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# Effectiveness of a Laboratory Course with Arduino and Smartphones

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**Abstract:** Arduino and Smartphones have been used since 2021 in a class of practicals held at Sapienza Università di Roma, to train physics undergraduates in laboratory activities. This paper briefly describes the organisation of the activities and report about the results of questionnaires administered to participating students before and after the course.

**Keywords:** arduino; smartphones; physics; laboratory

## 1. Introduction and Motivations

The pandemic in 2020 forced many courses to be taught remotely. This posed a serious problem for laboratory activities, where students are supposed to work, as a team, in dedicated laboratories. We then proposed a solution based on the usage of smartphones, that can be used at home to take quality measurements using readily available materials. Thanks to the positive experience gained in this occasion, we were asked to run a class of a course in laboratory of mechanics using digital tools, instead of traditional ones, to investigate about their effectiveness in physics teaching, and, in particular, in forming the correct attitude toward experimental work in a physics laboratory.

Besides a generic need (or, maybe, desire) for innovation, there are objective reasons to amend the way in which introductory laboratory courses are taught.

Traditionally, in these courses, students perform a number of experiments, aimed at demonstrating the validity of lectured materials, or at replicating historical ones, following detailed procedures prepared by the instructors. Students must conduct a detailed error analysis, whose aim is, again, to allow them to compare their own results with known ones. At the end of each practical activity, students write a concise report. This was the case for our course, too.

In order to include some active learning strategies, we redesigned it, to make more room for the students' engagement in conducting their own research, allowing them to build their own apparatus from scratch, and to decide the strategies to adopt to take measurements. They are free to include their personal research in the final report. Ultimately, we worked on two of the most critical aspects identified by research on physics labs, giving students more space to make decisions and reducing verificational goals in lab activities [1].

Moreover, the introduction of digital tools (smartphones and Arduino) as instruments, besides removing the need to take data manually, allow students to exercise their creativity in the software domain. We suggested using Python as a programming language to perform data analysis, whose learning curve is not steep, thus letting students focus on algorithms design and interpretation of results, rather than barely acquiring data. In essence, in the redesigned course only the objective, and one of the digital measuring tool (Arduino or smartphone) is assigned by the instructor, while students are free to achieve the assigned goal as they prefer.

As shown by [2], after attending strongly guided practical activities, the students attitude towards experimental physics deteriorates, despite the claim would be to train

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future researchers with the right skills and expertise. The authors of this work used a research-based assessment instrument known as E-CLASS, developed at the University of Colorado Boulder: the Colorado Learning Attitudes about Science Survey for Experimental Physics [3], designed to target students' beliefs about experimental physics, and their confidence in doing experiments.

This survey has been used extensively in the U.S. A summary of the results with E-CLASS is available in ref. [4]. Recently, E-CLASS has been translated and applied also in laboratory courses in Germany [5].

We compared the E-CLASS results of our redesigned laboratory course, with those of more traditional courses to assess the validity of our approach. The transformation of the laboratory activities was done gradually, in two steps: in 2020/21 the class was taught by the same professor, but it was divided into a *traditional* and a *pilot* sub-classes for practicals: the first was under the supervision of the professor who gave the lessons, while the second was under our supervision; in 2021/22 both the lessons and the practicals were under our entire responsibility.

The administered E-CLASS questionnaire was first translated in Italian (available here: https://www.physport.org/assessments/assessment.cfm?A=ECLASS - last access 1 Dec 2022) with the help of colleagues in the University of Padova and H. Lewandowski.

The E-CLASS dataset, which includes over 70,000 responses to the E-CLASS survey has been recently made available through a github repository, and can be used for research purposes [6].

## 2. Materials and Methods

In this section we illustrate the structure given to the course in 2021/22. The materials used in the laboratory, Arduino and smartphones, are described in this section, too. We then explain the rationale for our choices.

### *2.1. The Structure of the Course*

Besides laboratory activities, during which students learn how to take measurements, lessons during the course include the statistical analysis of data, probability theory and Bayesian reasoning. Students learn how to present measurements, evaluate uncertainties, estimate confidence levels, and upper and lower limits.

