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Real-Time Laboratory with a STEM Approach: A Social Semiotic and Quantitative Analysis of Their Impact on Graphical Competence in Kinematics among Upper Secondary Students

Sergio R. Betanzos Sarmiento[1], Cesar Mora[2], Fermin Acosta Magallanes[3]

Abstract

In this mixed-methods study, we evaluate the impact of the Real-Time Laboratory (RTL) with a STEM approach, implemented using Arduino technology, on conceptual learning and the development of graphical competence in one-dimensional kinematics among upper secondary students. The intervention follows a methodology based on prediction, experimentation, comparison, and data analysis, which is characteristic of RTL. Additionally, we rely on Social Semiotics to provide evidence of how students use RTL and the types of interactions that occur around it concerning tasks related to the interpretation and construction of kinematic graphs. This contribution is relevant as it assesses the pertinence of RTL as both a semiotic and didactic resource to achieve this goal.

Keywords: *Graphic Competence, One-Dimensional Kinematics, RTL, Social Semiotics, STEM.*

Introduction

Laboratories and hands-on experimentation play a fundamental role in physics education, providing an essential bridge between theory and practice. This experimental dimension not only complements theoretical learning but also offers critical opportunities for students to develop scientific skills and experience the research process firsthand (Thacker, 2023). The language of science integrates multiple modes of representation—including words, images, equations, and especially graphs—which are indispensable for a comprehensive understanding of physical phenomena (Stefanel, 2019).

In the realm of kinematics, graphical representations are key tools for describing and analyzing motion. However, seminal studies since the late 1980s have documented persistent difficulties among students when interpreting these graphs, such as confusing slope with height or treating graphs as literal pictures of motion (Nixon et al., 2016). Planinic et al. (2013) and Stefanel (2019) further demonstrate that, despite possessing the requisite mathematical knowledge, many students continue to face significant challenges in both understanding and constructing kinematic graphs. This is troubling, given that the ability to interpret and create graphs is not only crucial for grasping specific physical concepts but also essential for developing core scientific competencies such as data analysis and effective scientific communication (Glazer, 2011; Nixon et al., 2016).

[1] National Polytechnic Institute, Center for Research in Advanced Science and Technology (CICATA), Email: ing.sergiobetanzos@gmail.com
[2] National Polytechnic Institute, Center for Research in Advanced Science and Technology (CICATA), Email: cmoral@ipn.mx
[3] National Polytechnic Institute, Interdisciplinary Professional Unit of Engineering and Advanced Technology (UPIITA), Email: facostam@ipn.mx

Laboratory activities—considered an integral component of the physics curriculum—serve two fundamental objectives: cultivating "thinking like a physicist" and "constructing knowledge" (Nixon et al., 2016). In this context, graphs play a pivotal role by enabling students to analyze and interpret data, identify patterns and relationships, and draw connections between theory and observation. Moreover, proficiency with kinematic graphs has significant implications for the development of critical thinking, quantitative reasoning, and mathematical modeling skills (Stefanel, 2019). These transferable skills are vital for training future scientists and engineers and for fostering overall scientific literacy.

To address these challenges, Real-Time Laboratory (RTL) has emerged as a transformative tool in physics instruction. Also referred to as Microcomputer-Based Laboratories (MBL) or Real Time Physics (RTP), these systems employ data loggers fitted with motion sensors connected to microcontrollers—such as Arduino—that collect and display data in real time (Glazer, 2011; Sokoloff, 2017). Their defining feature is the simultaneous presentation of the physical phenomenon and its graphical representation, which has proven particularly effective in dispelling common misconceptions—such as interpreting the "graph as picture" and conflating height with slope (Stefanel, 2019; Glazer, 2011).

Beyond graphical interpretation, these systems have demonstrated significant benefits across multiple dimensions of learning.

