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Design of an open-lab activity for engineering students: A case study

D Persano Adorno[1], F Scardulla[2], L D'Acquisto[2], and N Pizzolato[3]

Abstract

Project- or discovery-based learning activities promote curiosity, enjoyment, and interest deriving from the stimulating context in which students operate. Providing a concrete contextualization of laboratory activities could improve student motivation and learning outcomes. In this contribution, a case study related to a workshop on laboratory activities proposed for Engineering Master students is presented, and designed with the aim of developing practical competencies, increasing problem-solving skills, and providing design abilities. Using the facilities available in the Measurements and Control Laboratory, the students, starting from concept knowledge acquired in basic subjects, such as Physics, Chemistry, Mathematics, and Electronics, design and implement their experiments, gaining a deeper understanding of core disciplinary concepts while strengthening soft and teamwork skills. The challenges and possibilities of these self-directed thinking and learning laboratory activities are also discussed.

Introduction

The development of soft and transversal abilities should be fostered within each course of study, enabling learners to acquire and maintain skills that facilitate full participation in social life, promoting active citizenship, social inclusion, and improving prospects for employment or self-employment. The European Union has recently updated the list of

[1]Department of Physics and Chemistry, University of Palermo, Palermo, Italy
[2]Department of Engineering, University of Palermo, Palermo, Italy
[3]ICS "Maredolce," Palermo, Italy

Corresponding author:
D Persano Adorno, Department of Physics and Chemistry, University of Palermo, Viale delle Scienze, Ed.18 90128, Palermo, Italy.
Email: dominique.persanoadorno@unipa.it

key competencies, for the fulfillment and development of the person and to promote employment, which is identified with reference to eight areas of a cognitive, implementation, managerial, relational, and communicative nature.[1] In this context, the Teaching & Learning Centre of the University of Palermo resolved to make available, starting in autumn 2020, a series of supplementary activities and courses to develop these transversal and soft competencies. The authors here present and discuss one of the activities proposed for the Engineering Master students, designed with the aim of developing practical competencies, increasing problem-solving skills, and providing design abilities. Using the facilities available in the Mechanical Engineering laboratories, the students, starting from an everyday-life problem to face and solve, using the concept knowledge acquired in subjects, such as Physics, Chemistry, Mathematics, and Electronics, design and carry out their own experiments, gaining a deeper understanding of core disciplinary concepts while strengthening soft and teamwork skills.

Traditional lecture-based instruction at university needs to be integrated with research-like experiences in order to provide the students with a concrete opportunity of connecting theoretical principles to laboratory practice, and, at the same time, develop transversal abilities. Among several ones, the most important skill a future scientist, physicist or engineer, should gain is the reasoning ability for problem-solving. This has nothing to do with content knowledge. It can be built only by performing experiments, facing problems in laboratory, planning investigations, designing measurement protocols, analysing data, drawing models for explanations, performing numerical simulations, discussing results, sharing ideas with peers and starting again if needed. All these activities are driven by reasoned questioning. All these reasoned phases of the learning process in science/engineering can only be experienced in research-like experiences.

The proposed learning workshop engages the students in practical knowledge and laboratory techniques hardly found in books, with learners performing hands-on activities aimed at investigating bioengineering phenomena through the preliminary analysis of a real problem, the designing of an experiment, and the handling of real data for scientific analysis and interpretation.

Results of research in science and engineering education strongly encourage the involvement of graduate/undergraduate students in laboratory activities based on inquiry-based strategies[2–7] of student-centered active learning.[8–11] In this work, the research-like workshop is designed to improve student comprehension and retention of theoretical concepts; develop critical thinking skills and reasoning abilities; encourage communication, sharing, and discussion among students; and enhance student satisfaction, curiosity, and desire to gain effective learning.

Participation in discovery-based[12,13] and problem-based learning activities[14–18] promote curiosity, enjoyment, and interest, deriving from the stimulating real-life context in which students are actively engaged. Providing a concrete contextualization of laboratory practice generally improves student motivation and learning outcomes.[3,6,12]

In this paper, the authors present the results of a case study on a laboratory workshop designed to provide engineering students with a learning experience of open-inquiry-based hands-on activities, designed to be both enjoyable, interesting, and helpful to achieve the desired learning objectives. In particular, students were asked to design, realize and test a prototype of the augmented protective mask with embedded sensors monitoring basic health parameters. In the following sections, all the phases of the lab activities will be described, by highlighting the student point of view on facing and solving a real-context scientific problem. Despite the limitation of a case study, our findings support the educational framework of effective instruction characterized by a concrete contextualization and student-centered laboratory activities, enhancing motivation, transversal skills and learning outcomes.