Data manipulation is done in Python, shortly introduced by examples during the lessons. There were no formal training on this language, as students have already attended a course on computing and programming in C-language in the first semester. We just introduce the constructs when they are needed, discussing only the features relevant for the particular application. Any further study is left to the good will of the students and, in any case, the content of these lectures is not part of the final assessment.

In order to foster teamwork, and to avoid the process of installing Python on students' own computers, we encourage them to work collaboratively using Google's Colab [7]. This way, data and code can be shared with the instructor and assistants, too, which provide comments and feedback.

After each laboratory session, students must electronically submit a report in PDF, which is read and commented by the instructors before the next laboratory session. They are invited to use LaTeX to prepare the manuscript, but they are free to choose their preferred method. Up to seven experimental sessions are distributed along the semester, two of which are done individually, while the rest are conducted in team. Teams are made of three or, at most, four students. When they work in group, students submit one report per group.

At the beginning of the semester, students are briefly trained to use PHYPHOX [8], in one dedicated session of two hours. PHYPHOX is a free, open-source App developed by RWTH Aachen to exploit the many sensors present in smartphones, turning them into real measuring instruments with which it is possible to obtain data from an accelerometer, a gyroscope, a magnetometer, a barometer, a camera, a microphone and a light sensor. Not all of these tools are available in every smartphone, and groups are formed such that each of them has the maximum possible number of sensors. This is one of the reasons for which we forbid the formation of spontaneous groups. The other is that we want students to get used to working in groups with people who are initially unfamiliar right away, both because this is what typically happens when starting a new work, and because, in this way, we avoid having groups in which someone is allowed to do little or nothing for reasons of friendship.

Besides smartphones, we use Arduino [9] to take data during experimental sessions. Instead of providing each group with Arduino boards and its accessories, we prefer to ask them to buy it, because managing the loan of kits at each session is time and resource consuming. If the Arduino boards are owned by the students, they can also use them at home to experiment on their own, learning more naturally and discovering new opportunities. On the other hand, the price of an Arduino board and the few required accessories is low enough for students to be affordable: it is equivalent to the price of a few notebooks.

The suggested Arduino kit includes, besides the Arduino UNO board, a breadboard and a kit of jumper cables, an ultrasonic sensor and a temperature sensor.

The illustration of the Arduino programming language is done in a dedicated two-hour long session. Being based on the C-language, there is no need to introduce the details of the language's syntax, already mastered by students, and the lesson is limited to the presentation of specific statements to read analog and digital pins, set digital pins and obtain information about the time elapsed. We make this session using an example program aiming at reading data from the ultrasonic sensor, with which it is possible to measure distances in a range between 3 cm and 3 m, with a resolution of few mm. The sensor emits ultrasonic signals with a dedicated trigger, and Arduino can measure the time elapsed since the emission of such signals and their echo, if any, recorded by the sensor itself. Knowing the speed of sound, one can measure the distance between the sensor and the obstacle that reflected the sound waves.

It is worth noting that, by training students in the use of Arduino and smartphones, we can introduce interesting physical phenomena that students already know about from a theoretical point of view, but have never thought about their actual use in technology.

The experiments done in 2020/21 and in 2021/22 were slightly different, due to constraints in the availability of the laboratory and of the devices needed. They are summarised in Table 1.

**Table 1.** The experiments done in 2020/21 and in 2021/22. Experiments in 2020/21 were all done using smartphones, either at home (H) or in our laboratory (L). All the experiments were done in our laboratory in 2021/22, with different technologies: Arduino (A), smartphones (S), or dedicated devices (D).

| | **2020/21** | | **2021/22** | |
|---|---|---|---|---|
| 1 | Measuring the density of a body | L,D | Measuring the density of a body | D |
| 2 | Studying the motion of a pendulum | H,S | Studying the motion of a pendulum | S |
| 3 | Studying the dynamics of a spring | L,A | Studying the dynamics of a spring | A |
| 4 | Radiation counters | H,S | Finding how the speed of sound depends on temperature | A |
| 5 | Measuring the moment of inertia of a rolling cylinder | H,S | Radiation counters | D |
| 6 | Studying the deformation of a slab | H,S | Measuring the moment of inertia of a rolling cylinder | S |
| 7 | – | | Studying the deformation of a slab | A |

During 2020/21, part of the lessons and the practicals had to be done remotely, because of the lockdowns resulting from the spread of the pandemic. When at home, students were connected to a synchronous Zoom session, each group being in a dedicated breakout room. Instructors cycled between breakout rooms to provide assistance, if needed, and to engage students in the discussion of their choices.

