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Microcontrollers and Digital Simulations in Physics Teaching: Effects of a Teaching Intervention on Students' Learning Motivation

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Abstract

The present study investigated changes in the learning motivation of Grade 12 students following of a teaching intervention in Physics on damped oscillations. In particular, it examined the extent to which different levels of teaching interventions—traditional experimental work, experimental work with a microcontroller, and an experimental combination of a microcontroller with a digital simulation—are associated with differential changes across the dimensions of learning motivation. The study involved 105 Grade 12 students assigned to three groups (one control group and two experimental groups). The research design is characterised as quasi-experimental, with measurements before and after the intervention. Learning motivation was assessed using the Students' Adaptive Learning Engagement in Science—SALES questionnaire, which captures four dimensions: learning goal orientation, perceived value, self-efficacy, and self-regulation. The results of the initial measurement before the teaching interventions showed no statistically significant differences between the groups, whereas the post-intervention results indicated that changes in motivation differed according to the teaching condition (a statistically significant Time × Group interaction). The two experimental groups exhibited stronger positive changes in the dimensions of motivation compared with the control group. In particular, the group that combined microcontroller and a digital simulation showed the greatest increase in self-efficacy. The findings support the view that a pedagogically designed combination of experimentation, microcontrollers, and digital simulations may be associated with the enhancement of critical dimensions of learning motivation in Physics. The study contributes to the investigation of how different levels of technology integration are associated with dynamic changes in students' motivation in Science.

Keywords: Microcontrollers, Digital Simulations, Learning Motivation, Self-Efficacy, Upper-Secondary Physics, Damped Oscillations

1. Introduction

Enhancing students' engagement in learning Science is one of the most important challenges in contemporary teaching practice. Learning in Physics depends not only on students' cognitive abilities or on the quality of the presentation of the subject matter, but also on the extent to which students are motivated, persist, attach value to the learning activity, and perceive themselves as capable of responding to demanding scientific tasks. The international literature has shown that learning motivation, expectations of success, perceived competence, and the broader learning environment are critical factors in students' active participation and successful learning in Science (Elliot *et al*., 2017; Gagné & Deci, 2005; Ryan & Deci, 2000; Vansteenkiste & Ryan, 2019) [16, 19, 47, 64].

Motivation to learn is a complex and multidimensional psychoeducational process associated with the activation, direction, and maintenance of effort towards a learning goal (Palmer, 2005; Schunk, *et al*., 2014) [39, 53]. According to Cavas (2011) [10], motivation is particularly important in the field of Science, as it affects students' interest, their willingness to investigate natural phenomena, their persistence in the face of cognitive difficulties, and their use of cognitive and metacognitive strategies.

According to contemporary theoretical approaches, motivation should not be treated as a stable individual trait, but as a dynamic state shaped through interaction with the subject matter, teaching practices, available tools, and the nature of the learning environment (Cleary & Zimmerman, 2012; Schunk, 2005) [13, 50].

Within this context, experimental and inquiry-based activities occupy a central place in Physics teaching because they offer students the opportunity to interact directly with natural phenomena, formulate hypotheses, collect data, control variables, and connect theoretical knowledge with empirical observations. However, traditional laboratory teaching often encounters limitations, particularly when phenomena evolve dynamically, require accurate data recording, or presuppose the connection of multiple representations, such as experimental measurements, graphs, mathematical relationships, and theoretical models. These limitations highlight the importance of the pedagogically grounded use of contemporary technological tools in Physics teaching. Empirical studies indicate that teaching approaches integrating laboratory activities, digital tools, and inquiry-based practices contribute to the formation of learning environments that enhance students' interest, engagement, and Self-efficacy (Hofstein & Lunetta, 2003; Tseng *et al*., 2007; Lazarević *et al*., 2024) [23, 58, 30].

Technology-supported learning environments, and particularly those combining microcontrollers and digital simulations, offer new possibilities for designing experimental activities with a high degree of student engagement. Microcontrollers, in combination with appropriate sensors, enable the collection and processing of experimental data in real time, making visible changes that would otherwise be difficult to record accurately. At the same time, digital simulations make it possible to control variables, investigate hypothetical or ideal conditions, and compare experimental results with theoretical models. In this way, they can function as a complement to the real experiment, enhancing understanding, autonomy, Self-efficacy, and the perceived value of the learning activity (Ramasundaram *et al*., 2005; Chen *et al*., 2025; Banda & Nzabahimana, 2023) [45, 12, 5].

At the same time, studies in different Science subject areas show that the pedagogically designed integration of inquiry-based and laboratory activities, as well as the use of a variety of teaching approaches, contributes positively to students' motivation to learn (Feng & Tuan, 2005; Cavas, 2011) [17, 10]. In addition, studies using motivation measurement tools demonstrate the importance of factors such as Self-efficacy, learning value, and active learning strategies in enhancing motivation (Tseng *et al*., 2007; Andressa *et al*., 2015) [58, 2].

Research in Science education has demonstrated that students' motivation is a critical component of the learning process at both the cognitive and affective levels, as it is associated with processes of conceptual change, active engagement in learning, and academic achievement (Lee & Brophy, 1996; Pintrich *et al*., 1993) [31, 43]. At the same time, psychoeducational theory proposes that factors such as goal setting, perceived competence, expectations of success, and the perceived value of learning constitute key components of motivation, influencing effort, persistence, and the use of cognitive and metacognitive strategies (Eccles & Wigfield, 2002; Schunk, Pintrich, & Meece, 2010) [15, 53].

Consequently, the combined use of real experimentation, microcontrollers, and digital simulations is of particular interest in teaching concepts that simultaneously require empirical observation and modelling (Tsihouridis & Vavougios, 2023) [60]. Damped oscillations constitute one such area, as their study presupposes an understanding of changes in amplitude, the effect of damping, the relationship between real and ideal conditions, and the representation of motion through data and graphs. The use of microcontrollers can support the accurate recording of the phenomenon's development, while digital simulation can help students interpret discrepancies between the theoretical model and the actual experimental process (Mitrakas *et al*., 2024; Tsihouridis *et al*, 2025, 2026) [35, 62, 61].

Despite the growing research interest in digital tools, laboratory activities, and learning motivation in Science, there remains a need for studies that systematically investigate how different levels of technology integration affect the individual dimensions of motivation to learn (Mitrakas *et al*., 2023, 2026) [36, 37]. It is particularly important to examine not only whether a technology-supported intervention is associated with improved motivation, but also whether the addition of different tools, such as a microcontroller and a digital simulation, leads to differentiated trajectories of change in learning goal orientation, perceived value, Self-efficacy, and Self-regulation (Tsihouridis *et al*., 2023).

The present study builds on this body of research by investigating the effect of a teaching intervention in upper-secondary Physics, focusing on damped oscillations, on students' learning motivation. Nimely's, it compares three teaching conditions: a traditional experimental approach, an intervention using a microcontroller to record and process experimental data, and an intervention combining a microcontroller with a digital simulation. In this way, the study seeks to contribute to understanding how pedagogical design and the level of technological mediation may be associated with dynamic changes in students' motivation in Physics teaching.

