz at the end of each one to measure the student's understanding of the subject. Such VR environments are very flexible, and numerous experiments, which could be potentially dangerous or expensive in reality, can be built. On the other hand, pure VR approaches suffer from limitations. In particular, when equipped with a Head-Mounted-Display, the student is isolated in a virtual world, and the communication with other students and teachers is harder. This contradicts pedagogical principles that emphasis the importance of social interaction in learning [12, 5]. Moreover, the way the student manipulates virtual optics components is very far from what she or he would do during a real experiment. Consequently, the transition from the virtual to the real environment might be a problem. At the opposite, with HOBIT, students and teachers interact around a tangible experiment that is very close to the true experiment.

Related to VR, Augmented Reality (AR) has grown in importance in the last years. By superimposing virtual elements to real ones, AR allows enriching the real world with additional information. In education, this can help students to understand

abstract concepts that may not be visible in real life (e.g. [8, 23]). With regard to optics education, a few AR experiments have been carried out. Yamaguchi and Yoshikawa [32] developed a system for the construction of an optical holography setup. The virtual optics components (e.g. lenses, and mirrors) were displayed on a screen on top of filmed markers. The students had to build an optical holography experiment by manipulating the markers in front of a camera. Compared to this approach where the augmentation is observed through a screen, with HOBIT, virtual information is directly projected onto the physical environment, using Spatial Augmented Reality [1].

Some authors like Underkoffler and Ishii [28], or Falcão and Price [9] had followed an approach similar to ours where projection is used to combine real and virtual information within a same physical space. Underkoffler and Ishii system aimed at simulating the interaction of laser light with various optical components in holographic setups. A projector situated above a table allows displaying augmented information (light path) around physical objects that are tracked thanks to a video/markers system. Similarly, the system of Falcão and Price consisted in an interactive tabletop environment for simulating some basic optics phenomena and was targeted at children. A projector situated on top of the table displayed the augmented information and the different physical objects were tracked from below the table thanks to a video/markers system. Continuing with AR, Yoon and Wang [33] developed a system to observe and manipulate magnetic fileds in real-time. A camera placed above the working area tracked the magnets and the augmented information (magnetic fields) was displayed on a screen situated in front of the user. These systems reproduce conceptual and simplified optics or magnetics experiments. In our case, with HOBIT, our goal is to mimic as much as possible true experiments, and to augment them with pedagogical supports.

Another interesting project related to HOBIT is *TinkerLamp*, developed by Do-Lenh et al. [7]. *TinkerLamp* tries to help logistics students learn the theoretical concepts through experimentation and AR in a scaled-down model of a warehouse. It is composed of an interactive tabletop, a projector and a camera placed above the tabletop, and a series of physical elements (sheets, models, cards, etc.) that can be tracked thanks to markers. HOBIT shares some of the ideas presented in *TinkerLamp* and some of the aforementioned projects. This notably includes tabletop configurations, top projectors, tangible interaction, and control cards.

Despite the effort that has been put to build these new educational tools, few studies have been conducted to assess the learning outcomes. Underkoffler and Ishii [28] performed a qualitative user study with 8 students. This study notably showed that the students were pleased with the fast prototyping capabilities provided by the system, but no learning outcomes were studied. In their study, Hayes et al. [11] showed that the VR module they proposed improved significantly the initial knowledge of the targeted pedagogical content. On the other hand, no comparison with a baseline condition was performed. The studies of Falcão and Price [9], and Yoon and Wang [33] were focused on children and the main goals focused on studying the collaboration between them. The results showed that AR and tangible interaction increased the teamwork of the children, but no learning outcomes were studied. Do-Lenh et al. [7] carried out a study to evaluate the learning outcomes of *TinkerLamp*. The authors suggest that *TinkerLamp* improved the learning outcomes compared to the other conditions.

In this paper, beyond describing the HOBIT platform, we report an experiment whose goal is to explore how a hybrid system as the one we propose impacts the building of new knowledge and skills. To this end, we conducted a study with a large number of participants (N = 101), and we compared HOBIT to a standard Michelson interferometer (see section *Evaluation*).

TECHNICAL DESCRIPTION

System Overview

HOBIT is an interactive platform dedicated to the simulation and the augmentation of optics experiments. The main components of the system are:

- A set of optical replicas whose goals is to mimic true optical elements (e.g. lenses and mirrors mounted on mechanical holders).
- A numerical simulation that computes in real-time interference patterns from a physical model, and for which the result is projected on a screen.
- An augmentation of the board by way of a second projector located on top of the experiment.