For their third experiment, students were asked to build their own pendulum, suspending their smartphone to two ropes attached to either a clothesline, an iron board, a ladder or other means.

The measurement with radiation counters was done using COSMIC RAYS LIVE [10]: an App developed by INFN (www.infn.it, accessed on 1 Dec 2022) which provides live data collected by a set of cosmic muon detectors installed in various parts of the world.

The last experiment was done using a ruler with a smartphone attached at one end by means of paper tape or rubber bands: fixing the other end of the ruler to the edge of a table, one can make the overhanging part to oscillate and measure the period of oscillations using the smartphone's accelerometer, as a function of the overhanging length.

In 2021/22 all experiments were done in the laboratory. Students, however, were asked to build their own device to collect the measurements. Sometimes they were asked to bring materials from home. Some other times we provided the necessary materials from which to choose.

The period of the pendulum was measured using the smartphone's accelerometer, as the latter was used as the suspended mass of the pendulum. The gravitational acceleration $g$ was obtained from a fit to the distribution of $T^2$ as a function of the pendulum length.

Using the ultrasonic sensor, they measured the position of the end of an oscillating suspended spring as a function of time, from which they measured the period $T$ to get the elastic constants by fitting the distribution of $T^2$ as a function of the suspended mass with a straight line.

The speed of sound was studied as a function of the temperature, measuring the time needed for the ultrasonic signal to travel back and forth to the opposite end of a box, while measuring the temperature inside with a temperature sensor. The air in the box was previously heated by a hair-dryer, then left thermalise with the environment.

We used Geiger counters to measure the radiation emitted by tufa blocks.

The dynamics of a cylinder rolling down an incline was studied fixing a smartphone inside a tube and measuring its angular velocity using the gyroscope.

The deformation of a slab were measured by taking the distance between the free end of a steel slab and an ultrasonic sensor, as a function of the hanging mass.

### 2.2. *The Rationale of the Choices*

Taking data with Arduino and smartphones makes data acquisition more similar to what is ordinarily done in real physics laboratories. In almost all the experiments, data are not manually recorded and analysed, yet they are collected using programmable devices and stored for offline analysis, often done with the help of some programming language or dedicated tool.

There is plenty of commercial systems which provide this feature, however, we believe that they hide one of the most interesting part of taking an experiment: the design of the apparatus, and its actual realisation. Using Arduino and smartphones, students are engaged in finding an efficient way to build the apparatus to take data, which is, at the same time, simple, cost effective, precise enough, and systematic errors free. They are forced to think about the consequences of their choices on the measurements, as well as to think deeply about the unavoidable differences between a model and the reality. Especially in an introductory course like our, models often require crude approximations. As an example, take the model of a pendulum: from the mathematical point of view, it is a point-like mass suspended to a massless and inextensible rope to a rigid support, which oscillates on a plane. If asked to build a pendulum, almost all students try to attach a (spherical) mass to a wire, tied to a horizontal support. The result is that the mass usually oscillates on many planes and it is very difficult to follow it and accurately measure the period. It is amazing to see how surprised they are in discovering that attaching a smartphone to, at least, two wires, it oscillates mostly on a plane perpendicular to that identified by the two wires, and there is no need that the mass is actually point-like. In fact, a massless wire is just an expedient to impose that the distance between the mass and the axis of oscillation is constant. It is enough to respect this condition to make the system to behave as predicted. Many other interesting considerations can be done about the fact that the wires must be as inextensible as possible, the role of the shape of the oscillating object, the presence of air drag and friction, and the amplitude of the oscillations.

In making their own apparatus, students learn how to predict, and avoid, systematic effects. They also learn how to take into account those remaining. Moreover, they reflect about how the tools determine the final resolution, and exercise their creativity to use sometimes original solutions, and get used to doing manual work, including precision work.