2. Theoretical Framework—Learning Motivation in Science and the SALES Questionnaire

In the field of Science education, learning cannot be approached exclusively as a cognitive process, but as the outcome of the interaction of cognitive, affective, and motivational factors.

Within the framework of constructivism, students actively construct their knowledge by connecting new concepts with pre-existing conceptions, experiences, and authentic contexts of application (Tuan *et al*., 2005) [63]. This process is significantly influenced by whether students attach value to the learning activity, feel capable of meeting its demands, persist in the face of difficulties, and use strategies to self-regulate their learning.

Learning motivation has emerged as a critical factor in students' engagement in Science, conceptual understanding, persistence in problem solving, and academic achievement.

Empirical evidence highlights motivation as a critical factor in conceptual change, the development of critical thinking, and the use of effective learning strategies (Kuyper *et al*., 2000; Velayutham *et al*., 2011) [29, 66]. At the secondary education level, consistent and statistically significant correlations have been recorded between motivational factors and achievement in Science (Tuan *et al*., 2005; Singh *et al*., 2002) [63, 54], while interest and motivation are associated with improved conceptual learning outcomes (Hynd *et al*., 2000; Yen *et al*., 2011) [24, 70]. Similarly, in higher education, Self-efficacy and the perceived value of the learning activity function as strong predictors of achievement (Zusho *et al*., 2003; Glynn *et al*., 2007, 2009) [73, 21, 22].

In conclusion, many studies highlight motivation as a central component of teaching and learning in Science, underlining the need for further investigation of the factors that contribute to maintaining high levels of motivation in demanding scientific environments. Therefore, the investigation of learning motivation is not merely a supplementary dimension of educational research, but an essential element in understanding the effectiveness of a teaching intervention (Tsihouridis & Mitrakas, 2025) [59].

To study these factors systematically, Velayutham, Aldridge, and Fraser (2011) [66] developed the Students' Adaptive Learning Engagement in Science—SALES questionnaire. SALES is a theoretically and psychometrically grounded instrument for assessing learning motivation and Self-regulation in the field of Science. Its development was based on important theoretical approaches, such as achievement goal theory, the expectancy-value model, Self-efficacy theory, and theories of self-regulated learning. At the same time, it drew on and extended pre-existing instruments for measuring motivation, such as the MSLQ, PALS, SMTSL, and SMQ.

More precisely, this questionnaire was developed following an extensive review of theories and empirical research on motivation and Self-regulation in Science learning and was based on a clear theoretical framework drawing on achievement goal theory (Ames, 1992; Kaplan & Maehr, 2007) [1, 28], the expectancy-value model (Eccles & Wigfield, 2002; Pintrich & De Groot, 1990) [15, 42], Self-efficacy theory (Bandura, 1977, 1986) [6, 7], and approaches to self-regulated learning (Zimmerman, 2002; Pintrich, 2000) [72, 40]. It was developed by adapting and refining previously validated questionnaires (Velayutham *et al*., 2011) [66], such as the Motivated Strategies for Learning Questionnaire (MSLQ, Pintrich *et al*., 1991) [44], the Patterns of Adaptive Learning Survey (PALS, Midgley *et al*., 1996) [33], Students' Motivation Toward Science Learning (SMTSL, Tuan *et al*., 2005) [63], and the Science Motivation Questionnaire (SMQ, Glynn *et al*., 2009) [22]. Reliability and factor-analytic evidence indicates that SALES have satisfactory internal consistency and a stable structure, making it suitable for research use. At the same time, the motivational constructs on which it is based have been empirically confirmed in a variety of cultural and educational contexts, strengthening the instrument's cross-cultural validity.

SALES comprise 32 questions distributed across four dimensions of learning motivation: (a) Learning Goal Orientation, (b) Task Value, (c) Self-efficacy, and (d) Self-regulation. According to Velayutham *et al*. (2011) [66], learning goal orientation refers to the extent to which students focus on understanding, improving their abilities, and meaningful learning. Task value concerns students' perceptions of the importance, usefulness, and interest of learning Science. Self-efficacy is associated with students' beliefs about their ability to respond successfully to demanding learning activities, while Self-regulation concerns their ability to organise, control, and sustain their effort during the learning process.

The international literature has used SALES in different educational, cultural, and disciplinary contexts. Studies by Velayutham, Aldridge, and Fraser (2013) [68] showed that dimensions such as Self-efficacy and task value are strongly associated with Self-regulation in Science learning.

Other studies used the instrument to examine the relationship between motivation, Self-regulation, and conceptual understanding, as well as to adapt and psychometrically validate it in different educational systems (Yetişir & Ceylan, 2015) [71]. These findings support the usefulness of SALES as an instrument for investigating the motivational dimensions of learning, particularly when research interest focuses on the changes that may be brought about by a specific learning environment (İnaltun & Ateş, 2015) [26].

A substantial number of studies have also documented the relationship of learning motivation with academic achievement, conceptual understanding, and the use of learning strategies. Self-efficacy, the perceived value of learning, and Self-regulation appear to function as important factors influencing students' persistence, cognitive engagement, and ability to respond to complex scientific activities (Mazlina *et al*., 2024; Ikhlas *et al*., 2021; Overal, 2021; Syauqi *et al*., 2024) [69, 25, 38, 56].

This finding is particularly critical for Physics teaching, where students are often required to connect abstract concepts, mathematical relationships, experimental data, and graphical representations. Several studies have also documented the relationship between motivation to learn Science and academic achievement. Tuan *et al*. (2005) [63] identified a moderate to strong correlation between motivational factors and achievement, while subsequent studies document consistent correlations between Self-efficacy, interest, and the perceived value of learning, and achievement in Physics and Chemistry (Zusho *et al*., 2003; Glynn *et al*., 2007, 2009) [73, 21, 22]. At the same time, a recent intervention study in Science, involving three different subject areas, showed that the systematic enhancement of learning motivation is associated with a statistically significant improvement in students' academic achievement and conceptual understanding, highlighting the central role of motivation in the learning process (Mantzavinos *et al*., 2024) [32]. Similar findings are also recorded in broader subject areas, where motivation is associated with the use of cognitive and metacognitive strategies and with overall learning success (Singh *et al*., 2002; Chatzistamatiou *et al*., 2015) [54, 11].

Despite the extensive use of motivation measurement instruments in Science, systematic investigation of how different levels of technology integration affect the individual dimensions of motivation to learn over time remains limited. More specifically, further studies are needed to examine whether the transition from traditional experimental activity to technology-supported forms of experimentation, such as the use of microcontrollers and their combination with digital simulations, is associated with differentiated changes in students' learning goal orientation, perceived value, Self-efficacy, and Self-regulation (Mitrakas & Tsihouridis, 2025) [34].

The present study uses SALES precisely within this context, investigating changes in the four dimensions above before and after a teaching intervention in upper-secondary Physics focusing on damped oscillations. By comparing three teaching conditions—traditional experimental activity, activity with a microcontroller, and activity combining a microcontroller and a digital simulation—the study seeks to contribute to understanding how the degree of technological mediation may be associated with different trajectories of change in learning motivation.