Inquiry-based science education and engineering practice: A brief introduction

Inquiry-based Science Education (IBSE) is a well-established pedagogical approach where teaching/learning activities foster the acquisition of both science content knowledge and reasoning skills. The core idea of IBSE is the promotion of a way of teaching focused on the activation of student reasoning by promoting stimulating learning environments, based on concrete research problems, and characterized by an active construction of meaningful knowledge. An inquiry-based instruction drives the students, at different levels of guidance, through the fundamental process of questioning. Students are actively engaged in several integrated activities of identifying a problem, planning studies and exploration activities, gathering data and evidence in a laboratory or real-life environment, creating models, distinguishing between possible explanations or solutions, searching for information, sharing results, and discussing in the context of peers.[19] In IBSE, developing problem-solving skills, abilities to carry out research, and sharing the responsibility for their learning, become more mindful and sophisticated.[20] The acquisition of new knowledge when looking for effective solutions to a problem lets the student be actively involved in the learning process, increasing student perception and awareness of the acquired capabilities.

Researchers typically distinguish between different levels of inquiry-based instruction (confirmation, structured, guided, and open), depending on the quantity and quality of specific directions (e.g., reasoned questions, lab procedures, and suggestions on expected results) provided to the learners. Instructors play the delicate role of guiding the scientific inquiry of their students by selecting different approaches for consolidating student reasoning and understanding. An entry level where the educator specifics every aspect, up to the highest grade where the student gains the intellectual and technical skills necessary to act as a scientist.[19] An increasing level of inquiry enables students to gradually develop their abilities to conduct more independent investigations.[19] At the highest level—*Open Inquiry* (OI), students derive their own questions, design and carry out their experiments, and the support from the educators becomes less instructive but more qualifying and perceptive. Results from OI learning experiences[21] suggest the students gain mindfulness of the process of scientific inquiry and a deeper view of the nature of science.[22,23]

In the field of engineering education, however, the inquiry-based approach should be properly revised or integrated. As a matter of fact, becoming a scientist is not the same as becoming an engineer, in terms of scientific thinking and transversal abilities. Scientists use the inquiry-based method to make testable explanations and predictions about the world. A scientist asks a question and develops an experiment, or set of experiments, to answer that question. Engineers use the engineering design process to create solutions to problems.[24–26] Engineering practice starts from the definition of the problem that needs to be solved, and moves through background research, asks for specific requirements to create alternative solutions, chooses the best one, and develops it by building a prototype, which is tested and redesigned as necessary.[24] And, finally, communicate and share the results (see Figure 1). There are always several good possibilities for solving a problem. Focusing on just one before looking at the alternatives, almost certainly brings to overlooking a better solution.

Good designers try to generate multiple possible solutions, with some meeting more requirements than others.[25] Throughout the development phase and a further design process, the refinement and improvement of a solution come out. Building and testing prototypes is a key step in the development of a final solution. Likely, subsequent testing of the solution opens to new problems, suggesting changes and new solutions before settling on a final design. The steps involved in the engineering design process can greatly enhance students' ability to apply science and mathematics concepts in solving real-world problems.[26] Creativity, designing abilities, out-of-the-box thinking, and real-context problem-solving seem to be the necessary skills a student needs to develop to successfully become an engineer. The main aim of our educational research is to explore the learning efficacy of inquiry-based laboratory activities integrated with the designing processing of real-world scientific/engineering problems.

Materials and methods

The open laboratory workshop described in this paper was designed by a group of academics (Physicists and Mechanical Engineers), in order to engage Engineering Master students in a research-like practice with the aim of fostering student learning through the project itself, by exploring new techniques and approaches, gaining transversal technical competences and improving their soft skills.

The working program presented in this paper aims to merge the benefits of three traditional learning activities which are highly important for the scientific and technical background of a future engineer, namely (i) a university open-lab experience, (ii) a work

Figure 1. The engineering design process.

experience within an engineering company, and (iii) a highly valued experience to increase the personal attitude to scientific entrepreneurship. Specifically, at the very beginning of the open-inquiry-based activity, a generic practical problem is delivered to the participants of the program, which are asked to find a solution, to develop a prototype of the potential commercial product, to complete some preliminary tests in order to evaluate the reliability and efficacy of the proposed solution, and, finally, to deliver a presentation explaining and convincing the audience that their solution adequately solves the problem and it is a good potential commercial opportunity to invest in for the full development.

Due to the transversal nature of the skills required, the proposed learning activity is appropriate for Master students belonging to the mechanical, biomedical, electrical, and management engineering classes; in such a way, the group of participants could be composed of students having different technical backgrounds and scientific profiles.