Users modify the parameters of the simulation by manipulating the optical replicas. As they would do with a real experiment, they can observe the result of their action on the projection screen. The augmentation aims at co-locating additional information within the physical experiment. Figure 3 illustrates the

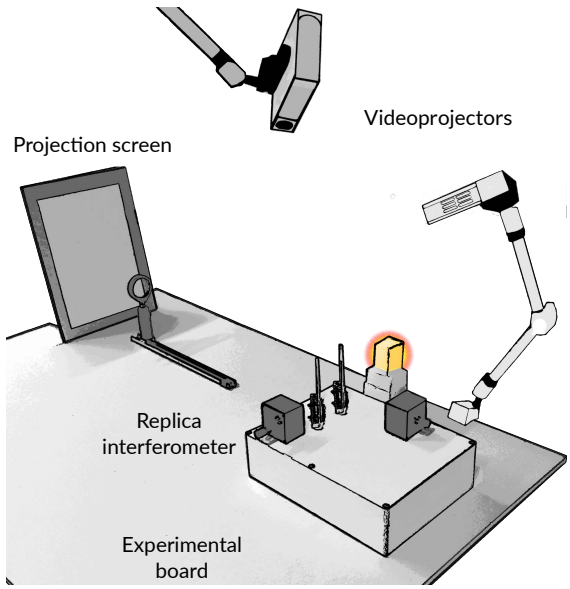


Figure 3. The HOBIT platform reproducing a Michelson interferometer.

HOBIT platform in a configuration that reproduces a Michelson interferometer.

The total cost of the components required to build the platform (laptop, videoprojectors, and sensors) is about four times cheaper than a standard Michelson interferometer, and several experiments can be built from the same platform. With HOBIT, the experiment is much faster to set up than with traditional optics experiments. Moreover, because the light sources are not real, HOBIT prevents from safety issues, in particular in the case of laser sources.

Optical replicas

Optical replicas are 3D printed objects equipped with electronic sensors. For the Michelson interferometer, we built the following components.

2 light sources (low-pressure sodium lamp and white LED) are plastic boxes with RFID tags. A stand equipped with a RFID reader allows detecting which light source is experimented.

2 mirror holders are equipped with knobs that mimic micrometric screws, which are used to control the position and orientation of mirrors in real experiments. One of them (mirror 1, see Figure 4) is equipped with one knob dedicated to control the axial translation of the (virtual) mirror. The other one (Mirror 2) is equipped with two knobs dedicated to the orientation of the mirror. It is worth noticing that translation and orientation changes on mirrors in reality are not perceptible. Hence, replicas appear as true mirror holders in the simulator. The resolution of the knobs is adjusted to mimic those installed in the real setup. In particular, for the axial translation, 1 full turn of the knob was set to induce a 500 µm translation. The same happens with the knobs of the Mirror 2 where one full turn of the knob is mapped to 1°.

1 movable lens mounted on a linear potentiometer allows simulating the modification of the lens-to-screen distance. One step of this sensor corresponds approximately to 0.29 cm.

2 passive elements mimic the role of the beam splitter and the compensator.

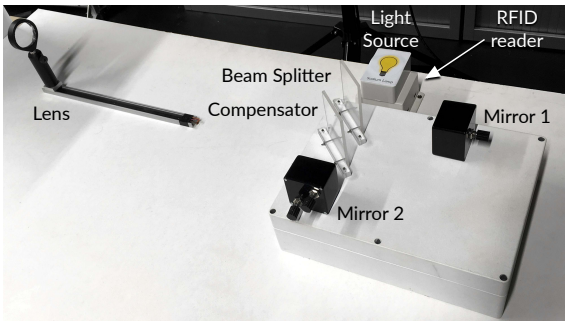


Figure 4. The optical replicas in a Michelson interferometer setup. The Arduino board is embedded under the platform on which the mirrors, beam splitter and compensator are fixed.

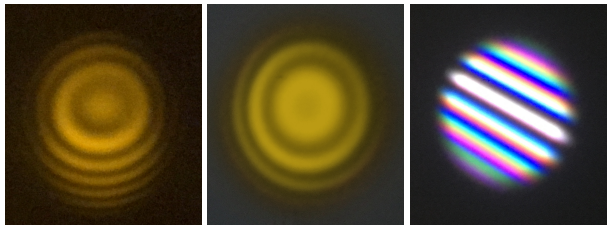
Figure 4 illustrates the optical replicas we build for the Michelson interferometer.

The RFID reader as well as all the sensors are connected to an Arduino board located under the platform where the mirrors, beam splitter and compensator are fixed. This board detects all the changes in the sensors states and sends them to the computer via an USB connection. The data is transmitted every 50ms.

Numerical simulation

The numerical simulation computes the interference pattern from the characteristics of the light source and the position and orientation of the mirrors and lens. The intensity of a point on the screen is computed based on the theory of interference involving two waves. The detailed model that is used to compute the interference patterns is described in the accompanying complementary file for reproducibility purposes.

At the end, the obtained interference patterns are very close to the ones that are obtained from a true Michelson interferometer, as depicted in Figure 5.