3. The Present Study

Despite the increasing use of technology-supported environments in Physics teaching, there remains a need to systematically investigate how different levels of technology integration are associated with the individual dimensions of students' learning motivation. The international literature has highlighted the importance of laboratory activities, digital tools, and multiple representations for engagement in learning; however, the question of whether the transition from a traditional experimental approach to more complex, technologically mediated forms of teaching is associated with differentiated changes in learning motivation remains less thoroughly investigated. The above rationale constitutes both the principal research concern and the focus of the present study.

More specifically, the present study focuses on changes in upper-secondary students' learning motivation following a teaching intervention using microcontrollers in the teaching of damped oscillations in Physics. The choice of damped oscillations is of particular teaching interest, since this phenomenon requires the connection of experimental observation, data collection and analysis, graphical representations, and theoretical modelling. For this reason, it constitutes a suitable field for investigating the teaching use of microcontrollers and digital simulations.

The study compares three teaching conditions: (a) a traditional experimental approach, (b) a technology-supported intervention using a microcontroller to record and process experimental data, and (c) an intervention combining the use of a microcontroller with a digital simulation. In this way, the study does not merely examine whether the use of technology is associated with changes in motivation, but investigates whether different levels of technological mediation differ in terms of their effect on the individual dimensions of motivation to learn.

Motivation was assessed using the Students' Adaptive Learning Engagement in Science—SALES questionnaire developed by Velayutham *et al*. (2011) [66], which was created specifically for the field of Science and has been used to investigate dimensions such as learning goal orientation, task value, Self-efficacy, and Self-regulation. In the present study, these four dimensions are examined before and after the teaching intervention in order to capture not only the existence of a possible change, but also differences in that change among the three groups.

Specifically, the present study seeks to answer the following research questions:

Research Question 1: To what extent does students' learning motivation change following the completion of the teaching intervention on damped oscillations?

Research Question 2: Does the change in learning motivation differ between the control group, which follows a traditional experimental approach, and the experimental groups, which use either a microcontroller or a combination of a microcontroller and a digital simulation?

Research Question 3: Are there differences between the two experimental groups in the change observed in the individual dimensions of motivation, namely learning goal orientation, task value, Self-efficacy, and Self-regulation?

On the basis of the above questions, the following statistical hypotheses were formulated:

Research Hypothesis 1—Time × Group Interaction

The change in the four dimensions of learning motivation from the initial to the final measurement is expected to differ according to the teaching condition in which the students participated.

Statistically, the null and alternative hypotheses can be formulated as follows:

$H0_1$: There is no statistically significant Time × Group interaction in the multivariate profile of the four dimensions of learning motivation.

$H1_1$: There is a statistically significant Time × Group interaction in the multivariate profile of the four dimensions of learning motivation.

Research Hypothesis 2—Change in Motivation from the Initial to the Final Measurement

Students are expected to exhibit changes in the dimensions of motivation from the initial to the final measurement, with the magnitude and direction of the change differing between groups.

$H0_2$: No statistically significant change is observed from the initial to the final measurement in the four dimensions of learning motivation.

$H1_2$: A statistically significant change is observed from the initial to the final measurement in at least one of the four dimensions of learning motivation.

Research Hypothesis 3—Comparison of the Two Experimental Groups

The experimental group combining a microcontroller and a digital simulation is expected to possibly exhibit a different change compared with the experimental group using only a microcontroller, particularly in dimensions associated with students' understanding, self-confidence, and perceived competence.

$H0_3$: There is no statistically significant difference in the magnitude of change between the two experimental groups in any of the four dimensions of learning motivation.

$H1_3$: There is a statistically significant difference in the magnitude of change between the two experimental groups in at least one of the four dimensions of learning motivation.

The contribution of the present study lies in examining changes in learning motivation not as a single, undifferentiated outcome, but as a multidimensional process that may be influenced by the type and level of technological mediation. By comparing three teaching conditions, the study seeks to shed light on the role of pedagogical design, experimental engagement, and digital representations in shaping students' motivation in Physics.

4. Methodology

4.1 Research Design

The present study followed a quasi-experimental, non-equivalent groups design with pre- and post-measurement. The design included one control group and two experimental groups, which participated in differentiated teaching conditions during the teaching of damped oscillations. The control group participated in a traditional experimental activity, the first experimental group used a microcontroller to record and process experimental data, while the second experimental group combined the use of a microcontroller with a digital simulation.

The intervention was implemented by the same teacher in all groups in order to ensure consistency in the teaching approach and to limit possible effects related to the "teacher" factor. Participants were assigned to the three conditions at the school-unit level (clustered assignment), with a total of five schools participating, rather than through randomisation of students at the individual level. For this reason, the design is characterised as quasi-experimental. The selection of this particular design was dictated by practical and educational constraints related to the operation of the schools, the maintenance of existing classes, and the smooth integration of the intervention into the school programme.

Learning motivation was assessed at two time points: before the start of the teaching intervention and after its completion. This made it possible to investigate changes in motivation over time, as well as to compare these changes across the three teaching conditions.

4.2 Participants

The study involved 105 Grade 12 students who had selected the Physics specialisation course. The students came from five schools in the prefecture of Magnesia. Their age was approximately 17 years, as corresponds to attendance in Grade 12. Differences by gender were not analysed, as this variable was not a subject of the present study. The distribution of students by school and research condition is presented in Table 1.

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 a digital simulation.

As shown in Table 1, the students were assigned to three research groups/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. Before the main data analysis, the initial equivalence of the groups was tested in relation to the four dimensions of learning motivation.

4.3 Main Research Instrument

The *Students' Adaptive Learning Engagement in Science—SALES* questionnaire developed by Velayutham, Aldridge, and Fraser (2011) [63] was used to measure learning motivation. SALES was developed specifically for the field of Science and captures four dimensions of motivation to learn: (a) learning goal orientation, (b) task value, (c) Self-efficacy, and (d) Self-regulation.

More specifically, the questionnaire comprises 32 questions distributed across four subscales of eight questions each. Questions 1–8 correspond to learning goal orientation, questions 9–16 to task value, questions 17–24 to Self-efficacy, and questions 25–32 to Self-regulation. According to Tsihouridis, Kryona, and Vavougios (2020) [75], these subscales were translated and adapted into Greek, demonstrating high internal consistency and retaining the distinctiveness of the four factors (Tsihouridis *et al*., 2020) [75].

Students responded on a five-point Likert scale, ranging from 1 = "Strongly disagree" to 5 = "Strongly agree". The instrument's four subscales are presented in Table 2.

Table 2: Scales of the Students' Adaptive Learning Engagement in Science-SALES Questionnaire

Motivational factor	Description	Number of questions	Sample question
K1 Learning Goal Orientation	The extent to which students focus on understanding, learning, and developing skills in Science.	8	One of my goals is to become proficient in new science-related skills.
K2 Task Value Task Value	Students' perceptions regarding the usefulness, interest, and importance of learning Science.	8	What I learn in Science is useful in my everyday life.
K3 Self-efficacy	Students' beliefs about their ability to understand and succeed in Science learning activities.	8	Even if the scientific content of a task is difficult, I can learn it.
K4 Self-regulation	Students' ability to plan, monitor, and regulate their learning effort in Science.	8	I do not give up even if what I have to do is difficult.

