Int. j. adv. multidisc. res. stud. 2026; 6(6):99-112

Received: 10-09-2026
Accepted: 20-10-2026

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Building the Experiment, Building Understanding: Student-Built Arduino Experiments for Teaching Damped Oscillations in Secondary Physics

[1] Mamouras D, [2] Simos CH, [3] Tsihouridis CH, [4] Karakasidis TH, [5] Vavougios D

[1, 2, 4, 5] Department of Physics, University of Thessaly, 35100 Lamia, Greece

[3] Department of Educational Sciences and Social Work, University of Patras, Greece

DOI: https://doi.org/10.62225/2583049X.2026.6.6.7106

Corresponding Author: **Mamouras D**

Abstract

The use of microcontrollers in school physics laboratories is typically associated with automated data collection and immediate graphical display. Less often examined are instructional conditions in which students actively participate in assembling, basic programming, calibrating, and testing the apparatus before using it to investigate a physical phenomenon. This study examined the learning outcomes associated with such an approach to teaching damped oscillations. A quasi-experimental pretest–posttest design with nonequivalent groups was adopted. Participants comprised 105 Grade 12 students from five schools, divided in three groups: an active control group that completed conventional laboratory activities and observed brief demonstrations of microcontroller applications (CG, n = 27), an experimental group that built and used an Arduino apparatus (EG1, n = 43), and a second experimental group that followed the same procedure with the additional use of a digital simulation (EG2, n = 35). The intervention lasted eight class periods, and achievement was assessed with a 30-item instrument covering three distinct cognitive domains: understanding physical concepts related to damped oscillations, functional knowledge of microcontrollers and Arduino, and the ability to read and physically interpret graphs. The mean total gain was 6.78 points in the CG, 19.44 in EG1, and 20.43 in EG2. ANCOVA results showed that, after controlling for the corresponding pretest score, the final performance of EG1 and EG2 was higher than that of the CG in all three cognitive domains ($p < .001$ for all analyses), whereas the differences between EG1 and EG2 were not statistically significant. Overall, the findings indicated that the instructional condition involving student construction and use of the apparatus was associated with higher cognitive performance than the control condition, whereas adding the simulation did not appear to yield additional learning gains.

Keywords: Arduino, Microcontrollers, Damped Oscillations, Graph Interpretation, Digital Simulation

1. Introduction

Laboratory teaching in physics aims to engage students not only with the products of scientific knowledge but also with the practices through which that knowledge is produced: observation, measurement, hypothesis testing, data representation, and evidence-based interpretation. The educational effectiveness of laboratory work, however, does not follow automatically from the physical presence of instruments and materials. When an activity is limited to carrying out a prescribed procedure or confirming a known law, students may operate the equipment without relating their actions to the physical model under study (Abrahams & Millar, 2008; Hofstein & Lunetta, 2004) [1, 16]. The experimental process must therefore be organized as a process of producing and interpreting data.

Real-time data acquisition systems offer an important opportunity in this direction. The close temporal link between a phenomenon and its graphical representation can, for example, help students connect motion with changes in physical quantities, particularly when they are asked to predict, compare, and explain the shape of a graph. Open-hardware microcontrollers, especially Arduino, extend this capability by combining low cost, compatibility with numerous sensors, programmable sampling, and immediate transfer of measurements to a digital environment (Mitrakas *et al*., 2024; Tsihouridis *et al*., 2024c) [26, 49].

Physical computing provides a suitable framework for this shift. Students connect sensors and actuators to a programmable system, organize the input–processing–output flow, troubleshoot wiring or code, and observe the consequences of their choices

in the physical system. Construction and debugging turn the technological object into an object of thought. In a school physics laboratory, this process can bridge the mechanical apparatus, the sensor, the digital values, the graph, and the theoretical model (Tsihouridis *et al*., 2025) [50].

Damped oscillations provide a productive but demanding context for this work. The motion unfolds continuously, the amplitude decreases, energy dissipates, and students must relate the observed motion to a time series of measurements and to a graph that combines periodicity with an exponential envelope. Manual recording can capture only a few values, whereas automated sampling can record the evolution of the entire phenomenon. Notable Arduino-based apparatuses for harmonic and damped oscillations have been presented (Buachoom *et al*., 2019; de Castro *et al*., 2015) [4, 9], but these are primarily technical proposals and do not include controlled assessments of cognitive outcomes.

This study examines an instructional approach in which the experimental groups were not given the final apparatus as a ready-made instrument. Students followed a scaffolded sequence introducing the microcontroller, sensors, wiring, calibration, and basic programming concepts before building and using the experimental apparatus to investigate damped oscillations. The second experimental group also used a digital simulation. The originality of the study therefore lies less in the device itself than in the learning sequence, which moves students from the role of users to that of creators and interpreters of the experimental tool.

This article presents the theoretical rationale, design, and cognitive learning outcomes of the intervention while maintaining a clear distinction between findings supported by the data and pedagogical interpretation. Particular emphasis is placed on (a) connecting constructionist learning and physical computing with the physics laboratory, (b) the sequence of construction, programming, measurement, visualization, and physical interpretation, (c) assessing performance in oscillation concepts, microcontrollers, and graphs, and (d) examining whether the additional simulation differentiated the outcomes.

2. Theoretical and Research Framework

2.1 Damped Oscillations

In a damped mass–spring system, resistance to motion gradually converts mechanical energy into heat, causing the amplitude to decrease over time. Depending on the strength of the damping relative to the system's natural frequency, the motion falls into three regimes. In underdamping, the body continues to oscillate with decreasing amplitude; under critical damping, it returns to equilibrium in the shortest possible time without oscillating; and under overdamping, the return is aperiodic but slower. A complete mathematical treatment is provided in any standard mechanics textbook (e.g., Serway & Jewett, 2019, pp. 388–404; Young & Freedman, 2020, pp. 431–450) [41, 53] and is not repeated here.

2.2 Experimental Investigation and Real-Time Data Collection

Laboratory work serves multiple purposes, including familiarization with instruments, observation of phenomena, testing of models, development of inquiry skills, and understanding the nature of scientific evidence. It is most effective when actions on physical objects are explicitly connected with ideas and reasoning (Abrahams & Millar, 2008; Hofstein & Lunetta, 2004; Mitrakas *et al*., 2023; Tsihouridis *et al*., 2024b) [1, 16, 27, 48]. Automated data acquisition can increase the number of measurements and free up time for analysis, but it does not remove the need for scientific judgment in sensor selection, calibration, and sampling frequency.

Microcontrollers differ from ready-made commercial systems in their capacity for modification: the code determines when the sensor is read, how the value is converted, and how frequently the data are transmitted, thereby making data collection itself an object of inquiry. The recent systematic review by Saramati *et al*. (2026) [38], which synthesized 38 empirical studies of microcontrollers in physics education, reports positive evidence for conceptual understanding and problem solving but emphasizes the heterogeneity of samples, interventions, and assessment instruments.

2.3 Applications of Microcontrollers in Education

The literature documents extensive use of microcontrollers across many areas of physics and chemistry, from mechanics and fluids to electricity and chemistry, mainly to construct low-cost instruments and provide immediate data visualization, although the educational evidence remains heterogeneous (Marín-Marín *et al*., 2024; Tsihouridis & Mitrakas, 2025; Saramati *et al*., 2026) [24, 44, 38].

For oscillations specifically, measurement apparatuses have been developed for pendulums and mass–spring systems (Buachoom *et al*., 2019; Boimau *et al*., 2022; Çoban *et al*., 2023; Escudero *et al*., 2024) [4, 3, 8, 11]. For damped oscillations, de Castro *et al*. (2015) [9], Rinaldi and Fauzi (2020) [35], and Wadhwa and Wadhwa (2023) [51] show that automated recording can be used to derive the period, damping constant, and amplitude envelope. In the Greek literature, Kyriazopoulos *et al*. (2019) [20] present comparable Arduino apparatuses, while Tsihouridis *et al*. (2024) report descriptively higher student performance with a BBC micro:bit than with a stopwatch. None of these studies, however, combines complete student construction with a controlled assessment of knowledge about damped oscillations, the gap addressed by the present study.

2.4 Student Construction of the Experimental Tool

Constructionist learning (Papert, 1980, 1991) [33, 34] holds that knowledge building is strengthened when students create public artifacts that can be tested, modified, and improved. In the physics laboratory, the object being constructed may be the experimental tool itself. Instead of allowing the sensor and software to function as opaque intermediaries, the connections and limits of measurement become topics of discussion, and students learn to diagnose whether a problem arises from the mechanical apparatus, wiring, code, or communication with the computer (Fields *et al*., 2021; Kafai *et al*., 2014; Litts *et al*., 2017) [13, 18, 22].