Sokoloff (2017) highlights how the integration of Real Time Physics (RTP) with Interactive Lecture Demonstrations (ILDs) and personal response systems promotes more active and participatory learning. Bodegom et al. (2019) show how adapting these systems for distance learning has expanded opportunities for conducting physics experiments beyond traditional laboratories, fostering student autonomy and critical thinking. Moreover, by eliminating the cognitive load associated with manual data collection, these systems allow students to focus more effectively on data interpretation and analysis (Glazer, 2011; Sokoloff, 2017).

The effectiveness of these systems is supported by substantial longitudinal evidence. A twenty-year study conducted by Thacker (2023) provides compelling data on the impact of different laboratory methodologies on physics learning. Although his research focused on an inquiry-based course (INQ), her comparative study reveals that Real Time Physics laboratories, when implemented according to principles grounded in Physics Education Research (PER), achieve comparable or even superior results in students' conceptual understanding.

The implementation of RTL and Arduino in educational contexts has demonstrated multiple pedagogical benefits. Arduino, an open-source hardware and software platform, facilitates the deployment of technological solutions in learning environments, distinguished by its ease of use and its ability to support practical projects across diverse educational settings (Organtini, 2021). Akış (2024) emphasizes that the use of Arduino in STEM activities significantly enhances students' conceptual understanding, computational thinking, and algorithmic skills. This platform particularly fosters active and experiential learning, enabling students to engage in hands-on projects that connect theoretical knowledge with real-world applications.

The successful implementation of Arduino in diverse educational contexts worldwide demonstrates its versatility and effectiveness. In Italy, for instance, an Arduino-based Educational Robotics workshop was implemented in fifty different classes, ranging from primary to secondary school, yielding notable results in student engagement and the understanding of scientific concepts (Akış, 2024). In Brazil, the State University of Maringá

incorporated Arduino into the training of future physics teachers, achieving significant improvements in both conceptual understanding and pedagogical practices (Munera et al., 2020). Geschwind et al. (2024) document how universities in 41 countries have integrated Arduino into their physics laboratories, highlighting its effectiveness in both introductory and advanced courses.

The integration of technologies such as RTL and Arduino into physics education not only addresses specific difficulties related to graph interpretation but also aligns with the integrated STEM approach, which promotes the interconnection of disciplines to solve real-world problems (Lederman & Lederman, 2020; Ortiz-Revilla et al., 2021). The acronym STEM, coined by Dr. Judith Ramaley in 2001, has evolved to represent an educational approach that seeks to cohesively integrate science, technology, engineering, and mathematics (Tytler, 2020; Ng, 2019). This integration is not merely a pedagogical preference but a necessity imposed by the very nature of contemporary problems (Lederman & Lederman, 2020).

Implementing STEM in educational systems requires the consideration of five key principles: integration of STEM content, problem-centered learning, inquiry-based learning, design-based learning, and cooperative learning (Thibaut et al., 2018). This theoretical framework is grounded in a social constructivist view of learning, emphasizing the importance of students actively constructing knowledge through meaningful and collaborative experiences. Domènech-Casal (2018) identifies three fundamental dimensions of scientific competence that must be addressed in integrated STEM education: the conceptual, procedural, and epistemic dimensions.

Real-time experimentation and data collection technologies, such as those provided by Arduino, emerge as fundamental tools in this context. Ellermeijer and Tran (2021) point out that these technologies enable students to connect the physical world with theoretical models, facilitating the transition from graphical representation to deep conceptual understanding of physical phenomena. According to Brasell (1987), as cited in Ellermeijer and Tran (2021), the immediacy between the phenomenon and its real-time graphical representation enhances conceptual understanding and is critical both for students' comprehension and their motivation.

Moreover, integrating Arduino into an RTL promotes authentic scientific practices and fosters critical scientific thinking skills. Perl-Nussbaum and Yerushalmi (2022) found that research-oriented laboratories enhance students' abilities to formulate hypotheses, engage in critical reasoning, make evidence-based decisions, and develop a deeper understanding of the scientific process. Ketonen et al. (2023) and May et al. (2022) highlight that when students are given opportunities for active inquiry and encounter inconsistencies during laboratory work, they develop better visualization of theoretical concepts and more sophisticated skills for resolving discrepancies between theory and observation.