The Greek version of the instrument, which has been translated and adapted to the Greek educational context, was used in the present study. Previous psychometric documentation of the Greek version has demonstrated satisfactory internal consistency and distinctiveness of the four factors. To further document the reliability of the instrument in the present sample, it is proposed that internal consistency indices be calculated for each subscale at the initial and final measurements.

In the present sample, the internal consistency indices of the four subscales were at satisfactory levels at both the initial and final measurements, with Cronbach's α values ranging from 0.70 to 0.90 at the initial measurement and from 0.70 to 0.93 at the final measurement.

4.4 Data Collection Procedure

Data collection was conducted in two phases. In the first phase, before the start of the teaching intervention, students in all groups completed the SALES questionnaire. In the second phase, after completion of the intervention, the same questionnaire was administered to the students again in order to record possible changes in the four dimensions of learning motivation.

Before completing the questionnaire, the students were informed about the purpose of the study and the voluntary nature of their participation. It was clarified that their responses would remain anonymous, would not be used to assess them in the course, and that they could choose not to

participate without any consequences. Completion of the questionnaire took approximately 20 minutes.
Students participated with the written consent of their parents/guardians and with the cooperation of the teachers. The study had been approved by the competent Research Ethics Committee of the Department of Physics at the University of Thessaly.

4.5 Teaching Intervention

The teaching intervention was designed within the context of doctoral research and focused on the teaching of damped oscillations in Grade 12 Physics. Its primary objective was to investigate the extent to which different levels of technological mediation in experimental teaching are associated with differentiated changes in students' learning motivation.
The intervention was implemented by the same teacher in all groups in order to limit the effect of differences that could be attributed to the "teacher" factor. Assignment to the three conditions was carried out at the school-unit level (clustered assignment), with a total of five schools participating. The schools were assigned to one control group and two experimental groups, without students being able to choose a condition. The study design can therefore be characterised as quasi-experimental. Investigation of the students' profiles established that the students had no previous systematic experience in using microcontrollers, with the exception of a very small number of individual cases.
All groups worked with structured worksheets and a collaborative group-work approach. The worksheets had a common teaching focus and corresponding subject-matter content, but differed in terms of the technological tools used in each teaching condition.
In the experimental groups, the intervention was preceded by a familiarisation phase involving the use of microcontrollers, sensors, and appropriate software. This phase included basic concepts of data collection, sensor connection, use of the microcontroller, use of online technical support resources, and development of simple measurement applications. The aim of this preparatory phase was for students to acquire the necessary technological and methodological skills so that they could participate meaningfully in the experimental activity on damped oscillations.
The experimental apparatus was based on a force sensor connected to a microcontroller, which recorded the force exerted by a vertical spring on an oscillating body. A body that could oscillate either in air or within a liquid medium was attached to the free end of the spring, allowing different degrees of damping to be studied. The linear dependence of the spring force on its extension enabled quantitative investigation of changes in the amplitude and period of the oscillation through digital recording and real-time data analysis. The basic structure of the experimental apparatus is presented in Fig 1.

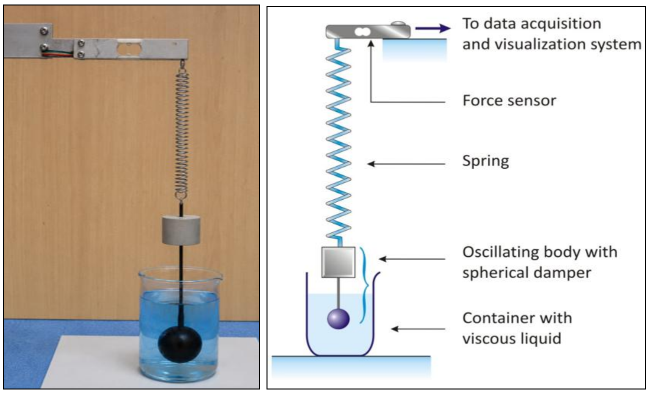

Fig 1: Image and Diagram of the Experimental Apparatus for Studying Oscillations

The use of this apparatus enabled students in the experimental groups to connect the physical development of the oscillation with the immediate digital display of the data. In this way, the experimental activity was not limited to observation of the phenomenon, but extended to the collection, processing, and interpretation of measurements, supporting the connection between the real experiment, the graphical representation, and the theoretical model.

Table 3: Phases, Duration, and Individual Processes of the Teaching Intervention

Duration	Control group CG	Experimental group EG1	Experimental group EG2
Preparatory phase			
6 teaching hours	Participation in traditional laboratory activities. Assembly of simple experimental apparatuses and collection and processing of experimental data. Each activity was followed by a demonstration of the corresponding experiment using a technological apparatus.	Familiarisation with the basic principles of microcontroller operation and programming, as well as with the connection and use of sensors. Construction of functional microcontroller-based apparatuses and assembly of the experimental apparatus for the main teaching phase.	Familiarisation with the basic principles of microcontroller operation and programming, as well as with the connection and use of sensors. Construction of functional microcontroller-based apparatuses and assembly of the experimental apparatus for the main teaching phase.
Main teaching phase			
2 teaching hours	Conducting a traditional damped oscillations experiment, without a microcontroller or digital simulation. Collection, processing, and interpretation of data without automated digital recording.	Use of the apparatus with a microcontroller and force sensor. Digital recording and processing of data in real time. Study of amplitude, period, and damping under different conditions.	Use of the same apparatus with a microcontroller and force sensor, in combination with a digital simulation. Comparison of experimental data with theoretical models and investigation of ideal and real damping conditions.

Before the main teaching intervention, a six-hour preparatory phase of equal duration for all groups was conducted, with activities adapted to each group's teaching condition. The control group (CG) participated in traditional laboratory activities, during which the students assembled simple experimental apparatuses and became familiar with the collection and processing of experimental data. Each activity was followed by a demonstration of the corresponding experiment using a technological apparatus, without the students actively participating in its use or construction.

Students in the two experimental groups (EG1 and EG2) became familiar with the basic principles of microcontroller operation and programming, as well as with the connection and use of sensors. During the preparatory phase, they constructed functional microcontroller-based apparatuses and assembled the experimental apparatus that they would use during the main teaching phase themselves.

The main teaching phase, which focused on the topic of damped oscillations, had the same duration and corresponding learning objectives across all groups. The groups differed primarily in the level of technological mediation involved in the experimental activity.

The control group (CG) participated in a traditional experimental activity. The students assembled a mechanical apparatus, followed written instructions, and studied damped oscillations without the use of microcontrollers or digital simulations. Data collection and processing were carried out without automated digital recording.