Arduino programming gets them used to describing, in detail, how an apparatus works, skills they would otherwise develop only in writing the reports. The need for a careful, precise, detailed description of the steps in the design of an algorithm, provides a big help for the preparation of the draft of the final report.

Data acquisition lasts for a very short time, indeed. This gives students much more time to devote to data analysis and interpretation.

The use of Python greatly simplify data analysis, whose focus shifts from the mechanical execution of calculations, which are simple but repetitive, to the interpretation of results. Plotting data and fitting them with a straight line is a matter of a few lines of Python code: the correct interpretation of the results is the most important ability to develop, rather than the one consisting in putting markers on a graph and computing tens of sums and ratios to derive the slope and the intercept of the line interpolating the data. Students gradually develop their own library of functions to be reused throughout the semester, and beyond.

## 3. Results and Discussion

In this section we discuss the results of the questionnaires administered to the class. All the questionnaires were anonymous, and it is not possible to trace the identity of the person who filled it out from the answers given. Moreover, they could be filled on a voluntary base.

The translated E-CLASS questionnaire was administer to our students both in 2020/21 and in 2021/22, as prescribed, at the beginning of the course and after its end. A few examples of typical E-CLASS questions are given below, where we discuss the results, analysed in accordance with the requirements of the developers [3]. Here, we summarise the results.

In an E-CLASS questionnaire, students must answer the same question twice: one from the student's point of view, the other trying to put him/herself in the shoes of a professional researcher and trying to give the answer he/she would give. The results are analysed separately and called the "student view" (labelled "YOU") and the "expert view" (labelled "EXPERT").

Students' answers are compared to the answers given by practicing experimental physicists, referred to here as the EXPERT reference. The EXPERT reference was assessed, submitting the questionnaire to a number of colleagues in Italy. The results are consistent with those found by the original authors in [3].

During the first year of experimentation, it was found that the E-CLASS overall score increased from $0.69 \pm 0.02$ to $0.74 \pm 0.02$ in the student's view, and from $0.80 \pm 0.02$ to $0.86 \pm 0.01$ in the expert view. We adopted, coherently with instructors' E-CLASS reports, a binary scale analysis scheme by assigning a numerical score of $+1$ for answers in agreement with the EXPERT reference and a score of 0 otherwise.

There were no significant difference between the pilot sub-class and the traditional one. If, from one point of view, this means that there is no significant effect from the introduction of Arduino and smartphones, on the other hand, it certifies that there is no harm in introducing these tools in an introductory level. One of the main concerns when implementing these innovations is the fear that the need to introduce new elements into the course programme will take time away from the in-depth study of more traditional topics, and distracts from the main objective of the course. With this research we have certified that such a fear is unfounded, as is also confirmed by the students' grades on the final exam. The difference of the two sub channel average grades is not statistically significant. It is worth noting, in this case, that the final assessment of each student was left to the professor who took the lessons, so there was no bias.

It must be said, too, that our "traditional lab", attended by one of the sub-classes, was traditional only in the sense that it used traditional instruments for those experiments done in the lab. The general structure of the text provided to students, with instructions on what to do, was the same, except for the part about using the instrumentation. Moreover, for the experiments that had to be conducted at home, both classes used a smartphone as a measuring device.

In 2021/22 only a mild increase of the overall score, not statistically significant, was observed between pre- and post-questionnaires, in both YOU and EXPERT views. For the YOU questions, the overall E-CLASS agreement score with the Expert Reference is $0.67 \pm 0.01$ at the beginning of the course and $0.69 \pm 0.02$ at the end of the course. The students' perspective of experts (EXPERT) increased from $0.82 \pm 0.01$ to $0.85 \pm 0.01$ as shown in Figure 1.