The instructional intervention followed the sequence construction → programming → measurement → visualization → physical interpretation. Construction reveals the structure of the tool; measurement links students' choices to the real system through calibration, noise, and repeatability; physical interpretation reconnects the graph with motion and energy. The approach extends beyond simple data logging: when students participate in construction, the tool changes from an external aid into an object of knowledge. The appropriate unit for interpreting

the results is therefore not the microcontroller alone, but the entire organized learning environment.

2.5 Real Experiment and Digital Simulation

Physical and virtual laboratory environments offer different but potentially complementary opportunities for science learning. A physical experiment exposes students to the material nature of the phenomenon, measurement uncertainty, noise, non-ideal conditions, and the need to operate and test the experimental apparatus. It therefore makes clear that real data do not correspond perfectly to the ideal behavior of a mathematical model.

Digital simulation, by contrast, usually permits rapid and systematic variation of parameters, repeated trials, and controlled visualization of relationships that may be more difficult to isolate in a physical experiment. In the case of damped oscillations, students can vary individual parameters and immediately observe their effects on the temporal evolution and shape of the graph.

The literature does not support a simple hierarchy in which physical or virtual experiments are generally superior. Educational effectiveness depends on the cognitive objective, the affordances of each representation, and how each is incorporated into the learning sequence (Rutten *et al*., 2012; de Jong *et al*., 2013; Tsihouridis *et al*., 2026) [37, 10, 46]. Research has also shown that an appropriate combination of physical and virtual resources can support conceptual understanding when the two forms of experimentation serve distinct and complementary roles (Olympiou & Zacharia, 2012; Zacharia & de Jong, 2014) [30, 55]. Similarly, the systematic review by Wörner *et al*. (2022) [52] emphasizes how the two environments are combined rather than seeking a generally superior form of laboratory.

In the present study, the simulation was not used as an alternative to the physical experiment. It was added for the second experimental group after students had completed the same core construction and experimental sequence as the first experimental group. The comparison between the two experimental conditions therefore does not address the question of physical experiment versus simulation. Instead, it examines a more specific question: whether adding a digital simulation provides an additional cognitive benefit after students have already helped build the apparatus, collected real data, and analyzed the corresponding graphs.

2.6 Research Gap, Purpose, and Research Questions

Existing research shows that microcontrollers can be used effectively to develop low-cost experimental apparatuses, automate data acquisition, and generate graphs immediately. Evidence also suggests that technology-supported laboratory activities can be associated with positive cognitive outcomes when incorporated into organized learning environments (Papadimitropoulos *et al*., 2021; Omari *et al*., 2023 [31]; Saramati *et al*., 2026) [32, 31, 38].

Several issues, however, remain insufficiently investigated. First, a substantial part of the literature focuses on the technical development and operation of experimental apparatuses without systematically assessing changes in student knowledge. Second, the degree of student involvement varies considerably. In some applications, students use a ready-made microcontroller as a data-logging system; in others, they participate in assembling, programming, calibrating, and testing the tool itself. It is therefore not always clear which learning outcomes are associated with simply using the technology and which are associated with active involvement in creating and understanding it. Third, empirical evidence remains limited on whether adding a digital simulation offers further learning benefits after students have already worked in a rich environment involving physical experimentation, student construction, and analysis of real data.

Accordingly, this study compared the cognitive outcomes of three instructional conditions for teaching damped oscillations to Grade 12 students: a conventional laboratory condition; a condition in which students followed a scaffolded process of familiarization, construction, and use of a microcontroller-based experimental apparatus; and a third condition involving the same construction and experimental process with the additional use of a digital simulation.

The cognitive assessment addressed three distinct but interrelated domains: understanding damped oscillations, functional knowledge of microcontrollers and Arduino, and the ability to read and physically interpret graphs. In interpreting the results, the second domain is treated as a more specific learning outcome directly related to the technological component of the intervention, whereas the other two concern learning about and representing the physical phenomenon more directly.

On this basis, the following research questions were formulated:

RQ1. What pattern of change was observed from pretest to posttest across the three cognitive components and the three instructional conditions?

RQ2. After controlling statistically for the corresponding pretest performance, did the final cognitive performance of students in the two conditions involving student construction and use of the Arduino apparatus differ from that of students in the control group?

RQ3. Was the additional integration of a digital simulation into the Arduino-based instructional condition associated with further improvement in cognitive outcomes compared with the Arduino condition without simulation?

The groups were also compared at pretest as a feature of the initial experimental design rather than as a separate research question.

3. Method

3.1 Research Design

The study used a quasi-experimental pretest–posttest design with nonequivalent groups and an active control group. The use of existing school classes precluded individual randomization, and convenience sampling was used. The design included three conditions: conventional laboratory teaching; construction and use of a microcontroller-based apparatus; and the same construction and experimental process supplemented with a digital simulation.

To limit alternative explanations, all groups received the same duration, core subject matter, instructional objectives, and degree of laboratory involvement. The same researcher implemented the intervention in collaboration with the school teachers, primarily on programming-related matters.

This choice increased consistency of implementation across groups, but it also meant that the same researcher designed

and taught the intervention and developed the assessment instrument, a factor discussed further under the study limitations.

3.2 Participants and Educational Context

The study sample comprised 105 Grade 12 students enrolled in an advanced-track physics course. The students attended five schools in the Magnesia regional unit of Greece and were approximately 17 years old, consistent with their grade level. Gender differences were not analyzed because gender was not a focus of this study. Tables 1 and 1a show the distribution of students by school and research condition.

Table 1: Distribution of Study Participants

Category	Subcategory	N	Percentage
School	2nd Model Upper Secondary School of Volos	27	25.7%
	3rd General Upper Secondary School of Volos	35	33.3%
	4th General Upper Secondary School of Volos	16	15.2%
	8th General Upper Secondary School of Volos	16	15.2%
	General Upper Secondary School of Nea Anchialos	11	10.5%
Research condition	Control Group — CG	27	25.7%
	Experimental Group 1 — EG1	43	41.0%
	Experimental Group 2 — EG2	35	33.3%
Total		**105**	**100%**

Note. CG = control group; EG1 = experimental group using a microcontroller; EG2 = experimental group combining a microcontroller and digital simulation.

Table 1a: Distribution of Participants by School and Research Condition

School	CG	EG1	EG2	Total
2nd Model Upper Secondary School of Volos	27	–	–	27
3rd General Upper Secondary School of Volos – Class 1	–	–	18	35
3rd General Upper Secondary School of Volos – Class 2	–	–	17	
4th General Upper Secondary School of Volos	–	16	–	16
8th General Upper Secondary School of Volos	–	16	–	16
General Upper Secondary School of Nea Anchialos	–	11	–	11
Total	**27**	**43**	**35**	**105**

As shown in Table 1, the students were assigned to three research groups or conditions: (a) the control group (CG), with 27 participants; (b) Experimental Group 1 (EG1), with 43 participants; and (c) Experimental Group 2 (EG2), with 35 participants.

Convenience sampling was used, and participation in the study was based on existing school groups. This choice allowed the intervention to be conducted under authentic classroom conditions, but it limits the generalizability of the results and does not permit the groups to be regarded as fully equivalent before the intervention. Pretest performance was therefore taken into account in the primary comparisons of posttest outcomes.

Furthermore, because students were nested within existing classes and schools, observations from students in the same educational setting may not have been fully independent. This potential intracluster dependence cannot be ruled out by the present design and is considered a methodological limitation when interpreting the findings.

3.3 Instructional Intervention

The intervention lasted eight class periods and was organized into two phases. The first phase, lasting six periods, prepared the groups for the final investigation. The CG completed conventional laboratory activities, including elastic collisions, beam equilibrium and torque, and conservation of angular momentum. After each activity, the researcher gave a brief demonstration of a corresponding microcontroller application. Students did not undertake the wiring, programming, calibration, or construction of the microcontroller-based apparatus.

Table 2: Phases, Duration, and Key Features of the Three Instructional Conditions

Phase	Duration	Control group (CG)	Experimental group EG1	Experimental group EG2
Preparatory	6 class periods	Conventional laboratory activities. Brief demonstrations of microcontroller applications by the researcher, without student wiring, programming, or calibration.	Familiarization with Arduino and sensors, basic programming, measurement activities, force-sensor calibration, and assembly of the final apparatus.	Same procedure as EG1.
Main	2 class periods	Conventional damped-oscillation experiment and manual processing of measurements.	Student-built Arduino apparatus, real-time recording, and graph analysis.	Same physical experimental procedure as EG1 + digital simulation.