In this paper, the authors report the first stage of an extended research study oriented to obtaining high-quality instruction outcomes in the field of engineering education and practice. Prior to performing a large-scale educational trial involving a great number of students, a relevant experimental design is required, analyzing the project feasibility, expected benefits, and critical aspects to face in order to obtain the best results in terms of student skills development. For this reason, a case study is the first step of the entire research protocol, the smaller-sized study will support the design of the main study. Usually carried out on few members of the relevant population, it represents a necessary preliminary investigation to avoid an inadequately designed teaching-learning environment. Moreover, in educational contexts, a pilot study offers a potentially valuable insight to increase the chances of clear outcomes, evaluate feasibility, duration, difficulties, and improve upon the learning environment design. As already mentioned, the experimental workshop that is presented in the following paragraphs was supposed to begin in October 2020. Unfortunately, the extension of the regulations against the spread of the Covid-19 pandemic prevented its starting, which was postponed for one year, and, therefore, authors cannot report any student group's participation yet. However, from the month of May 2021, trainee students were readmitted to laboratories. Therefore, in order to outline a potential approach to the problem highlighting the educational transversality, effectiveness, and feasibility of the proposed learning activity, two students, who were conducting an internship program in Mechanical Engineering Master at the Measurements and Control laboratory of the University of Palermo (Italy), performed this open lab activity, whose results are presented in the next paragraphs. Specifically, both students had already completed all the University courses for the Master in Mechanical Engineering and were close to take the final exam. Although the pandemic has prevented us from recruiting more people from different engineering courses, both students, for different reasons, had competencies related also to biomedical engineering and both had worked with photoplethysmographic (PPG) sensors, partially compensating for the lack of students from the biomedical degree courses. With the purpose of increasing the interest of the students, the problem proposed to them is about a topical issue, and it was conceived by taking into consideration a commercial product that is currently widely used to limit the spread of the same virus that made the laboratories impractical for students: the protective face mask.

The task: *Students were asked to design, realize and test a protective mask with embedded sensors in order to collect data on the main physiological parameters and obtain real-time monitoring of the stress level of surgeons during their practice*. Indeed, it is reported that the acute stress of surgeons and surgical trainees has an immediate impact on surgical performance and patient safety.[27] Different techniques have been adopted in the past years to estimate acute stress, including heart rate variability[28] and breathing rate[29] assessment.

Thus, the goal of the presented open inquiry learning environment is to design, develop, test, report, and, finally, promote a *sensorized* protective mask to be used within hospitals, which can detect as many physiological parameters as possible (at least including heart and breathing rate). All these phases allow students to put into practice different skills acquired during the five years of engineering courses such as, for example, designing, management, control, and measurements, also maturing those soft skills that only multidisciplinary activities of this type can actually improve. To go beyond a mere exercise of a purely technical nature, the authors decided to stimulate other skills that are essential for an engineer, namely the ability to create a product from an idea that can actually be marketed, and then, to promote it to a wide audience. For this reason, the design constraints provided to the participants took also into consideration some economical aspects (see Table 1).

The phases of the open laboratory workshop

The workshop activities can basically be grouped into four different phases (Figure 2), each designed to deliver specific stimuli and competencies to the students:

(i) *Phase 1: From the problem to the solution*: This phase aims to increase the student's ability to face a problem by working in a team, analyzing its aspects under different

Table 1. Objective and constrains of the learning program.

Objectives	Constrain
Prototype design and test	-Components should be relative cheap (under 50 euros) -The presence of the components within the mask should be almost imperceptible: weight and usability must be optimized -The system should be suitable for different types of masks -The system must guarantee adequate reliability for different external temperatures and for different breathing rates
Market eligibility	-Components must be cheap and readily available on the market; the cost of the potential final product must be adequate for market attractiveness
Miscellaneous	-Each group of participants, which must consist of 6–9 members, must complete the program and deliver the final pitch within 10 days

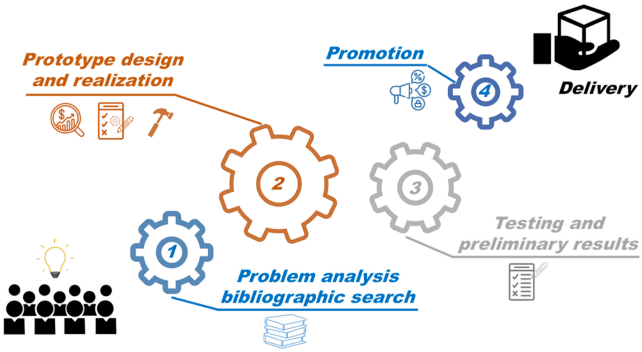

Figure 2. Schematic description of the scientific activities.

deeper scientific levels and inquiries, and improving the ability to access specific technical and scientific information. Then, in order to find an effective solution in compliance with the constraint (see Table 1), students should go through different technologies, comparing the physical principles governing different typologies of sensors, evaluating their appropriateness, and thus, improving their critical thinking skills.