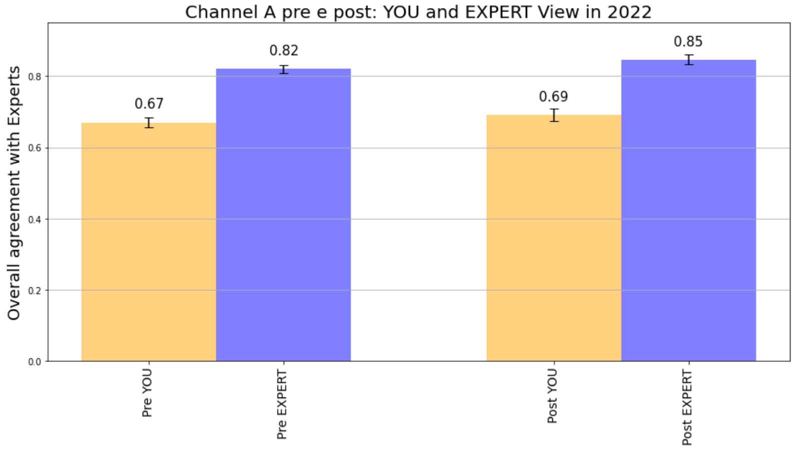

**Figure 1.** YOU and EXPERT view in pre- and post- questionnaires for year 2021/22.

A detailed analysis of the questions with lowest scores both before and after the course, *Q*17 (When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor) and *Q*29 (If I don't have clear directions for analyzing data, I am not sure how to choose an appropriate analysis method), indicates that most students still does not feel comfortable in taking decisions by themselves, they have little student agency and need the support of an instructor when they run into trouble. This conclusion is supported by direct observations, too. Students often ask for the permission to do something that manifestly can be done without any danger for them or the instrumentation. Sometimes they even ask the permission to experiment with programming. We attribute this attitude of fear toward instrumentation to the need to be reassured that they are doing the right things and to a reduced perceived self-efficacy.

Indeed, one of the objectives of our reform was to improve this aspect. However, the score for question *Q*17 was significantly lower than that of the preceding year (held primarily in remote mode, thus with less opportunity to ask the instructor), which was low too. A possible interpretation could be that, when they can profit from the presence of an instructor, students tend to use it, regardless of whether they really need it or not.

The effect of pandemic on Lab instruction has been investigated by using E-CLASS in [11], where also it is discussed the observed large positive shift in question *Q*17 in Lab courses in U.S.

The result in *Q*29 seems also not very surprising, as acquiring this ability takes time. The outcome on this question is not directly related to the technology, but rather to the active learning methodology in general. On the other hand, [12] shows that students often underrates their knowledge when exposed to this kind of teaching, while they actually learn much more than their companions exposed to traditional lecturing.

In fact, during the final assessment session of the 2021/22 academic year, we found that, while the distribution of the grades is not too much different from the traditional one, the best students really grasped the meaning of what they learnt, and they are able to correctly reason about data and their distributions, being capable of reaching informed and well argued conclusions. Manifestly, the latter is a rather qualitative observation, yet our perception is that they are significantly better with respect to the expectations, based on past experience. Indeed, after the first half of the course we were quite discouraged, because it seemed to us that students were not learning enough from their mistakes and from our lectures. It turned out that this could be physiological: being engaged in active learning implies a slow growth. In the face of initial dissatisfaction, on the part of both faculty and students, excellent final results are observed, when students finally begin, in the second half of the course, to digest the methods, and better understand the physical and methodological tools of their work.

The largest pre-post positive shifts, statistically significant, as obtained by using the Mann-Whitney U-test [13], are observed in the following questions:

- $Q1$ (When doing an experiment, I try to understand how the experimental setup works), with a two-sigma increase from 0.8 to 0.9: this is a clear indication that the approach in which students build their own apparatus meets its goal;
- $Q8$ (When doing an experiment, I try to understand the relevant equations), from about 0.7 to about 0.9. This is somewhat unexpected, but it can be an indication that, through the adoption of digital tools, students are more concentrated on the interpretation of the data, rather than on their collection.
- $Q10$ (Whenever I use a new measurement tool, I try to understand its performance limitations), which must be ascribed to the fact that students must design the apparatus in order to meet the required precision to observe what is required.

### 3.1. End-of-Course Questionnaires

At the end of any course, our University asks students to answer a questionnaire (OPIS) about their satisfaction: if they learnt what they expected to learn, if the instructors were good enough, if the organisation was adequate, etc. This OPIS questionnaire has been prepared and validated by a team of experts in our University, independent of us. The analysis is done by the University quality assessment group. We use the data, provided to us by that group, to assess the impact of active learning on a metric to which students are more used to.