In EG1 and EG2, the first phase included systematic familiarization with Arduino and sensors. Students identified parts of the board and its pins, made basic connections, and were introduced to program structure, particularly initialization and repeated execution. They used temperature, distance, and pressure sensors in scaffolded activities involving Newton's law of cooling, uniform rectilinear motion, and the pressure-volume relationship. They were then introduced to the force sensor and completed a calibration procedure. During the sixth period, the groups assembled the final experimental apparatus.

In the second phase, lasting two periods, all groups studied damped oscillations using the same core content and comparable worksheets. The CG used a conventional mechanical apparatus and processed measurements manually. EG1 used the student-built Arduino apparatus with a force sensor, recorded values in real time, and analyzed the graphs. EG2 completed the same physical experimental procedure and also used a digital simulation in which students could vary parameters and compare representations.

The experimental apparatus used a force sensor consisting of a load cell and an HX711/XFW-002 module connected to an Arduino Uno R3 microcontroller. The sensor was calibrated using a two-point linear procedure with known reference loads. At a sampling rate of 10 Hz, the system recorded the force exerted by a vertical spring on an oscillating body. A body attached to the free end of the spring could oscillate either in air or in a liquid medium (water, oil, or viscous detergent), allowing different degrees

of damping to be studied. The linear relationship between spring force and extension enabled quantitative investigation of changes in amplitude and period through digital recording and real-time data analysis. Fig 1 shows the basic structure of the experimental apparatus.

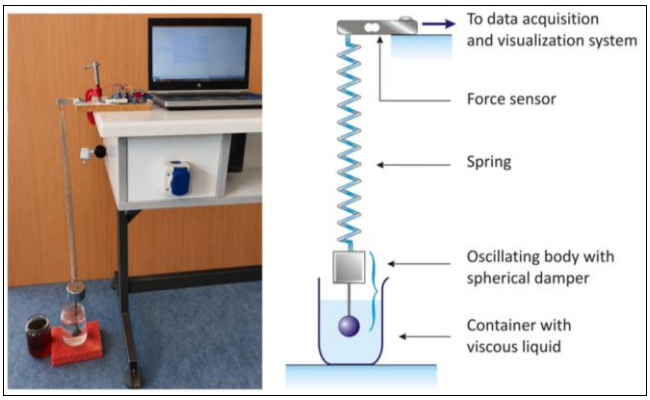


Fig 1: Photograph and diagram of the experimental apparatus used to study oscillations during the instructional intervention

The Harmonic Oscillator simulator used by EG2 is an interactive simulation with adjustable parameters that generates displacement-time graphs for a body suspended from a spring. The motion can be simple harmonic, damped, or forced (Falstad, n.d.) [12].

3.4 Cognitive Assessment Instrument

A 30-item cognitive assessment developed specifically for this study was administered at pretest and posttest. A purpose-built instrument was necessary because the intervention jointly addressed three distinct but interrelated domains of knowledge: understanding fundamental concepts and relationships in damped oscillations, functional knowledge of microcontrollers and Arduino, and the reading, analysis, and physical interpretation of graphs.

The items were organized into three cognitive components: C1 – Damped oscillations (Q1–Q10), C2 – Microcontrollers and Arduino (Q11–Q20), and C3 – Graphs (Q21–Q30).

Table 3: Structure of the Cognitive Assessment Instrument

Component	Items	Indicative content	Maximum score
C1 – Damped oscillations	Q1–Q10	Amplitude, period, damping, energy, envelope	10 × 3 = 30
C2 – Microcontrollers and Arduino	Q11–Q20	Sensors, pins, wiring, basic program flow, data acquisition	10 × 3 = 30
C3 – Graphs	Q21–Q30	Reading values, recognizing forms, comparing curves, physical reasoning	4 × 3 = 12 6 × 4 = 24
Total	Q1–Q30	Three cognitive components	96

The instrument was developed by aligning the items with the intended learning objectives and assigning them to the three cognitive components.

Items Q1–Q24 used structured responses and were coded as 1 = No response, 2 = Incorrect response, and 3 = Correct response. Items Q25–Q30 were open ended and received graded scores. Predetermined criteria for the open-ended items addressed scientific accuracy, completeness, and adequacy of the reasoning. Responses were coded as 1 = No response, 2 = Incorrect response, 3 = Partially correct response, and 4 = Correct response. The cognitive assessment therefore extended beyond recognizing a correct answer to include tasks requiring analysis and physical interpretation.

The content validity of the cognitive assessment was examined by six experts whose academic backgrounds were directly relevant to the study: a university professor specializing in physics; an emeritus professor of physics specializing in physics education; an associate professor of physics specializing in science education; a university laboratory teaching staff member with backgrounds in mathematics and computer science and expertise in microcontrollers; and two secondary-school physics teachers. The experts evaluated the items for alignment with the learning objectives, clarity of wording, and representative coverage of the three cognitive domains.

A pilot study was then conducted with 59 students assigned to three groups following the structure of the main study: 18 in the CG, 22 in EG1, and 19 in EG2. Each group came from a separate class in a different school. The pilot data were used to examine the comprehensibility of the wording, the functionality of the procedure, and the suitability of the scoring system; they were not included in the main study.

The open-ended items Q25–Q30 were scored by one rater using predetermined criteria for scientific accuracy, completeness, and adequacy of reasoning. Because no independent second rating was conducted, interrater reliability was not calculated.

The internal consistency of the complete instrument was examined using Cronbach's alpha. Across all 30 items, alpha was .728 at pretest and .786 at posttest. These values support using the total score as a supplementary indicator of cognitive performance. Because the instrument comprises three theoretically distinct cognitive components, their reliability was also examined separately. At posttest, internal consistency was .62, .69, and .61 for C1, C2, and C3, respectively. These values fall below the .70 threshold and should be interpreted in light of both the smaller number of items in each component and the heterogeneity of the knowledge assessed by the individual items. The lower alpha values for the separate components therefore do not negate the satisfactory internal consistency of the complete instrument, but they indicate that the component scores require greater caution in interpretation.

The broader research project also assessed learning motivation with a separate instrument. Results for that dimension have been reported elsewhere (Mamouras *et al.*, 2026) [23] and are beyond the scope of the present article.

3.5 Procedure and Ethics

The pretest was administered before the first instructional phase, and the posttest followed completion of the intervention. Responses were linked by a code, allowing the two measurement occasions to be compared without using names in the analysis. Participation was voluntary, and participants retained the right to withdraw.

Students participated with written consent from their parents or guardians and with the cooperation of their teachers. The study was approved by the relevant Research Ethics Committee of the Department of Physics at the University of Thessaly (122nd meeting, September 10, 2025).

3.6 Statistical Analysis

Statistical analyses were conducted in SPSS version 31.0 and were organized around the three research questions and the instrument's three cognitive components.

Descriptive statistics were first calculated for the pretest and posttest performance of the three groups and for the change between the two measurement occasions. Pretest performance was used to describe the groups' starting points and as a covariate in the primary comparisons of posttest performance. The absence of statistically significant pretest differences was not treated by itself as evidence that the nonrandomized groups were equivalent.

The primary comparison of the three instructional conditions used separate one-way analyses of covariance (ANCOVAs) for C1, C2, and C3. In each analysis, the posttest score for the corresponding cognitive component was the dependent variable, instructional condition was the independent variable, and the corresponding pretest score was the covariate.

Before interpreting the ANCOVAs, linearity between pretest and posttest scores, homogeneity of regression slopes, and homogeneity of variances were examined. Homogeneity of regression slopes was tested through the interaction between pretest score and group, and homogeneity of variances was examined with Levene's test.

Because residual normality was not strictly satisfied in all analyses, the robustness of the findings was examined using HC3 standard errors and sensitivity analyses. ANCOVA effect sizes were expressed as partial eta squared (η_p^2). When the overall group effect was statistically significant, adjusted pairwise comparisons with a Sidak correction were conducted. A Holm correction was also applied across the three primary analyses to control the familywise Type I error rate.

Comparisons at the level of individual items were not the primary basis for evaluating the effectiveness of the instructional conditions. Given the discrete or ordinal nature of the item-level data, nonparametric tests were used only as supplementary exploratory analyses. Kruskal–Wallis tests compared the three groups, Mann–Whitney U tests were used for selected pairwise comparisons, and Wilcoxon signed-rank tests compared pretest and posttest scores within groups. These findings were interpreted as supplementary evidence rather than as 30 independent confirmatory tests of the same hypothesis.

The total score across the 30 items was used as a supplementary descriptive indicator. Interpretation focused primarily on the three cognitive components because they represent different types of knowledge and because C2 directly reflects the content of the technological intervention.