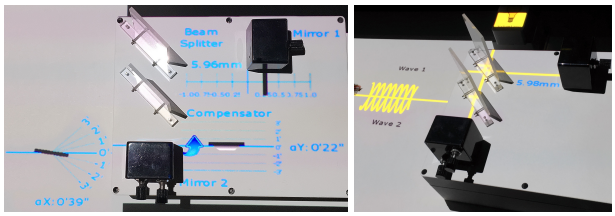
(a) (b) (c)

Figure 5. Examples of ring interference patterns of the low pressure sodium lamp from (a) a standard Michelson interferometer and from (b) the numerical simulation of HOBIT. (c) White light fringes interference pattern obtained with HOBIT.

Augmentation

The augmentation consists in projecting pedagogical information into the experiment. This information (e.g. texts, drawings, and animations) have been designed to support the students' needs. For example, with a standard Michelson, students may often be lost because they have no idea of what is happening when manipulating a mirror. Have they turned too much the screw? Or not enough? At the end, they may observe nothing without knowing why. With HOBIT, a schematic representation of the current state of the optical elements can be displayed next to them, as illustrated in Figure 6(a). This may help students to understand how their actions impact the observed phenomenon. Such an augmentation would not have been possible with a standard Michelson interferometer. Indeed, the precise state of the system needs to be known, which is not the case with a standard version.

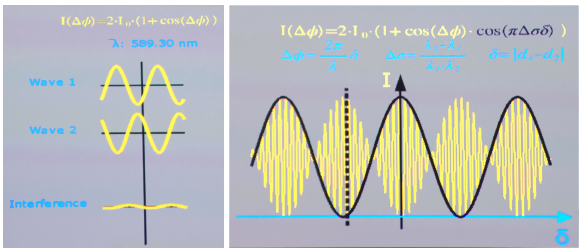
Animations may also help students to understand how light propagates. To this end, we propose the option to launch an animation that highlights the light path, and that shows how the waves coming from the two mirrors superimpose together. This is illustrated in Figure 6(b).



(a) (b)

Figure 6. (a) Augmented information displayed next to the mirrors. The blue arrow indicates that Mirror 2 is being tilted forward, and the current angle is $0'22''$. The drawing on the left gives an indication of the x orientation of Mirror 2, and the graduated linear scale on top magnifies the current position of Mirror 1. (b) Light path and waves combination.

Similarly, advanced pedagogical supports can be displayed directly onto the experimental board. For example, Figure 7(a) and 7(b), illustrates two representations of the signal that could be measured at a specific point of the visualized interference pattern. This point can be selected by way of a mouse input. Such representations aims for helping students to understand how the two waves combine together and, consequently, why a resulting intensity is observed at the selected location. They also provide explanation on the changing contrast that is observed in the case of low-pressure sodium lamp, which spectrum is characterized by two wavelengths very close one to the other. Formulas related with these phenomena can be displayed, too (see Figure 6). The parameters of these formulas are updated in real-time according to the actions performed by the students. This may help the students to strengthen the link between the observed phenomena, various representations, and the underlying concepts, all of them in a unique environment.



(a) (b)

Figure 7. Intensity of the interference pattern at a given location (a) and modulation of contrast (b) can be displayed close to the observed phenomena.

It is worth noting that all the augmentations and visual feedback features can be activated on demand. They are toggled from a keypad that stands next to the experiment. This keypad is active only when the *option* card equipped with a RFID tag is in contact with a dedicated RFID reader. A *start* card can also be used to instantly put the system back to an initial state, which is not possible with a standard Michelson interferometer. These cards give the teacher control over the application and the different pedagogical supports. At any moment, the teacher can place one of the cards in the RFID reader to enable or disable the privileges the card gives. For example, students are not able to run the simulation until the teacher has given them permission to do it by using the *start* card. The *option* card lets the teacher enable or disable the keypad in order to display or hide the augmented feedback. This notably gives the professor the ability to support his or her explanation of the theoretical concepts during the experiment. It also enables the teacher to control the difficulty of the experiment. Of course, the teacher can also decide to let the students manipulate the keypad by themselves, so they can experience, test, and discuss about the experiment.

EXAMPLE OF PRACTICAL WORK WITH HOBIT

After having switched on the computer and the two videoprojectors, the teacher runs the application. It will remain in a "stand by" mode until the teacher uses the *start* card on the RFID. Then, she or he provides an exercise form to the group composed of, typically, two or three students. The students have to experiment with the system to answer this form. For example, they have to find the right configuration of the setup for obtaining interference fringes with a sodium lamp. First, they place the (fake) sodium light on the dedicated stand. Then, they can manipulate the optical elements in order to find the concrete configurations that were theoretically presented during the lecture courses. If students encounter difficulties, the teacher can decide to display additional information like the current state of the mirror (see Figure 6(a)) and the place where the lens should be positioned to ensure adequate imaging conditions. To do so, the teacher just needs to activate the keypad with the *option* card, and toggle the corresponding option by pressing the associated key. Once the students have managed to obtain the expected interference pattern, they can physically measure the period of the fringes to determine the angle value of the mirror, directly on the projection screen (see Figure 8(a)), as they would do with a real Michelson interferometer. After the students have modified the system in order to observe rings on the screen, the teacher wants now to explain the modulation of contrast that can be observed on the pattern. The teacher decides to display a new visual feedback to support her or his explanation (see Figure 8(b)). Finally, the students have to observe what happens with a white light. Students just need to swap the sodium light box with the white light box, and they can now continue experimenting. After the experiment finishes, the teacher uses the *start* card to reset the system and begin a new experiment with the predefined conditions.