Effective implementation of these technologies requires careful consideration in the design of learning experiences. Molz et al. (2022) identified that explicitly connecting laboratory activities to classroom learning improves both affective and cognitive outcomes. Key elements for effective design include clearly defined learning objectives, an appropriate level of student autonomy, opportunities for reflection and discussion, and explicit links to theoretical concepts.

It is also important to consider issues of equity and access. Holmes et al. (2022) and Walsh et al. (2022) emphasize the importance of ensuring that experimental autonomy and skill development benefit all students equally. Creating inclusive learning environments, facilitating equitable participation in group work, and providing differentiated support as needed are essential

strategies to achieve this goal.

Nevertheless, research has identified challenges associated with the effective implementation of physics laboratories. Sulaiman et al. (2023) note that students may face significant barriers when transitioning from traditional academic environments to experimental settings, including adapting to authentic scientific practices and integrating theory with practice. Kayan-Fadlelmula et al. (2022) stress the importance of addressing gaps and barriers in STEM education to maximize its impact.

Theoretical Framework

The teaching of physics requires students to develop competencies for interpreting and constructing multiple representations of physical phenomena. In our research, we integrate three complementary perspectives: the STEM approach as an educational framework that promotes the integration of disciplines; Social Semiotics as a theoretical lens for analyzing how students construct meaning through various provided semiotic resources; and the Real-Time Laboratory (RTL) methodology, which stands out as a technological tool that facilitates the connection between physical phenomena and their representations. In this section, we will explore Social Semiotics, its key related aspects, and our conceptualization of graphical competence in one-dimensional kinematics.

Social Semiotics and Semiotic Resources

Social Semiotics, defined by Airey and Linder (2017) as "the study of the development and reproduction of specialized systems of meaning making in particular sections of society" (p. 95), provides a robust theoretical framework for analyzing how students use semiotic resources in the learning of physics. The concept of a semiotic resource refers to any medium used to create meaning within a specific social group, such as an academic discipline (Airey & Linder, 2017). In the context of physics teaching and learning, semiotic resources encompass a wide range of tools, actions, and representations that students and experts employ to interpret, represent, and communicate disciplinary knowledge.

In our research context, various semiotic resources are mobilized, such as: the Cartesian graph created by students, the experimental setup (including the ramp containing a cable duct, a bubble level, a ball, etc.), and the Real-Time Laboratory (RTL) as a complex semiotic resource.

Representation Changes: Transformation and Transduction

In Social Semiotics, changes in representation are considered crucial for meaning-making and learning. These changes occur through a process called "translation," which can take two forms: "transformation" and "transduction" (Airey & Linder, 2017). To understand this process, it is important to first describe what constitutes a semiotic system. A semiotic system can be understood as a system for constructing and representing concepts, where each semiotic system is qualitatively different from others. Semiotic systems are complete systems of representation and communication. For example, the verbal system includes the semiotic resource of spoken language; the gestural system encompasses resources such as specific gestures or particular movements—an example would be the hand gesture used to represent the right-hand rule and its meaning. Other examples of semiotic systems and their corresponding semiotic resources include:

- Graphical system (diagrams, graphs)

- Formulaic system (equations, functions)
- Experimental system (setups, measurements)

Transformation occurs when a semiotic resource is modified but remains within the same semiotic system, such as modifying a position–time graph into a velocity–time graph. Transduction, on the other hand, involves the movement between two different semiotic systems, such as converting numerical position data into a graphical representation.

Theory of Variation

The theory of variation, which posits that learning opportunities are maximized when the aspects students are expected to notice vary against an otherwise invariant background, has also been applied within Social Semiotics (Airey & Linder, 2017). This theory suggests that instructors can help students discern the disciplinarily relevant aspects of semiotic resources by systematically varying each aspect while keeping everything else constant.