The first experimental group (EG1) used an experimental apparatus with a microcontroller and a force sensor. The sensor recorded the force exerted by a vertical spring on the oscillating body, enabling the digital recording and processing of data in real time. The apparatus enabled the study of changes in the amplitude and period of the oscillation, as well as the investigation of damping under different conditions.

The second experimental group (EG2) used the same microcontroller-based experimental apparatus and, additionally, a digital simulation of oscillations. The simulation enabled students to compare the experimental data with theoretical models and investigate the differences between ideal and real damping conditions. In this way, this particular teaching condition combined empirical data collection with modelling and multiple representations of the physical phenomenon.

The teaching intervention was designed on the basis of the principles of active and inquiry-based learning. Particular emphasis was placed on connecting theoretical concepts with experimental data, discussing graphs, interpreting differences between the theoretical model and the real experiment, and actively involving students in the process of collecting, analysing, and interpreting data.

It is important to note that the total engagement time of the experimental groups also included the preparatory phase of familiarisation with the microcontrollers. In contrast, the comparison with the control group mainly concerns the main teaching phase on damped oscillations. This point is taken into account when interpreting the findings, since the additional time spent on technological familiarisation may have contributed to differences in students' engagement in learning.

All groups worked with structured worksheets and a collaborative group-work approach. The worksheets had a common teaching focus and corresponding subject-matter content, but differed in terms of the technological tools used in each teaching condition. The same questionnaires were administered to all groups before and after the intervention in order to assess changes in motivation. The intervention was designed on the basis of the principles of active and inquiry-based learning, with an emphasis on connecting theoretical concepts and experimental data in order to support dimensions such as Self-efficacy, the perceived value of learning, and Self-regulation.

5. Results

5.1 Test of the Initial Equivalence of the Groups

Before examining the effect of the teaching intervention, the initial equivalence of the three groups was tested with respect to the four dimensions of learning motivation. For this purpose, one-way analyses of variance (one-way ANOVA) were conducted, with Group as the independent variable and the values of the four factors at the initial measurement as the dependent variables: (a) K1: Learning Goal Orientation, (b) K2: Task Value, (c) K3: Self-efficacy, and (d) K4: Self-regulation.

The results showed no statistically significant differences between the groups in any of the four dimensions of learning motivation at the initial measurement, as all p values were greater than .05. This indicates that the groups were comparable before implementation of the teaching intervention. The Self-efficacy variable displayed a marginal trend, but did not reach the level of statistical significance. The results of the initial equivalence test are presented in Table 4.

Table 4: Test of Group Equivalence at the Initial Measurement (T1)

Variable	$F(2,102)$	p	partial η^2	Group Comparison	Mean Difference (I–J)	p (Tukey)
K1_T1 Learning Goal Orientation	2.20	.116	.041	CG–EG1	0.223	.113
				CG–EG2	0.083	.750
				EG1–EG2	-0.140	.364
K2_T1 Task Value	1.86	.162	.035	CG–EG1	0.179	.149
				CG–EG2	0.142	.327
				EG1–EG2	-0.037	.908
K3_T1 Self-efficacy	2.81	.065	.052	CG–EG1	0.297	.051
				CG–EG2	0.183	.347
				EG1–EG2	-0.115	.587
K4_T1 Self-regulation	0.16	.854	.003	CG–EG1	-0.001	1.000
				CG–EG2	0.048	.895
				EG1–EG2	0.049	.864

5.2 Descriptive Statistics

Table 5 presents the descriptive statistics for the four dimensions of the questionnaire for the three groups in the study (control group, Experimental Group 1, and Experimental Group 2) at the initial (T1) and final (T2) measurements. For each dimension, the number of participants (N), mean (M), and standard deviation (SD) are presented, with values expressed on the original five-point Likert scale (1–5).

Table 5: Mean and Standard Deviation of the Four Dimensions at the Initial and Final Measurements

Dimension	Group	N	Initial measurement (T1) M (SD)	Final measurement (T2) M (SD)
K1	CG	27	3.21 (0.41)	3.28 (0.35)
	EG1	43	2.99 (0.45)	3.38 (0.40)
	EG2	35	3.12 (0.47)	3.66 (0.47)
K2	CG	27	3.00 (0.35)	2.80 (0.40)
	EG1	43	2.82 (0.40)	3.43 (0.41)
	EG2	35	2.85 (0.39)	3.56 (0.36)
K3	CG	27	2.99 (0.48)	2.81 (0.56)
	EG1	43	2.69 (0.51)	3.32 (0.40)
	EG2	35	2.80 (0.53)	3.63 (0.46)
K4	CG	27	2.96 (0.34)	3.12 (0.36)
	EG1	43	2.96 (0.44)	3.42 (0.42)
	EG2	35	2.91 (0.43)	3.51 (0.40)

Note: T1 = pre-test, T2 = post-test, M = mean, SD = standard deviation.

Examination of the descriptive data shows that, before the teaching intervention, the three groups were at similar levels across all four dimensions of the questionnaire. After completion of the intervention, the two experimental groups showed a clearer increase in mean values, mainly in dimensions K2, K3, and K4, whereas the corresponding changes in the control group were smaller and, in some cases, marginal or negative. More specifically, the greatest descriptive improvement was recorded in Experimental Group 2 in dimension K3, while Experimental Group 1 also showed a notable increase in dimensions K2, K3, and K4. At the same time, the relatively limited standard deviation values indicate that students' responses did not exhibit particularly large dispersion around the means. These findings outline an initial trend in favour of the experimental groups, without, however, in themselves documenting statistically significant differences, which are examined in the analyses that follow.

5.3 Repeated-Measures Multivariate Analysis of Variance

To investigate changes in learning motivation from the initial to the final measurement and differences in these changes between groups, a 2 (Time) × 2 (Group) mixed repeated-measures multivariate analysis of variance (mixed RM-MANOVA) was conducted, with time (pre–post) as the repeated factor, group (experimental–control) as the between-subjects factor, and the four motivational variables (Learning Goal Orientation, Task Value, Self-efficacy, and Self-regulation) as the dependent variables.

The normality of the dependent variables was tested at each time point and within each group. The results showed no deviations from normality, allowing the application of repeated-measures multivariate analysis of variance.

Testing of the assumptions showed that Box's M test, which examines the homogeneity of the covariance matrices, was not statistically significant (Box's M = **97.67, p = .122**), indicating that the relevant assumption was not violated. However, according to the literature, Pillai's Trace is considered the most robust multivariate criterion, particularly in cases of possible deviations from the assumptions or unequal sample sizes, and was therefore preferred for interpreting the results (Ateş *et al.*, 2019; Tabachnick & Fidell, 2019) [4, 57].

The results of the repeated-measures multivariate analysis are presented in Table 6.

Table 6: Results of the Repeated-Measures Multivariate Analysis of Variance

Effect	**Pillai's Trace**	**$F(df_1, df_2)$**	**p**	Partial η^2
Group	.865	F(8, 200) = 19.05	< .001	.432
Time	.174	F(4, 99) = 5.22	< .001	.174
Time × Group	.514	F(8, 200) = 8.64	< .001	.257

Note: The multivariate tests were conducted using Pillai's Trace.