(a) (b)

Figure 8. Example scenarios. (a) A student measures physically the period of the fringes on the projection screen. (b) Teacher explaining the modulation of contrast.

EVALUATION

We conducted a user study to evaluate HOBIT in a real experimental class similar to the one described in the previous section. Our main objective was to explore how this system impacts scientific and technical learning compared to a standard corresponding experiment. We also explored the user experience and attractiveness of the system.

Subjects and apparatus

A total of 101 students (82 males and 19 females; mean age: 19.16±0.82 years old) and 6 teachers (5 males and 1 female; mean seniority in teaching position: 18.2±6.2 years old) participated to the study. The students were second-year students of a University institute of technology in optics. The teachers (3 assistant professors, 2 associate professors and 1 university professor) were those in charge of the optics lab work training program. All the teachers were experienced with standard Michelson interferometer teaching. They were all motivated by teaching in practical sessions and confident in their professional skills. All of them declared a professional use of standard digital technologies (e.g. creation of their teaching contents or their presentation slides). On the other hand, they were novice with emerging technologies (e.g. augmented reality and virtual reality). Before the experiment, the 6 teachers were invited to participate to a presentation and regulation session of the study methods. In order to get familiar with HOBIT, they first experimented with the system, guided by the research team, and they completed the problem-solving task corresponding to the upcoming students lab works. This took approximately 1 hour. After this training time, the mean perception of their *a priori* capability to use HOBIT during a lab work session was 5.1±2.2 on a Likert scale in 7 levels.

The study took place directly at the University of Bordeaux, during 3 months. Three conditions were tested:

- MI, a standard Michelson Interferometer
- SMI, a Simulator of a Michelson Interferometer, as described previously, but with no pedagogical augmentations. The SMI condition is thus a pure simulation of MI.
- ASMI, corresponding to the SMI condition, plus the pedagogical augmentations.

Our hypotheses were that

H1: replacing a real experiment (MI) by a simulated one (SMI) does not decrease the learning performance

H2: an augmented condition (ASMI) improves the learning compared to non-augmented ones (MI and SMI),

H3: the students who have learned with HOBIT (SMI and ASMI conditions) are able to transfer their knowledge to a real condition (MI).

MI and [A]SMI were installed in two separate rooms of the training lab, with similar setups (comparable room size, similar tables and chairs, similar lighting conditions).

Experimental protocol

One month before the lab work sessions, all students answered a pre-test questionnaire PT0 (see description in the *Results* section). This allowed us to estimate their preliminary knowledge on Michelson interferometer after the lecture courses period. Then, the students were divided into four homogeneous groups (see Table 1). The training sessions were carried out in pairs and lasted four hours (two hours per condition). The members of group A1 and A2 used SMI (resp. ASMI) first, and then MI. The members of group B1 and B2 used first MI and then SMI (resp ASMI). Students from each group were assigned to each teacher in order to limit a "teacher effect" (see [18]). During the first two-hours session, students had to solve a set of problems involving interferometry technical skills and knowledges. After the session, the students filled out a post-test learning assessment (PT1), and they swapped with the group having done the other condition. During the second two-hours session, students had to solve similar problems as in the first session. At the end of the second session, they answered a new post-test learning assessment (PT2), and they filled out a user experience questionnaire (UX) including the french translation of the simplified Attrakdiff survey [13]. The questions we asked in this UX questionnaire were oriented towards pedagogical needs, i.e. referring on usability, usefulness, and meaningfulness. Indeed, the personal perception of a pedagogical support could influence the learning quality, as it play a role in the extrinsic motivation of the user [21].

The pedagogical content, the training goals and the related exercises were prepared by the teachers team (see Table 2). A total of 95 students' forms were analyzed (4 students did not fill the forms, and 2 of them provided non-exploitable documents). Figure 9 summarizes the whole protocol. It is worth noting that in each session teachers explained how to use the system, either [A]SMI or MI. They were also available to clarify any doubts the students had, as done in ordinary lab work conditions. In order not to introduce possible inequity between the groups, no academic grade related to the Michelson interferometer was given.

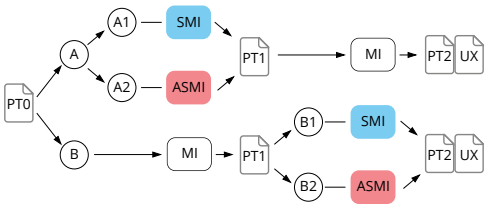


Figure 9. Summary of the protocol. A1, A2, B1, and B2 are the groups of students, PT0 refers to the pre-test, PT1 and PT2 to the post-tests, and UX to the user experience questionnaire. MI refers to the real Michelson interferometer; SMI refers to the Michelson interferometer simulator; and ASMI refers to the interferometer simulator with augmentation.