Finally, the statistical analyses were conducted at the student level. Because participants were nested within existing classes and the number of schools was relatively small, the analyses cannot be assumed to eliminate dependence associated with school or class membership. Together with the absence of individual randomization, this feature was considered when interpreting the findings and limits strong causal generalizations.

4. Results

The analysis included descriptive values for the total score and the three component scores. Because of the form of the item-level data and departures from the assumptions of parametric tests, nonparametric procedures were used. A separate Kruskal–Wallis test was conducted for each item to compare the three groups at pretest and posttest. The Wilcoxon signed-rank test was used for within-group pretest–posttest comparisons.

The ANCOVAs of the composite scores for each cognitive component, with a Holm correction, constituted the study's primary confirmatory analyses. Item-level comparisons are presented as supplementary descriptive and exploratory analyses without correction for multiple comparisons because of the large number of tests (30 per comparison). They should therefore be interpreted as indications of the direction and extent of change rather than as independent confirmatory evidence.

4.1 Pretest Performance and Group Comparability

The Kruskal–Wallis tests found no statistically significant differences among the three groups on any of the 30 pretest items. No statistically significant difference was found in the total pretest score either, $H(2) = 0.233$, $p = .890$.

To examine initial cognitive performance more fully, supplementary Mann–Whitney U pairwise comparisons were conducted between CG–EG1, CG–EG2, and EG1–EG2 for each of the 30 items and for the total score. The item-level comparisons showed no statistically significant differences for any pair of groups. The total-score comparisons were also not statistically significant:

CG–EG1, $p = .910$, $r = .014$;
CG–EG2, $p = .661$, $r = .056$; and
EG1–EG2, $p = .709$, $r = .042$.

In all cases, the effect sizes were negligible.

The convergence of the descriptive data, the Kruskal–Wallis test, and the supplementary Mann–Whitney U comparisons indicates that no clear pre-existing cognitive differences were detected among the groups in the measured domains.

4.2 Descriptive Statistics

Table 4 presents the mean total performance of the three groups at pretest and posttest and the mean change in both the total score and the three cognitive components. Values are reported as means and standard deviations, M (SD), and change was calculated for each student as the difference between posttest and pretest scores (T2-T1). The maximum total score on the instrument was 96 points.

Table 4: Descriptive Performance and Mean Change by Group, M (SD)

Measure	CG (n = 27)	EG1 (n = 43)	EG2 (n = 35)
Total score, pretest	69.70 (7.36)	68.91 (7.71)	69.46 (8.04)
Total score, posttest	76.48 (3.48)	88.35 (3.09)	89.89 (2.54)
Total gain	6.78 (6.37)	19.44 (7.07)	20.43 (6.84)
Gain: damped oscillations	2.30 (3.06)	5.28 (2.66)	5.60 (2.63)
Gain: microcontrollers	2.15 (1.94)	7.19 (2.00)	7.51 (2.25)
Gain: graphs	2.33 (3.82)	6.98 (4.30)	7.31 (4.25)

Note. Values are presented as mean (standard deviation). In the change rows, the SD refers to the individual posttest–pretest differences.

At pretest, the three groups had very similar mean total scores. At posttest, the CG mean increased from 69.70 to 76.48, a gain of 6.78 points; the EG1 mean increased from 68.91 to 88.35, a gain of 19.44 points; and the EG2 mean increased from 69.46 to 89.89, a gain of 20.43 points. At the descriptive level, therefore, the total gain in the two

experimental groups was approximately three times that in the CG.

The same pattern appeared in the separate cognitive components. For damped oscillations, the mean increase was 2.30 points in the CG, 5.28 in EG1, and 5.60 in EG2. For microcontrollers, the corresponding gains were 2.15, 7.19, and 7.51 points, whereas for graphs they were 2.33, 6.98, and 7.31 points. In absolute terms, the greatest improvement in the two experimental groups occurred in microcontroller knowledge, followed by graphs and damped oscillations.

EG2 showed a slightly larger mean gain than EG1 in all three components, although these small differences do not by themselves establish a statistically significant advantage. The smaller standard deviations of the final total scores also indicate reduced dispersion and greater concentration of scores around the respective means. Overall, the descriptive findings suggest a pattern favoring the two experimental groups, which is examined below using the appropriate inferential analyses.

4.3 Within-Group and Posttest Item-Level Comparisons

In the CG, the Wilcoxon test found no statistically significant change in any of the 30 individual items. Z values ranged from −1.906 to −0.933, and p values ranged from .057 to .351, remaining above $\alpha = .05$ in every case. Although positive ranks outnumbered negative ranks for all items, indicating a descriptive trend toward improvement, the change was not sufficiently consistent to reach statistical significance at the individual-item level. This result does not mean that conventional laboratory teaching had no effect, because the mean total score rose from 69.70 to 76.48 points, a gain of 6.78 points. Nevertheless, the null hypothesis was not rejected for any item; thus, no significant change was detected in any individual CG item between pretest and posttest.

By contrast, the Wilcoxon test in EG1 identified statistically significant pretest–posttest differences for all 30 items. Z values ranged from −5.324 to −2.904, and p values were below .05 in every case: $p < .001$ for most items, $p = .002$ for Q7, and $p = .004$ for Q29. For every item, the predominance of positive over negative ranks indicated that changes were directed mainly toward higher posttest scores. Overall, EG1 showed an extensive and consistent pattern of higher performance on the cognitive instrument at posttest than at pretest.

A similar pattern was recorded in EG2, where the Wilcoxon test identified statistically significant pretest–posttest differences for all 30 items. Z values ranged from −4.882 to −2.709, and all p values were below .05. Most items yielded $p < .001$, and the largest p value was .007. Positive ranks clearly predominated over negative ranks for every item, indicating that changes were directed mainly toward higher posttest scores. Overall, EG2 showed an extensive and consistent pattern of higher performance on the cognitive instrument at posttest than at pretest.

The consistency of the results in the two experimental groups indicates that improvement was not confined to a narrow category of knowledge but extended across different cognitive tasks: conceptual recognition, functional knowledge of the microcontroller, extraction of quantitative information from graphs, comparison of curves, and physical reasoning. The within-group analyses therefore document broad and systematic change in EG1 and EG2, although they do not by themselves establish its cause.

This differentiation also appeared in the between-group comparisons at posttest. Kruskal–Wallis tests identified statistically significant differences for all 30 items, with statistics ranging from $H(2) = 6.041$ to $H(2) = 35.972$ and corresponding p values from $p < .001$ to $p = .049$. The null hypothesis was therefore rejected for each item. This result indicates that, after the instructional interventions, the score distribution in at least one group differed significantly from that in another group.

Mann–Whitney U pairwise comparisons identified the source of these differences more precisely. CG and EG1 differed significantly on all 30 items, with p values ranging from $p < .001$ to $p = .038$ and consistently higher mean ranks for EG1. Similarly, CG and EG2 differed significantly on all 30 items, with p values ranging from $p < .001$ to $p = .034$ and higher mean ranks for EG2. Thus, the higher posttest performance of both experimental groups relative to the CG was not limited to the total score but appeared across the full range of items examined.

By contrast, the EG1–EG2 comparison showed no statistically significant differences for 28 of the 30 items. Differences were found only for Q23 ($p = .020$) and Q28 ($p = .032$), for which EG2 had the higher mean rank. Both items belong to the graphs component and provide a localized indication in favor of EG2 rather than evidence of a general advantage over EG1. This interpretation is reinforced by the small descriptive differences between the two groups: EG2 exceeded EG1 by 1.54 points in the final mean score and by only 0.99 points in the mean total gain.

It should be noted that, after applying a Bonferroni correction for this family of 30 comparisons ($\alpha = .05/30 \approx .0017$), neither Q23 ($p = .020$) nor Q28 ($p = .032$) remains statistically significant. These findings should therefore be treated as descriptive exploratory indications rather than statistically supported differences.

Overall, the results form a coherent pattern: the CG showed descriptive but nonsignificant improvement at the item level, whereas EG1 and EG2 showed statistically significant within-group improvement on all 30 items and systematically higher posttest performance than the CG. Adding the simulation in EG2 was not associated with a general difference relative to EG1, because the between-group difference was confined to two items in the graphs component.

Analysis by Cognitive Component

Analysis by cognitive component complements the total-score analysis by clarifying the domains in which improvement occurred and the features of the instructional activity that may be associated with it. C1 comprised Q1–Q10 and addressed the basic concepts and physical principles of damped oscillations. C2 comprised Q11–Q20 and assessed basic knowledge of microcontrollers, especially Arduino. C3 comprised Q21–Q30 and assessed the reading, analysis, and physical interpretation of displacement–time graphs. The shared direction of the results across the three components indicates that the learning gains in the experimental groups were multidimensional, while the component-level differences permit more precise interpretation of how the corresponding knowledge developed.