In general, the course has not been evaluated very positively. This can certainly be ascribed to the fact that this was the first year in which we fully applied the methodology, and we already observed, during the class, that some of our choices were too extreme.

This result, in any case, requires a more careful study. In fact, as anticipated in the previous section, ref. [12] shows that self-reported perception of learning of students is, on average, lower than their actual learning. The study's authors warn about the danger of inadvertently promote inferior pedagogical methods, based on the attempt to evaluate instruction based on students' perceptions.

Our perception, in fact, is the opposite: at least students with good grades learnt much more than in traditional courses. It is difficult to disentangle the effect of the laboratory approach from that of the lectures, but the overall result is that there is a clearly perceptible, yet difficult to assess, positive difference between the abilities acquired by our students and those obtained after traditional lecturing and practicing. In particular, we found that most (good) students do not limit themselves to answer questions, as they usually do during the assessment, but they tend to argue and to discuss the topics to a much greater detail, and answer questions with a deeper awareness. We look forward to exploring more on this side.

Besides the OPIS questionnaire, we administered a third questionnaire to understand how the general methodology, and, in particular, the requirement to make measurements using Arduino has been received by students. This is a rather informal questionnaire, not scientifically validated, which we used just to understand how the new course has been received by students. Figure 2 shows the answers to two of the questions in this questionnaire, specifically related to the use of Arduino.

We have observed the importance of surveying students often, not only so adjustments can be made, but for example to investigate students' reaction to laboratory activities whose outcome had surprised them.

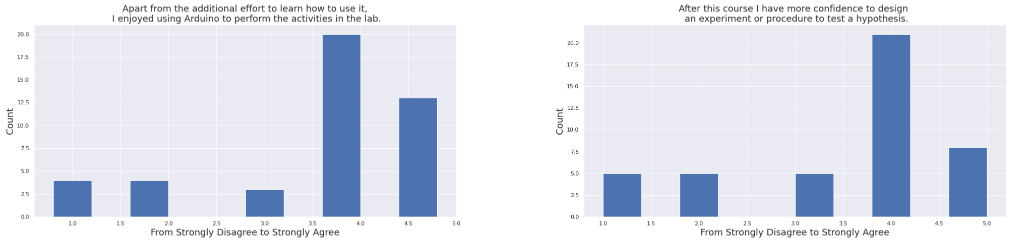

**Figure 2.** Two examples of distributions of the answers given to the supplemental questionnaire.

Students agree that the activities carried out in the laboratory are useful for the continuation of their career, as well as that the course helped them to develop the experimental skills and the right attitude towards physics experiments. The majority of them declares that they feel more confident in designing an experiment or procedure to test a hypothesis, and that they believe that it is worth investing energy and time in learning how to use Arduino. Besides finding it useful, they also enjoyed using it in the lab, and they are most probably going to make use of both smartphones and Arduino to perform experiments on their own.

### *3.2. Gender Issues*

In this third questionnaire, we asked about the preferences on the roles assumed during the team work in the lab. Even if not mandatory, we suggested to each group to rotate the roles assumed in each experimental session, such that every component of a group have the opportunity to try his/her own ability to perform a given role. Questionnaires were anonymous, but we asked about the gender of the filler. We found that, contrary to the common belief, the gender is certainly not a significant factor in the choice of the role of those who build the experiment and collect the data (Figure 3).

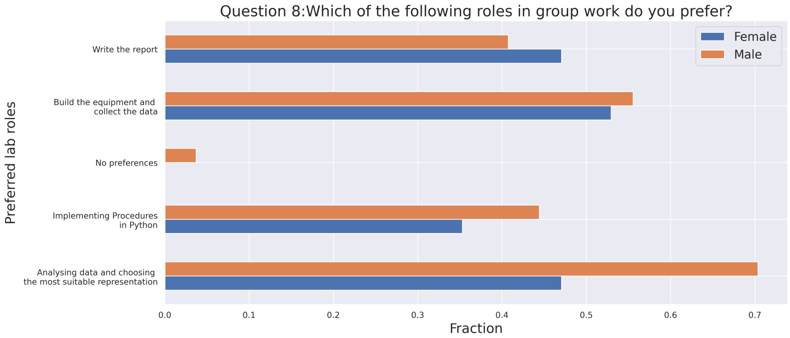

**Figure 3.** Preferred role within a group.

Programming is very mildly preferred by males (45% vs. 35% of females), while, surprising enough according to stereotypes, the analysis of the data and the choice of the most suitable representation of them is mostly indicated as the preferred role by the majority of males (70% vs. 45% of females).