Groups	A1	A2	B1	B2
Number of participants	19	27	22	27
Mean±SD age	19.00±0.75	19.04±0.81	18.95±0.90	19.46±0.71
Male/Female	13/6	21/6	20/2	22/5

Table 1. Distribution of the groups.

Training goals	Wave optics: Michelson interferometry
Learning content	Origin of interference fringes and rings Role of the optical components Influence of the light source (mono or polychromatic)
Technical skills	Mobilize precise adjustments Identify and set up a technical configuration for various interference phenomena

Table 2. Pedagogical objectives of the lab work training program

Global reliability and design relevance

Overall, the subjects found that HOBIT *worked well* (mean and SD score on a 7 points Likert scale: 5.73±1.57; 7 being *"fully agree"*). During their manipulations, the students declared that they were not disturbed by occlusion problems (1.74±1.14, 7 being *"fully disturbed"*) nor by problems of delay between their actions and the resulting system reaction (2.05±1.31). They globally felt that the operating mode of HOBIT (SMI and ASMI conditions) was *close* to a standard Michelson interferometer (5.09±1.48, 7 being *"fully agree"*). These declarative results tend to show that the physical proximity of HOBIT with a standard Michelson experiment is meaningful.

Results on learning

In order to estimate the pedagogical relevance of HOBIT, we assessed its effectiveness in regard to the achievement of the learning goals described in Table 2. This assessment focused on the students capability to schematize and to explain scientifically an interferometer configuration and the related observable phenomena (e.g. Figure 2). In the pre-test (PT0), the students had to report how to obtain interference fringes with a monochromatic light source. In PT1, they had to explain how to obtain interference rings with a monochromatic light source. Finally, in PT2, we assessed their ability to explain how to obtain interference fringes, as in PT0, but with a polychromatic light source (see Figure 5(c)). Competency is effective for a learner when the integrated set of knowledges, skills and judgment enable her or him to effectively perform in various situations [3]. Slight variation between the tests ensures that the students have to think again about the correct answer. These tests allow us to estimate the impact of the condition (MI, SMI or ASMI) on the evolution of the learning and on its stabilization.

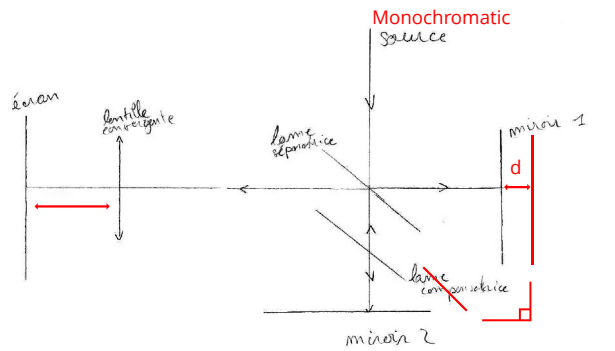
In addition to these tests, we also asked the students to answer a set of questions referring to general definitions and mathematical exercises about interferometry. These questions were asked after PT0, PT1, and PT2. They were related to previous courses (e.g. "definition of the parameters of an optics formula") and the corresponding skills were not targeted during the lab sessions (See Table 2). The assessment of these questions showed no differences between the groups, for each test. This allows us to verify that the observed learning evolutions were due to the learning condition only, and not to a group effect. Indeed, practical work may reactivate previous knowledge, and re-introduce non homogeneity concerning the initial knowledge of the groups.

The answers to the tests and the diagrams produced by the students were scored by a teacher and a researcher of the project team, using a scale from 0 to 5. The teacher and the researcher first scored 50 tests in a double-blind approach, with harmonization steps after 10, 30 and 50 assessments to validate the scoring scale. Then, i) the researcher assessed all the remaining tests and ii) the teacher checked the results in order to validate the scoring. Less than 10 equivocal tests were discussed. This analysis of the type of answers enabled us to estimate the learning level for each student after each session. The score of 5 was given to diagrams that were fully correct and adequately annotated. In this case, the learning is considered as acquired. The score of 4 corresponds to correct but partial answers with small omissions or broad wording. The score of 3 corresponds to correct but partial answers with notable omissions (i.e., optical element, angle, etc.) and confused explanations (i.e., lack of scientific vocabulary). Both 4 and 3 scores were counted as an underway learning. Finally, the scores of 2, 1, and 0 were given in case of wrong answers (diagram without any of the expected elements and/or conflicting explanations), off-topics, or blank answers, respectively. This refers to not acquired knowledge. Figure 10 illustrates an example of diagram.