First Cognitive Component (C1): Basic Concepts of Damped Oscillations

C1 showed descriptive improvement in all three groups, but the magnitude differed substantially. At pretest, the percentages of correct responses were 51.10% in the CG, 49.00% in EG1, and 48.00% in EG2. These small differences were not statistically significant. At posttest, performance reached 61.90% in the CG, 84.20% in EG1, and 87.10% in EG2. The reversal of the initial pattern and the large separation between the two experimental groups and the CG indicate that conceptual progress was considerably stronger under the conditions in which students participated actively in collecting, visualizing, and processing experimental data. The small posttest advantage for EG2 remained descriptive because no statistically significant difference between EG1 and EG2 was found for any of the ten items.

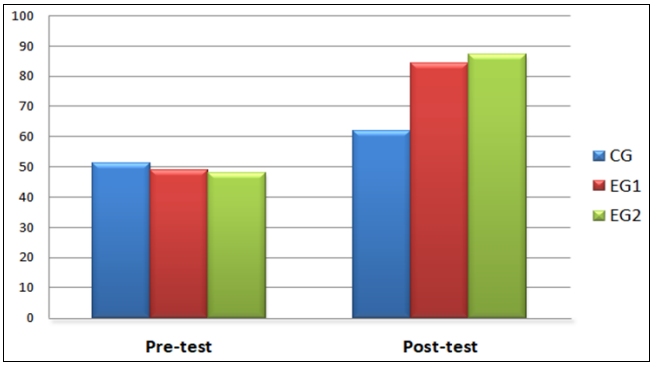


Fig 2: Mean percentage of items answered fully correctly by group at pretest and posttest for component C1. The same pattern was observed for C2 and C3

Second Cognitive Component (C2): Knowledge of Microcontrollers and Arduino

C2 is of particular interest because it assesses a domain with which students had very little prior familiarity. At pretest, the percentages of correct responses were 26.70% in the CG, 26.00% in EG1, and 28.00% in EG2, with no statistically significant differences. Across all 105 students, the mean was only 2.68 correct answers out of 10, and very few students reached five correct answers. This result is close to the theoretical chance level for four-option items, namely 2.5 correct responses or 25%. The pretest pattern indicates that students' general familiarity with digital devices was not accompanied by organized knowledge of how a microcontroller operates and is programmed, how it connects to sensors, or how it collects and processes measurements.

After instruction, the groups followed markedly different trajectories. The CG reached 37.80%, while EG1 reached 82.10% and EG2 reached 85.70%. EG1 exceeded the CG by 44.3 percentage points and EG2 by 47.9 percentage points. Both experimental groups showed statistically significant improvement on all ten individual items, with $p < .001$ in every case. In contrast, no change in the CG was statistically significant. Improvement in EG1 and EG2 covered a broad range of knowledge: the programmable nature of a microcontroller, connection to a computer, analog and digital pins, the role of sensors, the Arduino IDE, the setup()-loop() structure, and the concept of open source. The findings therefore indicate extensive acquisition of basic technological knowledge rather than improvement in a few isolated facts.

Third Cognitive Component (C3): Reading and Interpretation of Graphs

C3 addressed the reading, analysis, and physical interpretation of experimental data represented graphically. Descriptively, pretest performance was 40.00% in the CG, 38.30% in EG1, and 43.10% in EG2, with no statistically significant differences. At posttest, the CG reached 45.20%, EG1 reached 68.10%, and EG2 reached 70.80%. The two experimental groups therefore made substantially greater progress than the CG and followed broadly similar trajectories.

Testing Component-Level Differences with ANCOVA

Three one-way analyses of covariance (ANCOVAs) were conducted to determine whether the descriptive pattern across the three cognitive components remained after controlling for pretest performance. In each analysis, the posttest composite score for the corresponding component was the dependent variable, group was the independent variable, and the pretest score for the same component was the covariate. ANCOVA allowed posttest performance to be compared while accounting for differences present at pretest, even when those differences were not statistically significant.

All 105 students were included in the analyses because there were no missing values. Although each student participated in only one research condition, independence was not fully assured because students were clustered within classes and schools. In addition, all interventions were designed and implemented by the same instructor, reducing the possibility that between-group differences resulted from differences among teachers. Inspection of the scatterplots revealed no clear departures from linearity. The homogeneity-of-regression-slopes assumption was satisfied because the interaction between pretest score and group was not statistically significant for C1 ($p = .556$), C2 ($p = .462$), or C3 ($p = .547$). Similarly, Levene's test indicated no violation of homogeneity of variance for C1 ($p = .842$), C2 ($p = .684$), or C3 ($p = .078$). Residual normality was not strictly satisfied, with departures occurring mainly in the distribution tails. Although strict residual normality was unsupported, the stability of the conclusions was examined using HC3 robust standard errors and sensitivity analyses.

After controlling statistically for the corresponding pretest score, statistically significant group differences were identified for all three cognitive components (Table 5). The effect of group was large in all three analyses, and the adjusted posttest means for EG1 and EG2 exceeded that of the CG.

Table 5: ANCOVA Results and Adjusted Posttest Means by Cognitive Component

Cognitive component	*F(2, 101)*	*p*	η^2_p	Adjusted posttest mean		
				CG	EG1	EG2
C1	54.591	< .001	0.519	26.078	28.454	28.754
C2	214.148	< .001	0.809	23.078	28.185	28.540
C3	49.592	< .001	0.495	27.244	31.794	32.551

Note. In each analysis, the pretest score for the corresponding cognitive component was used as the covariate. C1 = damped-oscillation concepts; C2 = microcontroller knowledge; C3 = graph interpretation.

Sidak-adjusted comparisons showed that both experimental groups had higher adjusted posttest performance than the CG in all three components ($p < .001$). In contrast, no general difference between EG1 and EG2 was detected for C1 ($p = .532$), C2 ($p = .439$), or C3 ($p = .361$).

The overall effects remained statistically significant both with HC3 robust standard errors and in sensitivity analyses after the temporary exclusion of the most strongly flagged cases. All three tests also remained significant after the Holm correction ($p < .001$).

Table 6: HC3 Robust Tests of the Overall Group Effect

Cognitive component	F_{HC3}	df1	df2	p
C1 – Damped oscillations	47.197	2	101	< .001
C2 – Microcontrollers	183.023	2	101	< .001
C3 – Graphs	37.450	2	101	< .001

Note. HC3 = heteroskedasticity-consistent standard errors, type 3. The overall Group effect remained statistically significant for all three cognitive components.

Table 7: Adjusted Pairwise Group Comparisons with Sidak Correction

Component	Comparison	Adjusted mean difference	95% Sidak CI	p_{Sidak}
C1 – Damped oscillations	CG–EG1	−2.376	[−3.022, −1.731]	< .001
	CG–EG2	−2.677	[−3.350, −2.004]	< .001
	EG1–EG2	−0.300	[−0.896, 0.295]	0.532
C2 – Microcontrollers	CG–EG1	−5.107	[−5.788, −4.426]	< .001
	CG–EG2	−5.462	[−6.173, −4.752]	< .001
	EG1–EG2	−0.355	[−0.986, 0.276]	0.439
C3 – Graphs	CG–EG1	−4.550	[−5.876, −3.224]	< .001
	CG–EG2	−5.307	[−6.691, −3.923]	< .001
	EG1–EG2	−0.757	[−1.988, 0.474]	0.361

Note. Comparisons are based on adjusted posttest means. The adjusted mean difference is calculated as the mean of the first group minus that of the second; therefore, the negative values for CG–EG1 and CG–EG2 indicate higher adjusted posttest performance in the experimental groups. Significance levels and confidence intervals were adjusted using the Sidak method.

Table 8: Results of the Sensitivity Analyses After Temporary Exclusion of Flagged Cases

Component	Temporary exclusion	N	F	p	n_p^2	p_{Holm}
C1 – Damped oscillations	1 case from EG1	104	F(2, 100) = 63.528	< .001	0.560	< .001
C2 – Microcontrollers	1 case from EG2	104	F(2, 100) = 210.840	< .001	0.808	< .001
C3 – Graphs	1 from CG and 1 from EG1	103	F(2, 99) = 56.872	< .001	0.535	< .001

Note. Cases were temporarily excluded only for the sensitivity analyses and not from the primary analyses. Exclusion was performed separately for each component on the basis of the corresponding diagnostic results. n_p^2 = partial eta squared. The Holm correction was applied across the three overall tests of the Group effect.