In any case, by far, the most preferred approach to the team work is that in which everyone does everything together, by the females, while males prefer the assumed roles rotate among the components of the group, as shown in Figure 4.

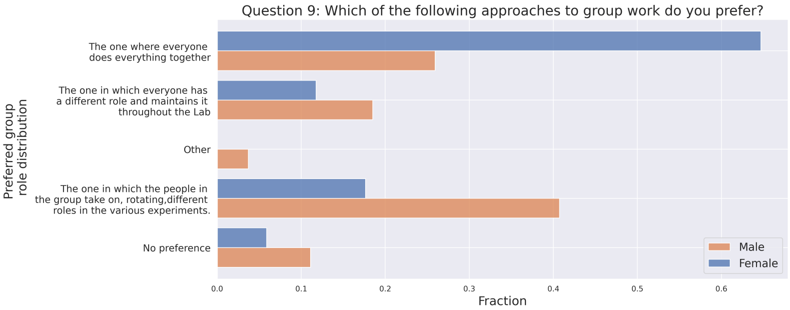

**Figure 4.** Preferred model of group work.

The results are consistent with observations in [14], and represent an interesting starting point for further investigations in this field of physics education. These outcomes will help us develop strategies to facilitate equitable group work in physics labs.

## 4. Conclusions

We run an experimental class of introductory laboratory physics based on the adoption of an active learning methodology, supported by the usage of digital tools to take data, like Arduino and smartphones.

The analysis of various questionnaires, as well as the results of the final exams, reveal that it is possible to introduce active learning strategies without detrimental of the outcomes of a laboratory course. In particular, it has been shown that by introducing Arduino programming, and greater freedom to design and implement their own experiments, not only does it not significantly increase students' workload; it does not require to renounce to teach important topics, and it allows students to achieve, at least, completely similar results in learning.

Indeed, when we proposed the reorganization of the course in these terms, the major concerns of our colleagues were just these, despite the evidence from physics education research.

There is still an issue to overcome, concerning the self-efficacy perceived by the students, that does not improve.

The impression, on the contrary, is that at least the best students have a tangible, much deeper awareness of how experimental data are correctly interpreted, and their meaning, although difficult to assess objectively.

We believe that our approach greatly improve the laboratory skills, and, especially, guides the students to the right attitude towards experimental work, in particular for what concern the understanding of the instruments characteristics and principles.

Some of the methods described in this paper can certainly be extended to laboratory courses for other disciplines. Many of the data collected in other fields are ultimately physical quantities that can be measured using Arduino and smartphones. The E-CLASS questionnaire has been developed specifically for physics courses, therefore, it cannot be used as such to assess the validity of other courses. However, our results are encouraging and the general conclusion that active learning strategies is of interest to improve students' soft skills, letting them exercise their creativity, by promoting relatively open hands-on activities, can probably be extended to other fields, and can certainly encourage others to imitate our approach.

This study allows us to objectively debunking the myth according to which female students do not like experimental work: indeed, the majority of females indicated the role of the builder of the apparatus as the preferred one. We thus consider it as an effective mean to fight against the gender-bias.

On the other hand, there is still much room for improvements: some of them already suggested from direct observations, before the analysis of the questionnaires. In particular, we intend to redesign the sequence of topics taught so as to introduce concepts more gradually to help students consolidate their knowledge. We look forward to test the effectiveness of updated strategies, and to a deeper investigation about the effectiveness of this work.

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**Informed Consent Statement:** Students were informed that the questionnaires were anonymous and that they answered on a voluntary base.

**Data Availability Statement:** Not applicable.

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**Conflicts of Interest:** Giovanni Organtini declares to be the author of a textbook about doing physics with Arduino and smartphones.

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