It is worth to mention that all the analyzes carried out for the learning data as well as the UX data use the Aligned Rank Transform for nonparametric factorial ANOVAs as described by Wobbrock et al. [30]. After the Aligned Rank Transform processes the data, ANOVA tests can be performed. One advantage of using the Aligned Rank Transform with ANOVAs over common nonparametric tests is that we can analyze multiple factors and their interactions.

Pre-test PT0

The scoring of PT0 showed that 94% of the students were not proficient in schematization and explanation of interferometer configuration before starting the lab work training session (mean score of the whole cohort: 2.52±1.21, see Table 3 and Figure 11). Most of their mistakes were linked to inappropri-



Mirror 1 and 2 have to be perpendicular and at different distances from the beam splitter.
The observed interference rings patterns depend on distance d.
The screen has to be on the focal plane of the lens.

Figure 10. Example of diagram produced by a student at PT1. She was asked to explain the configuration in which interference rings can be observed. This diagram has been marked as "under way". Indeed, the overall structure is correct, but important information is missing (e.g. lack of the shift distance d).

ate positioning or omissions of optical components, lack of relevant annotations, or confusions with other configurations or with other interferometer (e.g. Young's interferometer). It confirms previous studies indicating that university students do not easily understand the physical models and have many difficulties to construct mental images only with a theoretical approach (see e.g. [6]). A one-way ANOVA revealed no significant differences between the four groups ($F[3, 87]=1.33$, $p=0.27$, $\eta^2_G=0.04$; see also PT0 in Table 3).

Post-test PT1

A two-factor mixed ANOVA showed that after the first two-hours training sessions, the overall knowledge about the interferometer configurations has improved significantly ($F[1,86]=61.94$, $p<0.01$, $\eta^2_G=0.26$ / PT0: 2.48±1.21; PT1: 3.88±1.17). The ratio of students with insufficient knowledge decreased in all groups, as illustrated in Figure 11.

The ANOVA also revealed that there is an effect of the learning condition on the scores obtained in PT1 ($F[2,86]=3.51$, $p=0.03$, $\eta^2_G=0.04$). A Tukey's pairwise test showed that the scores obtained in the ASMI condition (4.44±0.77) are significantly higher than the ones obtained in the other conditions (MI: 3.67±1.26 ($p=0.02$) —SMI: 3.63±1.16 ($p=0.05$)). This confirms that augmentations enhance the building of the targeted knowledge (**H2**). On the other hand, no significant differences were found between SMI and MI ($p=0.99$), which does not contradict **H1**. The ratio of students having acquired the knowledge is comparable in both conditions (Figure 11, second line). The typologies of errors were very similar (e.g. error of mirror angulation and error of distance between the beam splitter and the mirrors). This tends to show that the SMI condition reproduces closely the MI one.

Post-test PT2

We observed the evolution of the scores from PT1 to PT2 (see Table 3 and Figure 11). A two-factor mixed ANOVA showed that, for group A2, no significant differences were found ($F[1, 24]=0.88$, $p=0.36$, $\eta^2_G=0.04$). This tends to indicate that the students who have learned with ASMI did not decrease their performance when moving to MI. Their scores remain higher than any other conditions. These students gained most of the understanding and skills required to calibrate and troubleshoot

Groups	A1	A2	B1	B2
PT0	(Mean±SD score, max=5)			
Target knowledge	2.63±1.21	2.59±1.12	2.86±1.25	2.11±1.28
General definitions	1.66±0.69	1.81±0.95	1.86±0.68	1.51±0.79
PT1	(Mean±SD score, max=5)			
Target knowledge	3.63±1.16	4.44±0.77	3.72±0.89	3.63±1.47
General definitions	3.18±0.68	3.28±0.68	3.39±0.46	2.92±0.71
PT2	(Mean±SD score, max=5)			
Target knowledge	2.32±1.38	4.12±1.13	3.11±1.49	3.48±1.55
General definitions	3.58±1.09	3.97±0.88	3.92±0.81	3.81±1.00

Table 3. Knowledge scores for the pre-test (PT0), and the post-tests (PT1 and PT2).

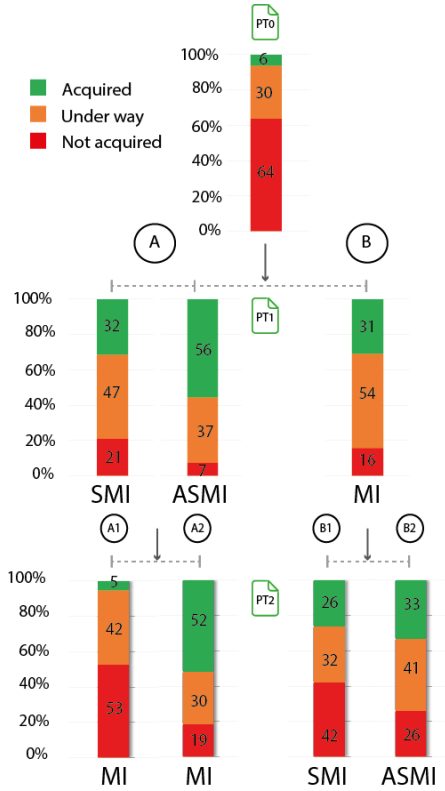


Figure 11. Learning results as ratios of students being at different levels of knowledge and skills acquisition—before the experiment (first line), after the first training session (second line), and after the second training session (third line)

setups used to make interferometry observations. It seems to indicate a stabilization of their learning; the knowledge that has been built with ASMI could be reinvested effectively with a classical interferometer. This would go in the direction of **H3**.