5. Discussion

5.1 Interpretation of the Overall Findings

The overall assessment shows a clear differentiation between the control group (CG) and the two experimental groups (EG1 and EG2) in both the total score and the three cognitive components (Tables 4–5). The groups' comparability at the pretest (Section 4.1) does not rule out interpreting their later divergence as related to their different instructional trajectories rather than to pre-existing differences. The breadth of improvement, encompassing conceptual recognition, functional knowledge of the microcontroller, and graph interpretation, is consistent with studies highlighting the educational value of active microcontroller-based data collection and visualization (Schnider & Hömöstrei, 2024; Çoban & Erol, 2025a) [40, 6] and the combination of physical and virtual experimentation (Olympiou & Zacharia, 2012) [30]. Similarly, the systematic review by Saramati *et al*. (2026) [38] identifies real-time data collection and active inquiry as key mechanisms for learning with microcontrollers.

The EG1–EG2 comparison did not show a general advantage for EG2 (Section 4.3; Table 5). The absence of a difference is consistent with Çoban and Erol (2025b) [7], who reported similarly substantial improvement with Arduino activities and simulations, and with research showing that physical, virtual, and combined experimentation can support conceptual understanding equally effectively when embedded in appropriately structured activities (Zacharia & Constantinou, 2008; Zacharia & Olympiou, 2011) [54, 56]. The only item-level indications favoring EG2, on Q23 and Q28, arose from unadjusted comparisons that did not survive a strict correction (Section 4.3) and should therefore be treated as descriptive rather than established findings. They are nevertheless consistent with evidence that the contribution of virtual experimentation depends on the specific cognitive task (Zacharia & de Jong, 2014) [55] and with the review by Wörner *et al*. (2022) [52], which found no consistent advantage for a particular sequence of physical and virtual experimentation.

Overall, most of the cognitive improvement was associated with the common foundation of the two experimental groups: active laboratory inquiry using Arduino and sensors, construction of the apparatus, and connection of real data with their graphical representation. The additional simulation used by EG2 was not accompanied by an established general advantage.

5.2 Analysis of Results by Cognitive Component

On the basis of the preceding descriptive and inferential analyses, the discussion now focuses on the three cognitive components to interpret both the shared direction of the

findings and their component-level differences.

First Cognitive Component (C1): Basic Concepts of Damped Oscillations

The statistically significant advantage of the experimental groups in C1 (Table 5) encompassed both basic and more demanding aspects of the phenomenon: distinguishing simple harmonic from damped oscillation, the behavior of amplitude and period, the effect of the medium and damping force, the exponential decrease in amplitude, and the loss of mechanical energy. This consistency suggests that students did more than recognize the damped form; they developed more organized relationships among the physical quantities. Repeated measurement and comparison of results allowed them to support their conclusions with data rather than relying only on verbal descriptions.

This direction is consistent with Sukmak and Musik (2022) [42], whose Arduino apparatus for recording mass–spring oscillations was associated with significantly higher posttest performance, and with Schnider and Hömöstrei (2024) [40], who showed that active collection and graphical representation of kinematic data were associated with immediate performance and knowledge retention. The inquiry-based nature of the intervention, involving changes in conditions, data collection, comparison of results, and evidence-based conclusions through structured worksheets, is consistent with the meta-analyses by Furtak *et al*. (2012) [14] and Lazonder and Harmsen (2016) [21], which link guided inquiry with positive cognitive outcomes.

Second Cognitive Component (C2): Knowledge of Microcontrollers and Arduino

C2 showed the strongest group effect (Table 5). The limited progress in the CG may be related to the observational, non-constructionist nature of its exposure to the apparatus: students observed demonstrations without undertaking assembly or programming themselves. In the experimental groups, by contrast, knowledge was developed through direct construction activities, including circuit assembly, sensor connection, program upload, testing, and troubleshooting. This involvement appears to have given functional meaning to concepts that might otherwise have remained abstract.

Johnson *et al*. (2023) [17] describe a similar pattern: the pretest performance of novice Arduino users (27.3%) was close to chance and almost identical to the 26.8% found in the present study; it increased to 80.7% after a hands-on activity, with 87.5% of participants successfully constructing and programming the circuit. Chung and Lou (2021) [5] likewise reported higher performance in algorithmic thinking and debugging, while Sarı *et al*. (2022) [39] associate a similar design–build–test–improve sequence with the development of problem-solving skills. The reviews by García-Tudela and Marín-Marín (2023) [15] and Marín-Marín *et al*. (2024) [24] note that, despite the growing presence of Arduino in school education, student exposure remains limited, a pattern consistent with the low pretest performance and strong response of the present sample.

No meaningful difference between EG1 and EG2 was detected for C2 (Section 4.3), consistent with both groups having received the same microcontroller instruction, whereas the EG2 simulation concerned the representation of oscillation rather than the structure of Arduino. Tselegkaridis *et al*. (2024) [43] reported a similar pattern: students using breadboards, modular boards, or a Tinkercad simulation improved equally, with no differences among modes of interaction.

Third Cognitive Component (C3): Reading and Interpretation of Graphs

The advantage of the experimental groups in C3 remained after controlling for pretest performance (Table 5) and extended to recognizing different forms of oscillation, interpreting the envelope, determining amplitude qualitatively and quantitatively, comparing graphs, and connecting damping with energy. Lower posttest performance on the more demanding items indicates that these abilities developed to different degrees rather than following a uniform pattern.

The complementary function of multiple representations (Ainsworth, 2006) [2] and improved understanding through real-time data display (Kozhevnikov & Thornton, 2006) [19], together with the findings of Sukmak and Musik (2022) [42] and Schnider and Hömöstrei (2024) [40], converge on the educational value of directly connecting phenomenon, measurement, and graph. Particularly relevant is the study by Okur and Güngör Seyhan (2025) [29], in which faster data collection and display left more time for discussion and interpretation, a mechanism consistent with the function of the present intervention. The review by Ruf *et al*. (2026, N = 54 studies) [36] further supports the importance of in-depth engagement with authentic data.

As noted in Section 5.1, the limited, unadjusted indication favoring EG2 on two C3 items is consistent with the finding that the usefulness of virtual experimentation depends on the cognitive task (Zacharia & de Jong, 2014) [55], but it does not establish a general advantage. Overall, C3 indicates that active involvement in collecting and interpreting real data was associated with substantial development of graph-interpretation skills.

5.3 Instructional Implications

The findings highlight the value of introducing Arduino into school physics gradually and with pedagogical guidance. Student involvement can progress from identifying components and using simple sensors to calibration, modification of basic code parameters, and independent investigation of a physical phenomenon, so that technical complexity does not overshadow the subject matter. Students do not need to write the entire program, but the code should be sufficiently transparent for them to understand the function of the main commands and their relationship to data collection. Sensor calibration and the analysis of non-ideal graphs can also serve as substantive scientific activities through which accuracy, uncertainty, and departures from the theoretical model are examined. Effective implementation of this approach also requires appropriate teacher professional development that combines technical familiarity with pedagogical design and connects construction activities to clearly formulated physics questions.

5.4 Limitations and Recommendations for Future Research

This study has several limitations. The sample comprised Grade 12 students from a specific geographic region, limiting the generalizability of the findings to other student populations and educational or cultural contexts.

Assignment occurred at the school level using existing student groups. The absence of statistically significant pretest differences indicates comparability but does not establish full equivalence or rule out the influence of unmeasured characteristics of students, classes, or schools.

Furthermore, as noted in Section 3.2, the intervention condition was completely confounded with school because each school participated in only one condition. This feature limits not only generalizability but also the causal interpretation of differences, particularly between CG and EG2.

Cognitive learning outcomes were assessed with a written test addressing specific dimensions of learning in the content domain under study. The results therefore reflect performance on the components assessed and do not necessarily cover the full range of conceptual understanding, problem-solving strategies, or the ability to transfer knowledge to new contexts. In addition, the sample size and the use of only two measurement occasions do not permit a more detailed examination of the trajectory of cognitive change. The absence of a delayed follow-up assessment also prevents determining whether the improvement in performance was sustained after the intervention ended.

Future research could use larger and more heterogeneous samples from a greater number of schools and designs that account for effects at the student, class, and school levels. Additional measurement occasions, including a delayed follow-up, would allow both the development and retention of cognitive change to be examined. Implementing comparable interventions at different educational levels, in other subject domains, and across cultural contexts would also permit a fuller examination of the external validity of the findings.

Further investigation of the additional contribution of simulations when combined with microcontrollers is of particular interest. Future studies designed to isolate their effects could examine potential differences in conceptual understanding, problem solving, graph interpretation, and transfer of knowledge. Finally, combining written assessments with classroom observations, interviews, and problem-solving protocols would strengthen methodological triangulation and provide a fuller understanding of the mechanisms through which these instructional interventions affect learning.