(ii) *Phase 2: Prototyping:* Participants are expected to design and create a low-budget prototype based on the specifications and requirements of the program dispositions. This phase of the learning activity reflects a typical corporate task in which engineers are required to interact with their team, using information and tools in an appropriate way and collaboratively creating a product, while maintaining the required standards. Students will be able to use all the equipment supplied by the laboratory, such as thermocouples, 3D printers, DAQs, and welders.

(iii) *Phase 3: Testing:* Once the prototype is ready, students have to plan and conduct a testing phase to gather preliminary results and confirmation on the performance of the system to be presented in the last phase of the open laboratory activity. Under the supervision of the laboratory manager, students learn the basis of how to design an experimental activity, taking into consideration all the different influencing parameters to be tested and choosing from time to time, if any optimization is needed in order to meet the output requirements.

(iv) *Phase 4: Promotion:* In this ending part of the workshop, students are supposed to present a pitch deck to the organizers of the learning environment. The participants should give a short summary of the adopted solution to the problem and promote the potential commercial product, pretending to speak to an audience of investors. This last experience is very important from multiple points of view: besides improving several soft skills (e.g., creativity, enthusiasm, oral communication and clear articulation, public speaking, and public engagement), it increases the ability to defend their own idea and their own choices under either technical, scientific, or commercial aspects. Plus, another advantage of this phase is to increase the entrepreneurial spirit and resourcefulness of each student.

Specifically, in the following sections, the activities performed on specific days (three hours per day) are described with the report of the related problems faced, the solutions chosen, and, more importantly, the skills that are implemented with each activity.

Problem analysis and solution identification (days 1 and 2)

The first part of the project is exploratory, and it is solely focused on the study of the problem. In our idea, in the first two days, the students, appropriately divided into groups of 6–9 people (equally distributed according to their study background), devote themselves to an in-depth analysis of the state of the art, which comprises the study of the problem and thus, the investigation of the characteristics of the masks available on the market, as well as the identification of the main physiological parameters which could predict the onset of a state of stress.

In particular, before the actual start of the activities of the project, students will be asked to mutually assign positions and tasks to each other, as well as to elect a principal investigator in each team, who would be assigned the function of coordinator of the open-lab activity and designated person to update the instructors on the progress of the project. Nevertheless, as expected in any open-inquiry activity, students will have maximum freedom of initiative and the support of the teachers will be limited to technical suggestions or in predicting the possible effects that different choices could have. In this phase, students are also expected to use the skills acquired in their academic curriculum in order to analyse data and acquisitions and to produce proper graphs and results for the final presentation. It would be desirable that, within each group, students autonomously split into subgroups, each composed on the basis of the specific skills of each educational profile. Thus, each subgroup would work independently but still in synergy, receiving input from the other subgroups and providing outputs. During the first two days, all groups work in parallel with continuous exchanges of information that make sure that each subgroup orients its work accordingly to the output received from the other subgroups. Specifically, this part of the study does not necessarily need to be carried out exclusively inside the laboratory and could, partially, be developed individually.

In our hypothesis, the first subgroup may provide a report to be shared with all the participants belonging to the group on the stress and attention state of the medical staff during surgical operations, identifying the most appropriate physiological parameters that can provide indications of the stress and attention level. The second subgroup will select, on the basis of the information gained from subgroup 1, all those sensors and suitable technologies that could be integrated into a mask, optimizing functionality, costs, and dimensions. Finally, the third subgroup, grounding on the information received from subgroups 1 and 2, could work on the possible integration of the sensors, performing an in-depth analysis concerning the availability on the market of the components and their costs.

At the end of the first two days, learners should be able to identify the physiological parameters to be measured: the heart rate and respiratory rate (with blood oxygenation as an optional additional parameter).

Faced problems: Problem identification and understanding, definition of the most appropriate physiological parameters to be detected and of the most appropriate technology to be implemented.

Adopted solutions: Intensive literature search through different academic databases under the supervision and guidance of the involved professors.

Outputs: State-of-the-art analysis; identification of the physiological parameters of interest; and the sensing technology.

Improved competencies: Soft skills, including teamwork, digital literacy, leadership, professional attitude, problem-solving attitude, and work planning, collaboration, organization, and decision-making.

