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A TLS for teaching magnetic field in secondary school

L. Addiucci(1)(*), L. Gabelli(2), C. Trifolelli(3) and P. Barone(4)

(1) *Department of Physics, Sapienza University of Rome - Rome, Italy*
(2) *Department of Physics and Astronomy "G. Galilei", University of Padua - Padua, Italy*
(3) *Liceo Scientifico Statale "Paolo Ruffini" - Viterbo, Italy*
(4) *Liceo Scientifico, Linguistico e Classico Statale "Enrico Medi" - Battipaglia (SA), Italy*

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Summary. — In this work, we present a Teaching-Learning Sequence (TLS) on the magnetic field developed within the ADELANTE project, aimed at integrating low-cost digital technologies into school laboratories and defining effective in-service teacher training models. The TLS uses smartphones to measure the magnetic field generated by a current-carrying wire and aims to explicitly connect experimental evidence with theoretical models. We report the structure, goals, and main results of a first implementation with three classes of a Scientific High School, highlighting both the potential of the approach and the difficulties that emerged, particularly in data analysis and modelling.

1. – Introduction

International literature in physics education has long highlighted that active and collaborative learning approaches can foster deeper and more durable learning outcomes than traditional frontal instruction, while also showing that traditional laboratory activities do not always produce the expected educational benefits [1, 2]. This has led the research community to question which competencies laboratory experiences should promote and under which conditions they can effectively support learning.

In response to these limitations, inquiry-based laboratory approaches have been proposed to foster students' autonomy, critical judgement, and awareness of scientific practices [3, 4]. In this framework, both the National Research Council and America's Lab Report emphasise the central role of scientific practices and the integration of laboratory activities within theoretical instruction, rather than treating them as isolated experiences [5, 6]. In many school contexts, however, laboratories lack adequate equipment for inquiry-based experimentation or rely mainly on demonstrative use, limiting students' active involvement. A promising solution to overcome these constraints is the use of accessible digital technologies, such as smartphone-based applications (*e.g.*, phyphox, FizziQ) [7] and Arduino microcontrollers [8], which allow students to collect and analyse experimental data using widely available and easily deployable devices. It is within this context that the ADELANTE project has been developed.

(*) Corresponding author. E-mail: `luca.addiucci@uniroma1.it`

2. – The ADELANTE project

ADELANTE (Adopting Digitally-Enhanced Laboratories in a Network of Teachers) was a national project funded under the PRIN-2022 scheme. It involved three universities and several secondary schools across the national territory and adopted an action-research approach. The project pursued a twofold objective: i) to design and validate Teaching-Learning Sequences (TLSs) based on the use of Arduino microcontrollers and smartphones; and ii) to implement in-service teacher training models that support the integration of digitally enhanced laboratory activities into school practice.

The project is grounded in the CoLLabora model [9], in which teachers and researchers form a Community of Learners engaged in the joint design, implementation, and reflection on educational innovations. Building on this model, ADELANTE developed a two-tiered community structure. During the first year, a national community of Teacher Leaders was established [10], whose members co-designed the TLSs in collaboration with researchers. In the second year, local teacher communities were created, involving the teacher leaders together with additional teachers.

Within the project, TLSs are conceived as structured sequences that explicitly articulate learning objectives, activities, and assessment tools, in line with the tradition of Physics Education Research (PER). Each TLS is co-designed by teachers and researchers following the Design-Based Research (DBR) methodology [11], implemented in classroom settings, and subsequently refined through shared analysis of the collected evidence. In this paper, we focus on the development and implementation of a TLS on magnetism. For a comprehensive account of the overall project and of the results obtained from the implementation of different TLSs see refs. [12,13].

3. – The TLS on the magnetic field

Magnetism is a critical topic for students [14], with documented difficulties in distinguishing electric and magnetic fields and in identifying the sources of the magnetic field. To address these challenges, a TLS was developed for the third year of the Scientific High School (total duration about 9 hours), with the following learning goals: i) distinguish electric and magnetic interactions; ii) identify the sources of the magnetic field; iii) interpret field representations in different configurations; iv) use experimental data to obtain a law of the form $B \propto 1/d$.