5.5 Conclusion

This study examined an instructional approach in which the microcontroller was not used merely to record a damped oscillation. Students in the experimental groups were prepared gradually, connected sensors, became familiar with the program's basic logic, calibrated the sensor, built the experimental apparatus, and related real measurements to the corresponding graphs and their physical interpretation. The technology was therefore embedded in an integrated inquiry process rather than used as a ready-made data acquisition system.

No statistically significant differences among the three groups were detected at pretest. Following the instructional intervention, the two experimental groups showed clearly greater total improvement and higher posttest performance than the control group. This pattern was consistent across all three cognitive components: concepts of damped oscillations, knowledge of microcontrollers, and graph interpretation. The additional simulation used by EG2 was not associated with an established advantage over EG1, although localized indications favored EG2, mainly on more demanding graph-interpretation activities.

Overall, the findings highlight the pedagogical value of the sequence construction → programming → measurement → visualization → physical interpretation. Through this sequence, students move from passive use of a ready-made data-logging system to participation in the creation, calibration, and evaluation of the experimental tool itself (Mitrakas & Tsihouridis, 2025) [25]. The conclusions nevertheless require caution: the study documents a consistent pattern of positive outcomes associated with the overall instructional condition, not an isolated causal effect of the microcontroller, construction, or simulation.

The main educational implication is that microcontrollers have greater learning value when they do not conceal the measurement process but instead make it an object of inquiry (Tsihouridis & Vavougios, 2023) [45]. A school experiment goes beyond simple data logging when students can explain not only what a graph shows, but also how it was produced, which choices shaped its data, and which limitations affect its interpretation (Mitrakas *et al*., 2026; Tsihouridis *et al*., 2024a) [28, 47].

6. References

1. Abrahams I, Millar R. Does practical work really work? A study of the effectiveness of practical work as a teaching and learning method in school science. International Journal of Science Education. 2008; 30(14):1945-1969. Doi: https://doi.org/10.1080/09500690701749305
2. Ainsworth S. DeFT: A conceptual framework for considering learning with multiple representations. Learning and Instruction. 2006; 16(3):183-198. Doi: https://doi.org/10.1016/j.learninstruc.2006.03.001
3. Boimau I, Mataubenu KDF, Asbanu DESI, Banu TBJ. A simple pendulum studied using Hall effect sensor and Arduino. AIP Conference Proceedings. 2022; 2542:060002. Doi: https://doi.org/10.1063/5.0103214
4. Buachoom A, Thedsakhulwong A, Wuttiprom S. An Arduino board with ultrasonic sensor investigation of simple harmonic motion. Journal of Physics: Conference Series. 2019; 1380(1):012098. Doi: https://doi.org/10.1088/1742-6596/1380/1/012098
5. Chung C-C, Lou S-J. Physical computing strategy to support students' coding literacy: An educational experiment with Arduino boards. Applied Sciences. 2021; 11(4):1830. Doi: https://doi.org/10.3390/app11041830
6. Çoban A, Erol M. Impact of Arduino based STEM education on cognitive domain level of mechanics and scientific creativity. LUMAT: International Journal on Math, Science and Technology Education. 2025a; 12(4), Article 16. Doi: https://doi.org/10.31129/LUMAT.12.4.2231
7. Çoban A, Erol M. Influences of Arduino and Algodoo based mechanics teaching on achievement. Necatibey Faculty of Education Electronic Journal of Science and Mathematics Education. 2025b; 19(1):30-64. Doi: https://doi.org/10.17522/balikesirnef.1559865
8. Çoban A, Akat E, Erdoğan AC. Two different experiments with the rope-attached sphere by using Arduino. Physics Education. 2023; 58(1):015022. Doi: https://doi.org/10.1088/1361-6552/aca19d

9. De Castro LHM, Lago BL, Mondaini F. Damped harmonic oscillator with Arduino. Journal of Applied Mathematics and Physics. 2015; 3(6):631-636. Doi: https://doi.org/10.4236/jamp.2015.36075
10. De Jong T, Linn MC, Zacharia ZC. Physical and virtual laboratories in science and engineering education. Science. 2013; 340(6130):305-308. Doi: https://doi.org/10.1126/science.1230579
11. Escudero R, Barrere N, Rodríguez Chialanza M. Using Arduino to study two-degree-of-freedom mass-spring system. Physics Education. 2024; 59(6):063009. Doi: https://doi.org/10.1088/1361-6552/ad7fbf
12. Falstad P. Harmonic oscillator [Interactive simulation], n.d. Retrieved July 30, 2026, from https://www.falstad.com/harmonicosc/
13. Fields DA, Kafai YB, Morales-Navarro L, Walker JT. Debugging by design: A constructionist approach to high school students' crafting and coding of electronic textiles. British Journal of Educational Technology. 2021; 52(3):1078-1092. Doi: https://doi.org/10.1111/bjet.13079
14. Furtak EM, Seidel T, Iverson H, Briggs DC. Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. Review of Educational Research. 2012; 82(3):300-329. Doi: https://doi.org/10.3102/0034654312457206
15. García-Tudela PA, Marín-Marín J-A. Use of Arduino in primary education: A systematic review. Education Sciences. 2023; 13(2):134. Doi: https://doi.org/10.3390/educsci13020134
16. Hofstein A, Lunetta VN. The laboratory in science education: Foundations for the twenty-first century. Science Education. 2004; 88(1):28-54. Doi: https://doi.org/10.1002/sce.10106
17. Johnson DM, Pate ML, Estepp CM, Wardlow GW. Using self-efficacy theory to design Arduino instruction for novices: A replication study. Journal of Research in Technical Careers. 2023; 7(1):68-84. Doi: https://doi.org/10.9741/2578-2118.1125
18. Kafai YB, Lee E, Searle K, Fields D, Kaplan E, Lui D. A crafts-oriented approach to computing in high school: Introducing computational concepts, practices, and perspectives with electronic textiles. ACM Transactions on Computing Education. 2014; 14(1), Article 1, 1-20. Doi: https://doi.org/10.1145/2576874
19. Kozhevnikov M, Thornton R. Real-time data display, spatial visualization ability, and learning force and motion concepts. Journal of Science Education and Technology. 2006; 15:111-132. Doi: https://doi.org/10.1007/s10956-006-0361-0
20. Kyriazopoulos N, Lazos P, Nezis A. To systima Arduino stin peiramatiki fysiki [The Arduino system in experimental physics]. In Proceedings of the 11th Conference on Informatics in Education 2019: I pliroforiki stin ekpaidefsi, 2019, 187-197. https://events.di.ionio.gr/cie/images/documents19/cie2019_Proc_OnLine/praktika.html
21. Lazonder AW, Harmsen R. Meta-analysis of inquiry-based learning: Effects of guidance. Review of Educational Research. 2016; 86(3):681-718. Doi: https://doi.org/10.3102/0034654315627366
22. Litts BK, Kafai YB, Lui DA, Walker JT, Widman SA. Stitching codeable circuits: High school students' learning about circuitry and coding with electronic textiles. Journal of Science Education and Technology. 2017; 26:494-507. Doi: https://doi.org/10.1007/s10956-017-9694-0
23. Mamouras D, Simos CH, Tsihouridis CH, Vavougios D. Microcontrollers and digital simulations in physics teaching: Effects of a teaching intervention on students' learning motivation. International Journal of Advanced Multidisciplinary Research and Studies. 2026; 6(4):1078-1092. Doi: https://doi.org/10.62225/2583049X.2026.6.4.6703
24. Marín-Marín J-A, García-Tudela PA, Dúo-Terrón P. Computational thinking and programming with Arduino in education: A systematic review for secondary education. Heliyon. 2024; 10(8):e29177. Doi: https://doi.org/10.1016/j.heliyon.2024.e29177
25. Mitrakas N, Tsihouridis C. Extended reality in science learning: A comparative study of real, virtual, and mixed environments. In L. T. De Paolis, P. Arpaia, & M. Sacco (Eds.), Extended reality: XR Salento 2025 (Lecture Notes in Computer Science, Vol. 15738). Springer, Cham, 2025. Doi: https://doi.org/10.1007/978-3-031-97769-5_5
26. Mitrakas N, Tsihouridis C, Vavougios D. Using Mixed Reality in the Educational Practice: An Inquiry-Based Process of the Fluid Expansion-Contraction Phenomena by Pre-Service Teachers. Education Sciences. 2024; 14(7):754. Doi: https://doi.org/10.3390/educsci14070754
27. Mitrakas N, Tsihouridis C, Batsila M, Vavougios D. Electromagnetic Waves and Their Quantum Nature. Starting from "Scratch" …. In: Auer, M.E., Pachatz, W., Rüütmann, T. (eds) Learning in the Age of Digital and Green Transition. ICL 2022. Lecture Notes in Networks and Systems, vol 633, 730-741, Springer, Cham, 2023. Doi: https://doi.org/10.1007/978-3-031-26876-2_69
28. Mitrakas N, Tsihouridis C, Karavasilis A, Batsila M. Using mobile inquiry-based learning as a V.E.H.I.C.L.E to enhance understanding of mechanical and light energy. In M. E. Auer & P. Toth (Eds.), Innovation via collaborative learning in engineering education (Vol. 1847). Lecture Notes in Networks and Systems. Springer, 2026. Doi: https://doi.org/10.1007/978-3-032-18885-4_23
29. Okur M, Güngör Seyhan H. Mobile technology-enhanced 5E learning model in physics labs: An analysis of graph drawing and interpretation skills. Journal of Science Education and Technology. 2025; 34:1441-1466. Doi: https://doi.org/10.1007/s10956-025-10222-3
30. Olympiou G, Zacharia ZC. Blending physical and virtual manipulatives: An effort to improve students' conceptual understanding through science laboratory experimentation. Science Education. 2012; 96(1):21-47. Doi: https://doi.org/10.1002/sce.20463
31. Omari S, Mamane A, Daoui A, Ben Ouahi M, Benjelloun N. Investigating the effect of a proposed educational robot on students' motivation and learning of thermodynamic concepts. International Journal of Information and Education Technology. 2023; 13(7):1085-1093. Doi: https://doi.org/10.18178/ijiet.2023.13.7.1908
32. Papadimitropoulos N, Dalacosta K, Pavlatou EA. Teaching chemistry with Arduino experiments in a