Identification of the most suitable sensors and components (day 3)

In this phase, students are asked to provide a report on the technical adopted solution motivating the reason for any choice, that should follow the constraints shown in Table 1. The motivations given by the two students involved in the pilot study were linked to functionality and metrological performance, cost, and integration into a mask without compromising its usability and safety or making it uncomfortable. A summary of their experience is reported below:

Heart rate detection. Among different technologies for the detection of heart rate, students have chosen a PPG sensor[30], which is an optical sensor that, for instance, students in biomedical engineering face during their studies. It consists of a LED, which emits light at a given wavelength, and a photodetector (PD) which convert the light into an electric signal. Specifically, the light emitted by the LED travels within the skin into the tissues. Part of this light is reflected back and returns to the PD, which transforms it into an electrical signal. The alternate component of the electrical signal corresponds to the volume variation of the small arteries and capillaries and therefore it is possible, through this sensor, to indirectly measure the heart rate by detecting a volume variation. The cost and the dimension of this sensor are extremely low and small as it is essentially composed of few electrical components and a small conditioning circuit. Thus, it can be easily integrated into the mask and positioned in the lace in correspondence with the ear and, then, fixed to the earlobe through a simple clip.

Moreover, students made careful literature research,[30,31] which elects the earlobe as one of the best sites for the acquisition of the PPG signal as it is very vascularized, without the presence of cartilage or muscles that can create motion artifacts or movements that can damage the signal or change the contact pressure of the sensor against the skin.[32]

Students have also asserted that by using the same sensor equipped with two different wavelengths (i.e., red and infrared), it is also possible to detect blood oxygenation, adding an additional parameter to achieve with higher accuracy the user's stress and attention level.[33]

Our students studied some scientific papers that state the possibility of obtaining the respiratory rate from the PPG signal.[34] Nevertheless, they decided to adopt another strategy to have a more accurate result. The sensor chosen by the students to carry out the first feasibility tests is a PPG sensor (DFRobot, Shanghai, China) equipped with a green wavelength and commercialized with an integrated circuit and thus, ready for use.

Respiratory rate detection. After a careful study, students decided to create a temperature sensor to be inserted within the mask to measure indirectly the respiratory rate by detecting the changes in temperature occurring with breathing. The sensor proposed by the students is the thermocouple, which is a temperature sensor composed of any pair of electrically conducting thermoelectrically different material legs in contact at a junction, which is achieved by twisting or welding the very end of the two wires.

Specifically, a thermocouple produces as an output a voltage which is temperature dependent as a result of Seebeck effect, and this voltage can be used to measure temperature. The junction used for measurement is conventionally called the hot junction while the other end, consisting of the free ends of the two conductors, is conventionally called the cold junction or reference junction. Thus, as the temperature changes at the hot junction, a voltage is created, and it can be interpreted to read the temperature. The electric potential variation across the free ends of the two conductors corresponds to a temperature value since this electric potential is a direct function of the temperature difference, according to a non-linear law. Students also provided additional motivations to support the use of a thermocouple as a respiratory rate sensor: it is an extremely cheap sensor which is accurate for the aim and, being essentially made up of two wires, it can be inserted inside the mask without altering its weight or functionality. Plus, since it is not essential to quantify the actual real temperature inside the mask but only the fluctuation, it is not necessary to equip the sensor with an additional thermal sensor to compensate for the reference junction, thus, minimizing costs and size even further.

Faced problems: Identification and adaptation of the proper technology.

Adopted solutions: PPG sensor and thermocouple.

Output: Choice and design of the most suitable sensors; selection of the key components of the device.

Improved competencies: Creativity, design, deepening of the physical principles behind each sensor, multiple soft skills.

Realization and integration of the sensors within the mask (days 4 and 5)

Authors assume that on the fourth day the students have defined all the technical aspects of the integration within the mask, as well as the choice of all the hardware components. A schematic representation of the integration of all components is shown in Figure 3.

Specifically, the students of the pilot study stored all the electronic components in a 3D printed case (Figure 3, detail A) that also acts as a clip to fix the mask at the nape. They explained that this solution has a double advantage: on one hand, it ensures that the weight of these elements does not create discomfort for the user as it is partially balanced by the elastic bands of the mask itself. On the other hand, it creates the opportunity to

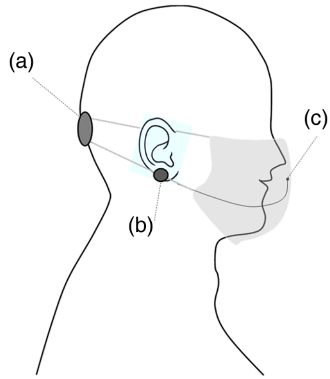

Figure 3. Integration of the different components within the surgical mask; specifically, A is a snap fastener which integrates electrical components (i.e., acquisition board, battery and amplifiers), B is the PPG sensor and C is the thermocouple inserted between the internal layers of the mask.
PPG: photoplethysmographic.