The analysis showed a statistically significant main effect of Group, a statistically significant main effect of Time and, most importantly, a statistically significant Time × Group interaction.

The Time × Group interaction is the central finding of the analysis, as it shows that the change in the four dimensions of learning motivation from the initial to the final measurement was not the same for all groups. In other words, the groups followed different trajectories of change over time.

The existence of a statistically significant interaction justifies further investigation of the individual changes from the initial to the final measurement in order to determine in which dimensions of motivation and between which groups the differences occur.

5.4 Main Effects

The analysis showed a statistically significant main effect of Group, Pillai's Trace = .865, F(8, 200) = 19.05, p < .001, partial η^2 = .432. This finding indicates that there were differences between the groups in the overall multivariate profile of the dependent variables, with a large effect size, irrespective of measurement time.

At the same time, a statistically significant main effect of Time was observed, Pillai's Trace = .174, F(4, 99) = 5.22, p < .001, partial η^2 = .174, indicating that, overall, the dependent variables changed from the first to the second measurement, irrespective of group. This finding shows that the participants as a whole exhibited difference in the values of the variables over time, confirming the existence of temporal development in the phenomenon under study.

Time × Group Interaction

Of critical importance to the research question, the analysis revealed a strong and statistically significant Time × Group interaction, Pillai's Trace = .514, F(8, 200) = 8.64, p < .001, partial η^2 = .257. This result demonstrates that the change in the dependent variables from the first to the second measurement was not the same for all groups, but differed substantially among them. In other words, the groups followed different trajectories of change over time, indicating that the magnitude and/or direction of the change depended on group membership.

Simple Effects Analysis: Difference Scores (T2−T1)

To clarify the Time × Group interaction, changes from the initial to the final measurement were calculated for each dimension of learning motivation. These changes were expressed as difference scores, that is, as T2–T1 differences, for the four dimensions: dK1, dK2, dK3, and dK4. One-way analyses of variance were then conducted, with Group as the independent variable and the four changes as the dependent variables.

The means and standard deviations of the changes by group are presented in Table 7.

Table 7: Means and Standard Deviations of T2–T1 Changes by Group

Group	N	dK1 M	dK1 SD	dK2 M	dK2 SD	dK3 M	dK3 SD	dK4 M	dK4 SD
CG	27	0,074	0,200	-0,194	0,162	-0,306	0,178	0,162	0,216
EG1	43	0,392	0,321	0,611	0,277	0,631	0,292	0,456	0,296
EG2	35	0,536	0,260	0,707	0,208	0,829	0,257	0,596	0,246
Total	105	0,358	0,325	0,412	0,474	0,456	0,523	0,427	0,309

Table 7 shows that the control group exhibited limited or negative changes in some dimensions, whereas the two experimental groups exhibited positive changes in all four dimensions. The greatest difference appears to be in Self-efficacy, where the second experimental group showed the highest mean change.

For the difference scores, the assumptions of normality and homogeneity of variances were tested, with no serious violations identified that would affect the validity of the results. The difference scores were subjected to one-way analyses of variance (one-way ANOVA), with Group as the independent factor, in order to examine whether the magnitude of change differed between groups. Where statistically significant results emerged, pairwise comparisons with a correction for multiple comparisons (Tukey HSD) followed in order to determine precisely between which groups the differences were located.

This approach enables a clear decomposition of the Time × Group interaction observed at the multivariate level and facilitates interpretation of the results in the individual dimensions by directly capturing differences in the magnitude of change between groups.

The results of the one-way analyses of variance and subsequent comparisons are presented in Table 8.

Table 8: Univariate Analyses of Variance and Post-Hoc Comparisons for Changes (T2–T1) in the Motivational Factors

Variable	F(2,102)	p	partial η²	Group Comparison	Mean Difference (I–J)	SE	p (post-hoc)
dK1	22.16	<.001	.303	CG–EG1	-0.318	0.062	<.001
				CG–EG2	-0.462	0.058	<.001
				EG1–EG2	-0.143	0.066	.082
dK2	136.68	<.001	.728	CG–EG1	-0.805	0.057	<.001
				CG–EG2	-0.902	0.059	<.001
				EG1–EG2	-0.097	0.053	.163
dK3	131.29	<.001	.720	CG–EG1	-0.807	0.062	<.001
				CG–EG2	-1.005	0.065	<.001
				EG1–EG2	-0.198	0.058	.002
dK4	21.52	<.001	.297	CG–EG1	-0.294	0.064	<.001
				CG–EG2	-0.434	0.067	<.001
				EG1–EG2	-0.140	0.059	.053

Note: The F values are derived from univariate between-group tests. Subsequent comparisons were conducted using the **Tukey HSD** method when the assumption of homogeneity of variances was met, whereas for the **dK1** variable, where this assumption was violated (**Levene's test: p = .047**), the Bonferroni **post-hoc** test was applied. **Partial η²** was used as an effect size index. Negative values in the mean difference (I–J) indicate a greater change for group J.

5.5 Results of the Difference Scores Analysis (dK1–dK4)

5.5.1 dK1 Category—Change in Learning Goal Orientation

The analysis showed a statistically significant effect of Group on the change in dK1, $F(2, 102) = 22.16$, $p < .001$, indicating a large effect size (partial $\eta^2 = .303$). Pairwise (post-hoc) comparisons revealed that both Group EG1 and Group EG2 exhibited a significantly greater positive change compared with Group CG, while the difference between Groups EG1 and EG2 was not statistically significant.

This result shows that the technology-supported interventions were associated with a greater increase in students' orientation towards learning and understanding compared with the traditional experimental approach.

5.5.2 dK2 Category—Change in Task Value

Similarly, for the dK2 category, a statistically significant effect of Group was observed, $F(2, 102) = 136.68$, $p < .001$, with a very large effect size (partial $\eta^2 = .728$). The post-hoc comparisons showed that Group CG exhibited a significantly smaller change compared with Groups EG1 and EG2, while no statistically significant difference was found between Groups EG1 and EG2, indicating a similar degree of improvement in these two groups.

This result indicates that the two technology-supported conditions were associated with a clearly greater enhancement of the perceived value of the learning activity.

5.5.3 dK3 Category—Change in Self-efficacy

For the dK3 category, the effect of Group was particularly strong, $F(2, 102) = 131.29$, $p < .001$, and substantively significant (partial $\eta^2 = .720$). Pairwise comparisons revealed statistically significant differences between all groups, with Group EG1 exhibiting a greater change than Group CG and Group EG2 exhibiting a significantly greater change than both Group CG and Group EG2. This result indicates a clear ordering in the magnitude of change in the dK3 category (Group CG < Group EG1 < Group EG2).

This finding indicates a clear gradation in the change in Self-efficacy: **CG < EG1 < EG2**. This is the only dimension in which the second experimental group also differed statistically significantly from the first experimental group.