mixed virtual-physical learning environment. Journal of Science Education and Technology. 2021; 30:550-566. Doi: https://doi.org/10.1007/s10956-020-09899-5
33. Papert S. Mindstorms: Children, computers, and powerful ideas. Basic Books, 1980.
34. Papert S. Situating constructionism. In I. Harel & S. Papert (Eds.), Constructionism. Ablex Publishing, 1991, 1-11.
35. Rinaldi RG, Fauzi A. A complete damped harmonic oscillator using an Arduino and an Excel spreadsheet. Physics Education. 2020; 55(1):015024. Doi: https://doi.org/10.1088/1361-6552/ab539d
36. Ruf V, Thüs D, Malone S, Küchemann S, Becker-Genschow S, Vogel M, *et al*. A systematic review of empirical research on graphing numerical data in K-12 STEM education. International Journal of Science and Mathematics Education. 2026; 24, Article 28. Doi: https://doi.org/10.1007/s10763-026-10653-3
37. Rutten NPG, Van Joolingen WR, Van Der Veen JT. The learning effects of computer simulations in science education. Computers & Education. 2012; 58(1):136-153. Doi: https://doi.org/10.1016/j.compedu.2011.07.017
38. Saramati B, Vidak A, Mešić V. Learning physics with microcontrollers: A systematic review of empirical research. Eurasia Journal of Mathematics, Science and Technology Education. 2026; 22(6):em2848. Doi: https://doi.org/10.29333/ejmste/18710
39. Sarı U, Çelik H, Pektaş HM, Yalçın S. Effects of STEM-focused Arduino practical activities on problem-solving and entrepreneurship skills. Australasian Journal of Educational Technology. 2022; 38(3):140-154. Doi: https://doi.org/10.14742/ajet.7293
40. Schnider D, Hömöstrei M. Arduino-supported kinematics measurements. Physics Education. 2024; 59(5):055015. Doi: https://doi.org/10.1088/1361-6552/ad672a
41. Serway RA, Jewett JW Jr. Physics for scientists and engineers with modern physics (10th ed.). Cengage Learning, 2019.
42. Sukmak W, Musik P. Real-time graphing of simple harmonic motion of mass on springs with an Arduino based on an experiment set for teaching and learning physics. Turkish Online Journal of Educational Technology. 2022; 21(1):114-123.
43. Tselegkaridis S, Sapounidis T, Papakostas D. Learning circuits and coding with Arduino board in higher education using tangible and graphical user interfaces. Information. 2024; 15(5):245. Doi: https://doi.org/10.3390/info15050245
44. Tsihouridis C, Mitrakas N. The Phenomenon of Seasons Through a Hyper-Interactive 3D Environment. Aiming at Highlighting Prospective Teachers' Creativity. In: Auer, M.E., Rüütmann, T. (eds) Futureproofing Engineering Education for Global Responsibility. ICL 2024. Lecture Notes in Networks and Systems, vol 1281. Springer, Cham, 2025. Doi: https://doi.org/10.1007/978-3-031-83520-9_7
45. Tsihouridis C, Vavougios D. Experimental Environments in PER: A Critical and Comparative Evaluation of the International Literature-Trends. In M. F. Taşar & P. R. L. Heron (Eds), The International Handbook of Physics Education Research: Teaching Physics. AIP Publishing LLC, 2023. Doi: https://doi.org/10.1063/9780735425712_004
46. Tsihouridis C, Mitrakas N, Batsila M. The S.T.E.M. teaching approach with an emphasis on inquiry-based learning: Development and pedagogical utilization of a self-built robotic model of the Earth's orbit. In M. E. Auer & P. Toth (Eds.), Innovation via collaborative learning in engineering education (Vol. 1847). Lecture Notes in Networks and Systems. Springer, 2026. Doi: https://doi.org/10.1007/978-3-032-18885-4_5
47. Tsihouridis C, Mitrakas N, Batsila M, Vavougios D. A Holistic View of Using Real and Virtual Models in Teaching Astronomy Concepts. In: Auer, M.E., Cukierman, U.R., Vendrell Vidal, E., Tovar Caro, E. (eds) Towards a Hybrid, Flexible and Socially Engaged Higher Education. ICL 2023. Lecture Notes in Networks and Systems, vol 900. Springer, Cham, 2024a. Doi: https://doi.org/10.1007/978-3-031-52667-1_12
48. Tsihouridis C, Mitrakas N, Koutropoulos P. Investigating the effectiveness of using a real and a virtual model in teaching astronomy concepts to elementary students. The cases of the eclipse phenomena. International Journal of Educational Innovation. 2024b; 6(1):102-112. Doi: https://doi.org/10.69685/VLOG2059
49. Tsihouridis C, Mitrakas N, Karavasilis A, Vavougios D. Diepistimoniki prosengisi didaskalias tou fysikou ekkremous me ti voitheia tou BBC micro:bit [An interdisciplinary approach to teaching the physical pendulum using the BBC micro]. Panellinio Synedrio tis Didaktikis ton Fysikon Epistimon kai Neon Technologion stin Ekpaidefsi. 2024c; 13:473-482. Doi: https://doi.org/10.12681/codiste.6974
50. Tsihouridis C, Mitrakas N, Karavasilis A, Vavougios D, Batsila M. The Invisible World of Gas Molecules in the Light of Mixed Reality. Educating Prospective Teachers. In: Auer, M.E., Rüütmann, T. (eds) Futureproofing Engineering Education for Global Responsibility. ICL 2024. Lecture Notes in Networks and Systems, vol 1261. Springer, Cham, 2025. Doi: https://doi.org/10.1007/978-3-031-85649-5_15
51. Wadhwa A, Wadhwa A. Investigating damped oscillations in simple pendulum. Physics Education. 2023; 58(6):065016. Doi: https://doi.org/10.1088/1361-6552/acf433
52. Wörner S, Kuhn J, Scheiter K. The best of two worlds: A systematic review on combining real and virtual experiments in science education. Review of Educational Research. 2022; 92(6):911-952. Doi: https://doi.org/10.3102/00346543221079417
53. Young HD, Freedman RA. University physics with modern physics (15th ed.). Pearson, 2020.
54. Zacharia ZC, Constantinou CP. Comparing the influence of physical and virtual manipulatives in the context of the Physics by Inquiry curriculum: The case of undergraduate students' conceptual understanding of heat and temperature. American Journal of Physics. 2008; 76(4-5):425-430. Doi: https://doi.org/10.1119/1.2885059
55. Zacharia ZC, De Jong T. The effects on students' conceptual understanding of electric circuits of introducing virtual manipulatives within a physical manipulatives-oriented curriculum. Cognition and Instruction. 2014; 32(2):101-158. Doi:

https://doi.org/10.1080/07370008.2014.887083
56. Zacharia ZC, Olympiou G. Physical versus virtual manipulative experimentation in physics learning. Learning and Instruction. 2011; 21(3):317-331. Doi: https://doi.org/10.1016/j.learninstruc.2010.03.001