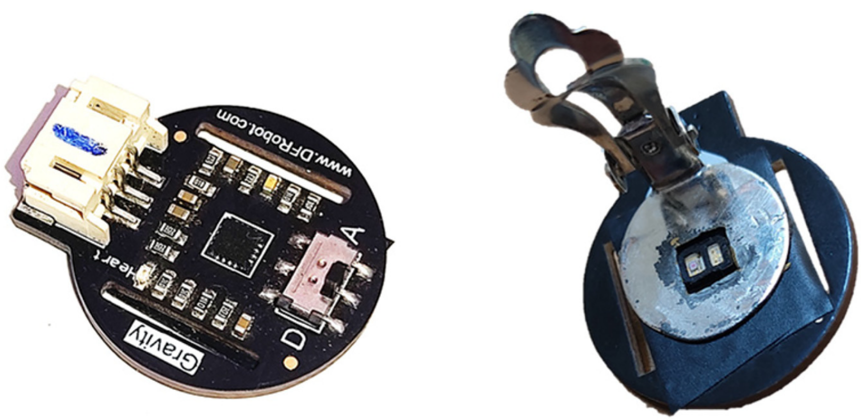

Figure 4. PPG sensor equipped with the clip to be worn in the earlobe.
PPG: photoplethysmographic.

make this component reusable, thus reducing the eventual cost of the mask itself in a possible marketing phase.

The PPG sensor is hooked to the elastic of the mask, and it can be positioned to the earlobe thanks to a clip which has been adapted and integrated into the sensor (see Figure 4).

Finally, the thermocouple is inserted inside the layers of the mask and the cold junction is carried inside the elastic elements of the mask to the case on the back (Figure 3). Students involved in the pilot study realized two identical transducers using a K-wire for

Figure 5. K-wire for thermocouple and hot junction (on the right).

thermocouples (measurement range from −200 °C to 1200 °C) and an RS Pro L60 welding machine, integrating them both in FFP1 and FFP2 masks. A detail of the thermocouple is shown in Figure 5.

Subsequently, the two students developed hardware and software aspects to make the prototype ready for use. Specifically, the Arduino Nano acquisition board (Arduino, Turin, Italy) was used to acquire both the PPG and the thermocouple signal. In this preliminary phase, a MAX 6675 module was used for the amplification and reading of the voltage at the ends of the thermocouple legs as well as for the conversion of the output directly into Celsius degrees.

On day 5, the protocol for the evaluation of the effectiveness of the indirect respiratory rate measurement technique, under different external conditions, was designed. In particular, tests were planned to be performed under the effect of different influencing parameters, in compliance with the prescriptions reported in Table 1. Thus, our students decided to test two types of masks (FFP1 and FFP2, respectively), at two different room temperatures (namely 30 °C and 23 °C), at two types of breath (only from the nose and only from the mouth) and, finally, at three different respiratory rates (namely 40, 50 and 60 bpm), as summarized in Table 2.

Faced problems: Sensor integration, tests planning.

Adopted solutions: Reusable case for the hardware components, stable positioning of the PPG sensor, appropriate protocol design.

Output: Realization of the prototype and definition of the testing protocol.

Improved competencies: Design in compliance with project constraints, integration, thermocouple realization, and hardware development.

Preliminary tests and prototype optimization (days 6 and 7)

The experimental protocol was carried out by the two students, testing the effect of all the variables presented in Table 2 in order to verify the effectiveness of the proposed system at different conditions of use. One of the participants in the pilot study conducted the tests

Table 2. Potential influencing parameters and variables to be tested within the testing protocol.

Influencing parameters	Affecting factors	Variable to be tested
Mask type	Affects the dispersion of the heat outside the mask	FFP1 and FFP2
External temperature	The temperature gradient between the inside and outside the mask affets the dispersion of the heat outside the mask	23 °C and 30 °C
Breath type and respiratory rate	These parameters influence the air flow and thus the temperature's variation within the mask	Mouth and nose at 40, 50, and 60 bpm

wearing either the two types of masks both outdoors ($T = 3$ °C) and indoors ($T = 23$ °C), at three different respiratory rates and breathing alternately only from the nose or only from the mouth, for a total of 21 tests of 1 minute each.

To identify any unsatisfactory system performance in advance, the student started the test with the worst possible case scenario, which is wearing an FFP2 mask with an external temperature of 30 °C and breathing from the nose at a respiratory rate of 60 bpm. Indeed, in these conditions, the student obtained unsatisfactory results with a temperature variation detected by the thermocouple so low as to produce an error of up to 20% with respect to the actual respiratory rate of the student. Thus, first tests established that one thermocouple is not adequate in terms of sensitivity to detect temperature variations inside the mask for specific unfavorable conditions.

In order to overcome the problem, students realized a thermopile composed of two thermocouples connected in series, where both hot junctions should be exposed to the same temperature within the mask, as shown in panels A and B of Figure 6.

The purpose of a thermopile is to create a more sensitive transducer with respect to a single thermocouple, as the output of a thermopile is the sum of the voltages across the individual junctions, giving larger voltage and power output. With this solution the students were able to achieve more reliable results in any condition, obtaining accurate respiratory rate even in the worst possible conditions.