The sequence is articulated into four phases, including qualitative explorations with magnets and compasses, a smartphone-based experiment aimed at measuring the magnetic field generated by a current-carrying wire using the smartphone magnetometer via the Phyphox app [15], and a final phase devoted to theoretical consolidation through the analysis of the graphs $B(d)$ and $B(1/d)$ (fig. 1).

4. – Methodology and assessment tools

Following the Design-Based Research (DBR) methodology, the Teaching-Learning Sequence (TLS) was designed by a group of teacher leaders and implemented in three third-year secondary school classes, involving a total of 68 students. The implementation phase was followed by an evaluation cycle and subsequent revision of the TLS.

To evaluate the effectiveness of the TLS, multiple assessment tools were employed, including pre- and post-questionnaires on students' attitudes toward laboratory activities, self-assessment instruments targeting scientific competencies, an analytic rubric,

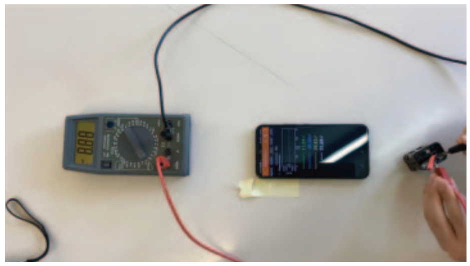

Fig. 1. – Students performing the smartphone-based experiment to measure the magnetic field generated by a current-carrying wire during the TLS implementation.

and teacher observation logs documenting difficulties, behaviours, and classroom dynamics [16].

In addition, a questionnaire adapted from the Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS) [17] was used to investigate students' perceptions of laboratory work and of the effectiveness of the TLS. Students responded retrospectively with reference to their perceptions before the intervention and again after the intervention [18]. These tools make it possible to connect cognitive and affective data and to inform both revisions of the TLS and teacher professional development initiatives.

5. – Main results

5˙1. *Analysis of experimental data.* – The smartphone experiment produced data consistent with the inverse dependence of the magnetic field on distance. The representation of B as a function of $1/d$ showed an almost linear relationship, facilitating the transition from empirical regularity to theoretical formalisation. Students recognised the trend of the field and the role of current.

5˙2. *Students' perceptions.* – Post-questionnaire responses indicate that: i) engaging in the smartphone-based experiment increased motivation and engagement; ii) introducing experimental activities before formal theoretical instruction was perceived as useful; iii) competencies in experimental design and data analysis were perceived as improved. Qualitative student comments further support these results. In particular, students appreciated the active and inquiry-based nature of the activities, noting "the possibility to have autonomy in an activity that required us to reason about what we were doing" and "discovering magnetism in the laboratory before the theoretical explanation", as well as the use of digital tools, such as "using the Phyphox app to measure magnetic fields around us".

5˙3. *Rubric and teacher observations.* – The rubric shows good performance in the sections related to identifying the phenomenon and describing the apparatus, while difficulties remain in mathematical modelling and in the conscious use of spreadsheets. Teacher observation logs confirm high interest and participation, but reveal widespread difficulties in quantitative data analysis and in producing structured written reports.

6. – Discussion and conclusions

The TLS on the magnetic field proved to be an effective tool for connecting experimental observations with the theoretical law, thanks to the targeted use of smartphones as measuring instruments. The approach is scalable and compatible with ordinary school constraints.

The difficulties that emerged in data analysis and modelling highlight the need to further develop transversal data literacy skills and to strengthen support for teachers in designing open and digitally enhanced laboratory experiences. Following the design-based approach adopted in the ADELANTE project, future work will focus on refining the TLS through guided analysis tools, deepening the qualitative analysis of student productions, and using the results to define more targeted in-service teacher training pathways.

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