On the other hand, for group A1, i.e. the students who experienced with MI after having learned with SMI, a two-factor mixed ANOVA highlighted an unexpected result. In this group, the learning achievement significantly decreased ($F[1, 18]=8.92$, $p=0.01$, $\eta^2_G=0.33$, see Table 3). This partly refutes **H3**. The amount of students who were underway or without any clear acquisition was quite similar to those noticed in PT0. We observed that 20% of the A1 students did not answer to all the questions of PT2. They rushed their work or did a lot of basic mistakes. In comparison, this ratio was between 2 and 6% for all the other groups. A1 was the group that indicated the lowest motivational advantage to use a hybrid system compared to a standard Michelson interferometer in their UX results (see next section). Therefore, it appears as if they were demotivated. That leads us to the idea that these results could probably be linked to the hope the students put in simulator to support their learning. It might destabilize their first understanding noticed in PT1 and act as a disruption in the learning process by stating that they still had some difficulties to setup the classical Michelson interferometer even if they trained on a simulator just before. This needs to be confirmed

by further analyzes and replications of the experiment. However, it opens the question of the students representation of the role of a simulator in educational context.

For the groups that have initially started with MI, no noticeable improvement can be observed after using SMI (B1) nor ASMI (B2). It tends to show that the augmentations that have shown undeniable benefits after PT1 (group A2), have little impact when activated in a second round of training session. Students may mainly built their knowledge during the first training session, where no augmentation were available. However, it worth noting that the typology of mistakes were different between the two groups. For instance, in the group using SMI at the second round (B1), 37% of the students forget to position the lens and the compensator. This indicates that they did not perceive the role of these components. At the opposite, with ASMI (B2), most of the mistakes were only due to incomplete annotations of the diagrams.

The results obtained for the questions that were not directly linked to the targeted knowledge and skills (i.e. general definition and mathematical exercises) for each step of the learning process (PT0/PT1/PT2) did not show any significant differences between the four groups. Additionally, all teachers confirmed the absence of notable modifications on their teaching practices induced by the study conditions (5.83±1.60; 7 being "fully similar"). Moreover, the participants declared that they were not stressed during the study (students: 1.21±0.63; teachers: 1.66±0.81, 7 being "fully stressed"). All these results allow us to exclude a group effect; the observed learning evolutions are due to the system only.

Understanding the role of the augmentations

To gain insight on the relevance of the augmentations, we have looked at the declared perceptions of the ASMI users (groups A2 and B2) and the declared perception of the SMI ones (groups A1 and B1). A one-way ANOVA was performed for each of the asked questions. The ASMI users perceived the tool as less complex to operate than the SMI users, in comparison with the MI condition ($F[1, 92]=12.66$, $p<0.01$, $\eta^2_G=0.12$ - see Figure 12). Similarly, the augmented version was perceived as more motivating ($F[1, 91]=10.98$, $p<0.01$, $\eta^2_G=0.11$), and more efficient ($F[1, 74]=25.80$, $p<0.01$, $\eta^2_G=0.26$) than a tool without augmentation (see Figure 12).

Among the augmentations, the indications displaying the state of the manipulated components (Figure 6(a)) were the ones that the ASMI students cited first (69% of the them). 5 of the 6 teachers reported that they considered this augmentation as the most important. The students and the teachers also endorsed the schematic projections of the wave interferences (Figures 6(b) and 7).

A large majority of the ASMI users (91%) declared that the system they used have met or totally met their needs to their learning goals (5.95±1.15, 7 being *"fully agree"*). In comparison, the mean score for the SMI users is 4.19±1.54. About this question, the open-ended spontaneous answers (multiple answers were possible) of the ASMI users were that the system i) helped them to understand the theoretical aspect of the interferometry phenomena (49% of the answers), ii) supported

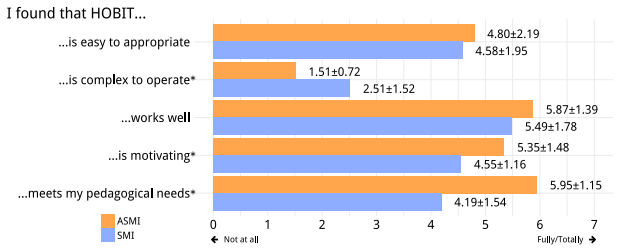


Figure 12. Results of the UX questionnaire (selected questions). The symbol * indicates statistical significant differences between SMI and ASMI.

or enhanced their cognitive conception (conceptualization) of the wave phenomena (32%), iii) highlighted the causal effect between their interferometer adjustments and the observed interference patterns (20%), and iv) supported or enhanced their understanding of technical adjustments of an interferometer (14%).