Faced problems: Inadequate performances of the system under specific conditions.
Adopted solutions: Development and integration of a thermopile within the mask.
Output: Optimized prototype.
Improved competencies: Problem solving, critical reasoning.

Signal processing and preliminary results (day 8)

Once the testing protocol was finished and all the signals were acquired, students processed the signals in order to verify the performances of the device and obtain preliminary results.

Data provided by both the PPG sensor and by the thermopile were processed off-line by using a dedicated Matlab® algorithm (MathWorks, Inc., Natick, MA, USA), designed to reduce noise, remove any outliers, detect positive, and negative peaks in the time domain and then, to provide both the respiratory rate and the heart rate. Since the PPG sensor used in the experiment was a commercial product and a reference sensor was

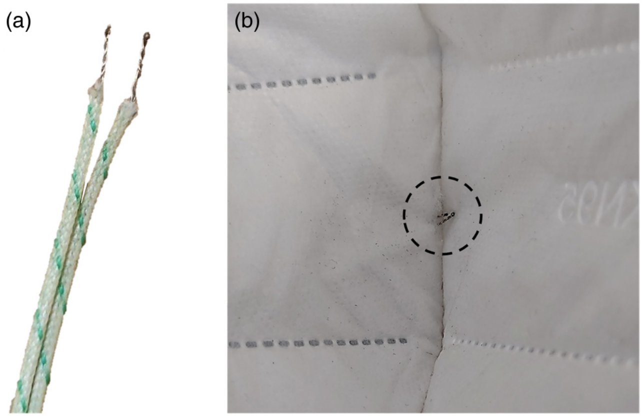

Figure 6. Realization of the thermopile (panel A) and integration within the mask (panel B), where it is also possible to observe the two hot junctions of the thermopile protruding from the internal layer of the mask.

not used at this preliminary stage, the heart rate results will not be reported. However, it is worth mentioning that from a qualitative analysis, a stable signal was observed, with few outliers and good amplitude.

From a qualitative perspective, it is possible to observe that the thermopile produced a reliable signal both for the most and the least favorable conditions (Figure 7).

In this preliminary phase, the respiratory rate was set by a metronome and the student adhered to the predetermined frequency during the inhalation and exhalation phases. As a reference signal was not acquired, it was not possible to carry out a consistent quantitative evaluation. Nevertheless, the students reported preliminary results in order to evaluate the feasibility of the system, as shown in Table 3.

As it was expected, the difference between the actual breathing rate and the one provided by the device is slightly bigger with an external temperature of 30 °C and by wearing an FFP2 mask. Nevertheless, students were happy with their results since they considered both that the prototype has large hardware and software margins for improvements, and that it is reasonable to expect that the device, designed for use within hospitals, unlikely would be used in such extreme conditions. Therefore, the students moved on to the final phase of the learning activity.

Faced problems: Signal processing.

Adopted solutions: Matlab code implementation.

Output: Preliminary results and graphs.

Improved competencies: Coding, data collection, results analysis, and presentation.

Pitching and promotion/defence of the project (days 9 and 10)

At the end of the experimental tests, students are required to prepare a pitch deck to present the product and the potential business idea, pretending to present the idea to a possible audience of industrialists and investors.

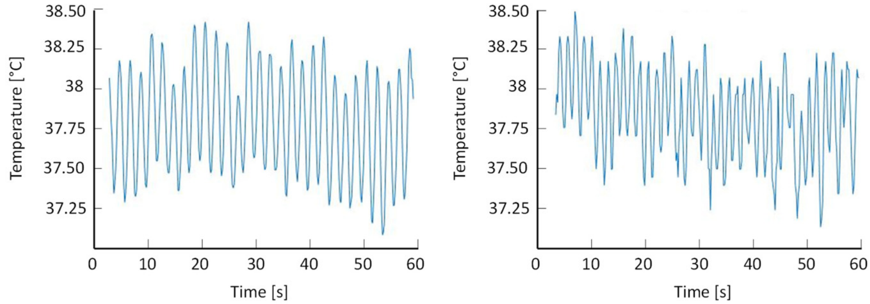

Figure 7. Thermopile's signal acquired with FFP1 mask with a respiration rate of 40 bpm and at a room temperature of 23 °C (left panel) and with a FFP2 mask with an external temperature of 30 °C and a respiration rate of 60 bpm (right panel).

Table 3. Preliminary results at different operating conditions.