5.5.4 dK4 Category—Change in Self-regulation

Finally, for the dK4 category, the analysis also showed a statistically significant effect of Group, $F(2, 102) = 21.52$, $p < .001$, with a large effect size (partial $\eta^2 = .297$). The post-hoc comparisons showed that Group CG differed significantly from Groups EG1 and EG2, exhibiting a smaller change, while the difference between Groups EG1 and EG2 was not statistically significant.

This result shows that the experimental groups exhibited a greater enhancement of Self-regulation compared with the control group, without, however, documenting a statistically significant difference between the use of a microcontroller and the combination of a microcontroller with a simulation.

5.6 Summary of the Main Findings

Overall, the results show that the three groups were comparable at the initial measurement with respect to the four dimensions of learning motivation. After the intervention, however, a statistically significant Time × Group interaction emerged, indicating that the change in motivation differed according to the teaching condition.

The two experimental groups exhibited greater positive changes compared with the control group in learning goal orientation, task value, Self-efficacy, and Self-regulation. The difference between the two experimental groups was statistically significant only for Self-efficacy, where the group combining a microcontroller and a digital simulation showed the greatest increase.

6. Discussion

6.1 Interpretation of the Main Findings

The present study investigated changes in the learning motivation of Grade 12 students following the implementation of a teaching intervention in Physics focusing on damped oscillations. More specifically, it examined whether changes in the four dimensions of motivation—learning goal orientation, task value, Self-efficacy, and Self-regulation—differ according to the teaching condition: a traditional experimental approach, use of a microcontroller, or a combination of a microcontroller and a digital simulation.

The principal conclusion of the study was the statistically significant Time × Group interaction, which shows that the changes in motivation from the initial to the final measurement were not the same for all groups. The two experimental groups exhibited greater positive changes compared with the control group, while the group combining a microcontroller and a digital simulation differed particularly in terms of Self-efficacy. This finding is particularly important, as it suggests that the level of technological mediation of the experimental activity may be associated with different trajectories of change in learning motivation.

The results support the view that learning motivation does not constitute a stable and unchanging characteristic of students, but rather dynamic beliefs that can be influenced by the nature of the learning environment. The statistically significant Time × Group interaction identified through the repeated-measures multivariate analysis indicates that changes in the dependent variables do not follow a uniform or linear pattern, but are shaped in relation to the learning context in which students are engaged. This finding is consistent with theoretical models that treat development and change as dynamic processes of interaction between the individual and the environment (Sameroff, 2009) [49], according to which cognitive and affective changes arise from the continuous coordination of individual characteristics and contextual experiences.

At the same time, the results are aligned with contemporary approaches to motivation that highlight its dynamic and contextual nature (Kaplan & Garner, 2017; Schunk & DiBenedetto, 2020) [27, 51]. From this perspective, the differentiated trajectory of change observed in the Experimental Groups can be interpreted as a result of the qualitative differentiation of the learning context, which provided increased opportunities for active engagement, control of the experimental process, and connection of theoretical concepts with empirical data (Tsihouridis *et al.*, 2026) [61].

The integration of microcontrollers and digital simulations may have influenced both students' expectations of success and the perceived value of the learning activity, dimensions that, according to Expectancy-Value Theory (Eccles & Wigfield, 2002) [15], are key determinants of engagement in learning. Immediate feedback through digital data recording and the possibility of experimental control probably strengthened competence beliefs, an element associated with Self-efficacy theory (Bandura, 1997) [8] and explaining the enhancement observed in the relevant dimension.

Consequently, the findings support the view that learning motivation does not constitute a stable characteristic of students, but dynamically shaped beliefs that respond to qualitative changes in the educational context.

Further decomposition of the interaction through the difference scores showed that Group CG consistently exhibited a smaller change in all categories, in contrast to Groups EG1 and EG2, which showed greater and largely comparable improvement. This pattern indicates that the differentiation of the learning context substantially influenced the intensity and direction of the change in motivation. More specifically, the conditions that incorporated technological tools and increased opportunities for active experimental engagement appear to have functioned as catalysts for motivation.

This finding is consistent with theoretical and empirical approaches that highlight engagement and active participation as critical factors in learning outcomes and development (Fredricks *et al.*, 2004; Appleton *et al.*, 2008) [18, 3]. According to these models, cognitive, behavioural, and affective engagement constitute interconnected dimensions that can be strengthened through learning environments that provide authentic activities, a sense of control, and a meaningful connection with the subject matter.

At the same time, theories of motivation, and Self-Determination Theory in particular, maintain that the provision of appropriate support and the satisfaction of basic psychological needs—such as the need for autonomy, competence, and relatedness—enhance intrinsic motivation and activate mechanisms of change (Ryan & Deci, 2017) [48]. In contrast, environments that offer limited opportunities for autonomous action and control tend to be associated with weaker changes in motivation, which explains the smaller change observed in Group CG.

The **K3** category is of particular theoretical significance, as complete differentiation between the groups was observed in this category, with a clear ordering of the magnitude of change (CG < EG1 < EG2). This pronounced differentiation indicates that Self-efficacy is particularly sensitive to qualitative changes in the learning context. In the literature on motivation in Science, Self-efficacy is recognised as a central dimension associated with increased effort, persistence, and achievement (Glynn *et al.*, 2011) [20], functioning as a regulatory factor in engagement in learning.

At the same time, efficacy beliefs are regarded as dynamic and contextual, as they are shaped through specific learning experiences and the quality of the educational environment (Eccles & Wigfield, 2002) [15]. From this perspective, the stronger change recorded in the Experimental Groups can be interpreted as a result of the active engagement, ability to control the experimental process, and immediate feedback provided by the technological tools. The combination of a microcontroller and a simulation, in particular, appears to have offered multiple representations of the phenomenon and increased opportunities for inquiry, elements that may have further strengthened students' competence beliefs (Tsihouridis *et al.*, 2023; Mitrakas & Tsihouridis, 2024).

Consequently, the differentiation in **K3** is not merely a statistical finding, but strengthens the view that targeted changes in the learning environment can directly affect key motivational beliefs.

In contrast to Group CG, which was not exposed to the same form of teaching experience, Groups EG1 and EG2 exhibited a greater change in most categories, indicating that their differentiation is related to the qualitative characteristics of the learning context in which they participated. The convergence of the trajectories of change between Groups EG1 and EG2, despite the individual technological differences, indicates that their common participation in active, technologically mediated, and inquiry-based practices was the determining factor in the change in motivation.

This finding is aligned with contemporary theoretical and empirical approaches that recognise teaching interventions as critical environmental factors activating dynamic processes of change capable of influencing the development of attitudes, beliefs, and skills over time (Darling-Hammond *et al*., 2020; Schunk & DiBenedetto, 2020) [14, 51]. The literature points out that systematic and coherent teaching practices are associated with comparable patterns of change in motivation and engagement in learning, whereas the absence or substantial differentiation of the teaching context tends to lead to divergent developmental trajectories (Reeve & Cheon, 2021) [46].

Consequently, the observed convergence of the Experimental Groups cannot be attributed simply to statistical similarity, but reflects the effect of common pedagogical characteristics that appear to have activated similar mechanisms of motivational change.