At the opposite, the answers of the SMI users were more neutral. They rarely declared pedagogical gains compared to the MI condition, except for the *restart* functionality.

Regarding the perceived attractiveness, the students of the ASMI condition found the system really appealing both for its pragmatic and hedonist attributes. Based on the Hassenzhal's model [10] applied on the Attrakdif results, the augmented version of HOBIT appears as a desirable pedagogical tool (see Figure 13). In contrast, the students of groups A1 and B1 who did not experienced augmentations were a bit less enthusiastic.

The answers of the students are in line with the teachers comments. Teachers reported that the ASMI students were more motivated and engaged than the SMI ones. Three of them indicated that many of the SMI students did not perceived the added value of a simulated system without augmentations. All the teachers agree that the augmented version of HOBIT is much more interesting than a version without augmentations.

The pedagogical augmentation seems to be necessary to support students in their understanding of technical specificities of the interferometer configurations and on their adjustments.

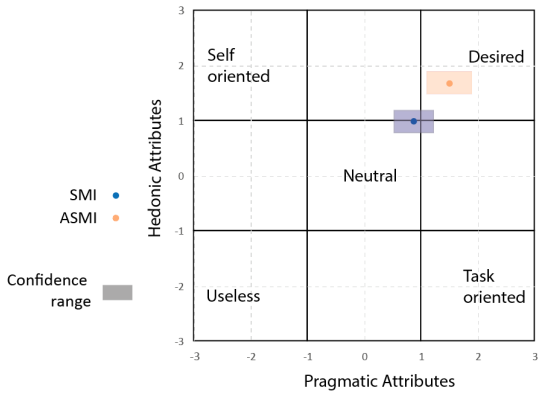


Figure 13. Perceived attractiveness of SMI and ASMI from the Attrakdiff survey [10].

Each user constructs his or her personal representation of the system by defining (consciously or not) various attributes. The high perception of usefulness and attractiveness provided by the pedagogical augmentations, and the perception of the users that the system addresses their needs, could explain the fact that the ASMI group obtained the best learning results.

To strengthen these results, new experiments should be conducted to assess how the acquired knowledge stabilizes over long periods of time.

DISCUSSION AND CONCLUSION

To overcome the limitations of standard setups, we developed a hybrid platform, HOBIT, which allows us to mimick true optics experiments. This platform reduces the cost as well the setup and maintenance time as no real optical components are used. Beyond the simulation, we showed that HOBIT offers the opportunity to augment the experiment with pedagogical supports. A study conducted in an ecological situation allowed us to demonstrate that such an approach, which mixes simulation of the real phenomena and virtual augmentations, enhances the learning of students compared to traditional setups. HOBIT does not aim at fully replacing true optics experiments. Similarly to a flight simulator, this platform makes training sessions more convenient. Because we took care to mimic as much as possible the real condition, and because we embed relevant augmentations within the simulation, the good transfer to the real condition is favored.

In this work we focused on the Michelson interferometer experiment. HOBIT is not limited to this particular experiment. Numerous other augmented optics experiments can be designed from this platform. As an example, we are currently building new pedagogical activities for simulating and augmenting Young's interferometer and polarization experiments. Beyond optics, a similar approach could benefit other domains. This is notably the case of scientific fields were the visualization of abstract concepts is important. With augmented information it is possible to create new representations that can help students to observe those abstract concepts or invisible phenomena [31]. For example, in the electronics field, an efficient learning and understanding of complex concepts remains a challenge.

We hope that our work will help practitioners to design new relevant learning environments in a variety of fields. To this end, we would like to remind the importance of taking into account the nature of the scientific knowledge and the pedagogical orchestration of practical works at the early stages of the technological design process. Co-design with experts and teachers of the targeted field is a key element for the design of meaningfulness systems that remain as close as possible to the real experiences. We also encourage evaluations in ecological situations, as we did with HOBIT. Both quantitative comparative studies and UX surveys help gaining insights about the factors that play significant roles in learning. Finally, we would like to remind that a technological enhanced tool in and of itself is not necessarily a golden bullet that enhances learning. Without proper pedagogical support, it can actually backfire, as we have shown in our study.

In this paper, we have focused on the evaluation of the learning efficacy by looking at the individual performances of the students. Beyond these performances, it would be interesting to explore how a system like HOBIT modifies the interactions between the students, and how it impacts teaching practices. Indeed, education has to be considered in a larger spectrum than learning performance only. This is one axis of development of our current work.

We hope that the approach we have described in this paper will open the way to a new generation of hybrid pedagogical systems used in real conditions at schools or at Universities.

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