Mask type	Troom (°C)	Breath type and rate	BPM calculated	Difference
FFP1	23	Nose—40 bpm	40.1	0.1
FFP1	23	Mouth—40 bpm	40.4	0.4
FFP1	23	Nose—50 bpm	50.1	0.1
FFP1	23	Mouth—50 bpm	50.2	0.2
FFP1	23	Nose—60 bpm	58.5	1.5
FFP1	23	Mouth—60 bpm	59.1	0.9
FFP1	30	Nose—40 bpm	38.9	1.1
FFP1	30	Mouth—40 bpm	40.8	0.8
FFP1	30	Nose—50 bpm	49.9	0.1
FFP1	30	Mouth—50 bpm	50.1	0.1
FFP1	30	Nose—60 bpm	57.6	2.4
FFP1	30	Mouth—60 bpm	59.9	0.1
FFP2	23	Nose—40 bpm	39.7	0.3
FFP2	23	Mouth—40 bpm	38.8	1.2
FFP2	23	Nose—50 bpm	49.9	0.1
FFP2	23	Mouth—50 bpm	50.2	0.2
FFP2	23	Nose—60 bpm	58.2	1.8
FFP2	23	Mouth—60 bpm	59.1	0.9
FFP2	30	Nose—40 bpm	39.4	0.6
FFP2	30	Mouth—40 bpm	40.5	0.5
FFP2	30	Nose—50 bpm	52.1	2.1
FFP2	30	Mouth—50 bpm	47.3	2.7
FFP2	30	Nose—60 bpm	56.6	3.4
FFP2	30	Mouth—60 bpm	60.5	0.5

The presentation should include all the slides that are contained in a traditional pitch[35]: the presentation of the problem, the adopted solution, the business, the market, the funds needed to launch the product and the return on investment and, finally, the introduction of the team involved in the project. The presentation will be followed by a question session in which the instructors raise technical and commercial criticisms and perplexities. Students should therefore be able to defend the choices made and to promote their work at their best. At the end of the pitch session, students will receive a formal evaluation on the following aspects:

- Prototype cost
- Predicted commercial product cost
- Simplicity of the measuring system
- Marketability
- Availability of materials
- Innovation
- Functionality and measurement accuracy

This last part of the open-lab activity aims to stimulate the resourcefulness of future engineers, developing a potential product starting from the concept idea, passing through the realization, and, finally, the promotion, without neglecting the economic and commercial aspects which are part of the skills that good engineers should develop.

Faced problems: Prepare a clear persuasive and catchy oral presentation.

Adopted solutions: In-depth study of the techniques of pitching.

Output: Technical pitch.

Improved competencies: Development of an engaging and attractive presentation which provides compelling evidence to support themselves, oral competencies, assessing in advance the need of the audience, PowerPoint and graphical skills, anxiety controls, and handling any technical or commercial criticism.

Conclusion

This learning workshop has been designed to provide the students with the possibility to experience on a voluntary basis (not compulsory) a specific learning path to be for a duration of 10 days. This optional and supplementary activity can be carried out during the two breaks from the compulsory lectures, in the winter (January–February) or in the summer (June–July), in order to not affect the students' duties during the other curricular units. Moreover, the entire activity, lasting a total of 30 hours, recognizes educational credits to students.

In this paper, the design and description of the pilot study of a potential 10-day-long working/learning experience are presented, which can be very profitable for the training of the students of engineering courses because of the many transversal aspects that this learning activity provides. Indeed, by exploiting the diffusion of a daily use common product, students are asked to design and realize a possible business idea that occupies them, with teamwork, both in technical aspects (hardware and software), in experimental testing, and in the relative promotion of the device. The two students involved in the pilot experience, as a part of their internship program at the Measurements and Control laboratory (Master in Mechanical Engineering), achieved all the intended learning outcomes while enjoying the open-inquiry laboratory experience.

The relationship between this proposed laboratory learning activity, the student's cognitive and affective development, and the motivation to learn was qualitatively analysed by means of a questionnaire consisting of nine specific items, selected among those listed in the Intrinsic Motivation Inventory and already utilized in previous studies.[7] The investigation was limited to three subscales: the perceived competence, the interest/enjoyment and the required effort. The evaluation of the answers was based on a 5-point Likert scale. The results, which were all positive, are not reported in this paper as they are statistically insignificant and only have an exploratory intent; nevertheless, the authors are willing to share results upon request as the number of students involved in the activity will increase in the future. The answers to the questionnaire seem to indicate a satisfactory and active engagement of the students in the learning environment, and a great appreciation of their activity and awareness of the acquired knowledge.

The positive feedback from the two participants in the case study encouraged us to pursue this pedagogical approach. Thus, in the present paper, authors' educational experience is shared in the hope that this could encourage the creation of new open-inquiry laboratories integrated with design-based experiences, promoting this type of initiatives that are of great importance in the training path of young engineers and students belonging to the STEM area.

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ORCID iD

D Persano Adorno https://orcid.org/0000-0001-7655-1114

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