The results of the present study are consistent, albeit within the context of a relatively limited sample, with findings from previous studies in Science education (Mantzavinos *et al*., 2024; Caballero-García & Fernández, 2019; Spandana, Rani & Devi, 2020; Tsihouridis & Vavougios, 2023; Mitrakas *et al*., 2024) [32, 9, 55, 60, 35], as well as with studies in Physics that use technology-supported environments, such as those by Lazarević *et al*. (2024) [30] and Tsihouridis *et al*. (2025) [62], which highlight the positive contribution of inquiry-based and digitally mediated approaches to enhancing learning motivation. Although the studies above adopt different methodological approaches—with or without two measurements—and differ in how they substantiate their results, they converge in highlighting the role of the learning context in shaping changes in motivation.

Within this context, the graded superiority observed in the present study (Group CG < Group EG1 < Group EG2) can be interpreted on the basis of the qualitative characteristics of the teaching intervention. The combination of experimentation with a microcontroller and a digital simulation provided students with multiple representations of physical phenomena, increased opportunities to control variables, and immediate feedback, elements considered critical for enhancing cognitive engagement and perceived competence.

A similar interpretation emerges from recent research in Physics, according to which the use of digital inquiry environments in combination with laboratory activities is associated with increased motivation and engagement in learning. Chen *et al*. (2025) [12] showed that the implementation of laboratory activities through digital simulations within a structured inquiry framework leads to a statistically significant increase in learning motivation, attributing the result mainly to the pedagogical design rather than exclusively to the technology itself. Similarly, Banda and Nzabahimana (2023) [5] demonstrated that the use of interactive PhET simulations is associated with increased levels of motivation and achievement in Physics.

Overall, the findings of the present study are aligned with the international literature, according to which students' active participation in laboratory and digital activities—particularly when these are integrated into a coherent pedagogical design—contributes to enhancing their motivation, interest, and engagement in the learning process (Feng & Tuan, 2005; Cavas, 2011; Gagné & Deci, 2005; Hofstein & Lunetta, 2003; Tseng *et al*., 2007) [17, 10, 19, 23, 58].

Beyond its convergence with the findings of the relevant literature, the present study contributes to a further understanding of how differentiated forms of technologically mediated experimental teaching affect learning motivation over time. In contrast to studies that examine individual interventions or are based on unidimensional measurements, the use of repeated-measures multivariate analysis enabled the capture of differentiated trajectories of change and highlighted the dynamic nature of motivation over time. In addition, the comparison of graded forms of technology integration (traditional approach, microcontroller, microcontroller with simulation) provides empirical data on the relative contribution of the individual elements of the pedagogical design. In this way, the study offers not only confirmatory but also discriminating findings regarding the conditions under which learning motivation is substantially enhanced.

6.2 Limitations and Suggestions for Future Research

The present study has certain limitations. The sample comprises Grade 12 students from a specific geographical region, which may limit the generalisability of the findings to broader student populations or different educational contexts. Although the study was based on assignment at the school level (cluster-based assignment), no significant differences between the groups were observed at the initial measurement, which strengthens the internal validity of the findings. In addition, the assessment of motivation was based exclusively on self-report data. Although the SALES questionnaire is a psychometrically grounded instrument, self-report measures may be influenced by subjective factors, such as socially desirable responding or changes in the way students perceive themselves. Finally, although the repeated-measures design and multivariate analysis strengthen the validity of the conclusions, the sample size and the use of two time points limit the investigation of the dynamics of change.

Future research could examine larger samples and more measurement time points, as well as incorporate theoretical mediators in order to clarify the mechanisms leading to the observed differences. In addition, further investigation of the trend that emerged regarding the combination of microcontrollers and simulations, which appears to be associated with stronger changes in learning motivation compared with the use of microcontrollers alone, would be of interest. Finally, the implementation of similar interventions at different educational levels, in different subject areas, or in different cultural contexts would contribute to investigating the external validity of the findings. At the same time, the combined use of self-report data with alternative sources of information, such as classroom observations, interviews, or indicators of behavioural engagement, could strengthen methodological triangulation. Future studies could also examine the relationship of motivation with cognitive learning outcomes, such as conceptual understanding, the ability to interpret graphs, and performance on Physics problems. This would make it possible to investigate whether the enhancement of learning motivation is also associated with corresponding improvements in cognitive learning.

7. Conclusions

The present study investigated changes in the learning motivation of Grade 12 students following the implementation of a teaching intervention in Physics focusing on damped oscillations. More specifically, three teaching conditions were compared: a traditional experimental approach, an experimental activity using a microcontroller, and an experimental activity combining a microcontroller and a digital simulation. The assessment of learning motivation was based on the four dimensions of the SALES questionnaire: learning goal orientation, task value, Self-efficacy, and Self-regulation.

The findings showed that the groups were comparable at the initial measurement, while differentiated trajectories of change in motivation emerged after the intervention. The two experimental groups exhibited greater positive changes compared with the control group, indicating that technology-supported experimental teaching may be associated with the enhancement of students' learning motivation. Of particular interest is the finding that the group combining a microcontroller and a digital simulation showed the greatest increase in Self-efficacy, highlighting the importance of connecting the real experiment, digital data recording, and theoretical modelling.

The contribution of the study lies in the fact that it does not examine technology as a single and undifferentiated teaching intervention, but compares graded levels of technological mediation. In this way, the study provides empirical data on how the use of microcontrollers and their combination with digital simulations may be associated with different changes in the individual dimensions of learning motivation. This approach is particularly important for Physics Education, as it highlights that the effective integration of technology depends not only on the use of contemporary tools, but mainly on the pedagogical design within which they are embedded.

At the teaching level, the results underline the value of learning environments that combine real experimentation, real-time data collection, graphical representations, and digital modelling. In the teaching of damped oscillations, this combination appears to offer students more opportunities for active engagement, data interpretation, understanding of the relationship between the theoretical model and the real phenomenon, and the development of competence beliefs in relation to demanding subject matter.

Despite its contribution, the study should be interpreted in light of certain limitations. The sample came from a specific geographical region and involved Grade 12 students taking the Physics specialisation course. In addition, the design was quasi-experimental, assignment was carried out at the school-unit level, and the measurement of motivation was based on a self-report questionnaire. The additional familiarisation phase of the experimental groups with the microcontrollers should also be taken into account when interpreting differences between the groups.

Future research could extend the investigation to larger and more diverse samples, different educational levels, and other subject areas in Physics. The incorporation of additional measurement time points would be of particular interest in order to examine the maintenance of changes in motivation, as would the combination of quantitative and qualitative data, such as interviews, observation of student engagement, and analysis of worksheets. In addition, it would be useful to investigate the relationship between changes in learning motivation and improvements in students' conceptual understanding or achievement in Physics.

Overall, the present study highlights that microcontrollers and digital simulations can constitute meaningful tools for supporting experimental Physics teaching when integrated into a well-designed, inquiry-based, and pedagogically grounded learning environment. Under this condition, technology does not function as a simple addition to teaching, but as a means of enhancing active engagement, Self-efficacy, and the construction of meaning in Science learning.

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