Disciplinary Discernment

Airey and Linder (2017) describe disciplinary discernment within the framework of Social Semiotics as the ability to identify and utilize the disciplinarily relevant aspects of semiotic resources. Eriksson et al. (2014) introduce disciplinary discernment as a hierarchy that describes four different levels of understanding from a disciplinary perspective. These levels, ordered from lower to higher discernment, are presented below:

1. Disciplinary Identification: The student can name aspects of a representation using specific disciplinary terminology.
2. Disciplinary Explanation: The student can explain how the aspects are related within the representation in a disciplinarily appropriate manner.
3. Disciplinary Appreciation: The student appreciates the value of the representation with respect to its disciplinary content.
4. Disciplinary Evaluation: The student can evaluate and identify flaws in the representation from a disciplinary perspective.

Graphic Competence in One-Dimensional Kinematics

Stefanel (2019) highlights that graphical competence in one-dimensional kinematics is fundamental in physics education. According to the author, graphical competence in kinematics involves the skills of reading, interpreting, and constructing graphs, all of which are essential for developing this competence. Moreover, he acknowledges the importance of graphical representation as a powerful tool for interpreting data and representing relationships between quantities.

From a Social Semiotics perspective, developing graphical competence entails achieving fluency in the use of specific semiotic resources, such as motion graphs. Airey and Linder (2017), building on a definition originally proposed in 2009, assert that it is impossible to participate adequately in disciplinary meaning-making without reaching a certain degree of fluency in the use of a specific semiotic resource. They define fluency as "a process through which handling a particular [semiotic resource] with respect to a given piece of disciplinary content becomes unproblematic, almost second-nature" (as cited in Airey & Linder, 2017, p. 103).

For the purposes of our research, we adhere to the description of graphical competence provided by Stefanel and the associated skills. Our approach to fostering these skills involves understanding and promoting student progress through the four levels of disciplinary discernment. Furthermore, applying the theory of variation in the design of activities involving RTLs can assist students in discerning key relationships by systematically varying specific aspects of motion (Airey & Linder, 2017).

Methodology

The study was conducted with students from the "Telebachillerato in Chiapas," a public upper secondary education system in the state of Chiapas, Mexico. The research took place at Campus No. 08, where two fourth-semester groups (4A and 4B) were selected to participate. The experimental group (4A, with 21 participants) worked under a Real-Time Laboratory (RTL) methodology with a STEM approach, while the control group (4B, with 23 participants) received traditional instruction.

Students in the experimental group participated in both individual and team-based activities. At the beginning of the intervention, a specific individual activity was administered as a pretest, and the same activity was reapplied at the end of the intervention as a posttest to compare graph construction skills. During the intervention, students also engaged in individual graph prediction activities, which were subsequently compared and discussed within teams.

For the team-based activities, students in the experimental group were organized into groups of four and followed a PEC cycle (Prediction–Experimentation–Comparison) to address kinematic concepts of position, velocity, and acceleration. In two activities that were particularly suitable for obtaining mathematically ideal graphs, an additional data analysis phase was integrated, resulting in a PECD cycle (Prediction–Experimentation–Comparison–Data Analysis). This was done to identify the ideal mathematical model for the phenomena of Uniform Rectilinear Motion (URM) and Uniformly Accelerated Rectilinear Motion (UARM) involved.

Each team was provided with a portable Real-Time Laboratory, consisting of an Arduino Uno board, a Time-of-Flight (ToF) position sensor, an HC-06 Bluetooth module, a battery pack as a power source, and a custom-designed board that facilitated the connection of all these components (see Figure 1). In addition, one member of each team installed an application called "ArduLab"—developed by the lead author—on their mobile device. Within the RTL context, the instructor (lead author) supported the teams throughout the entire process: from installing the application and guiding its use across different experimental options to exporting the collected data for activities that required curve fitting.

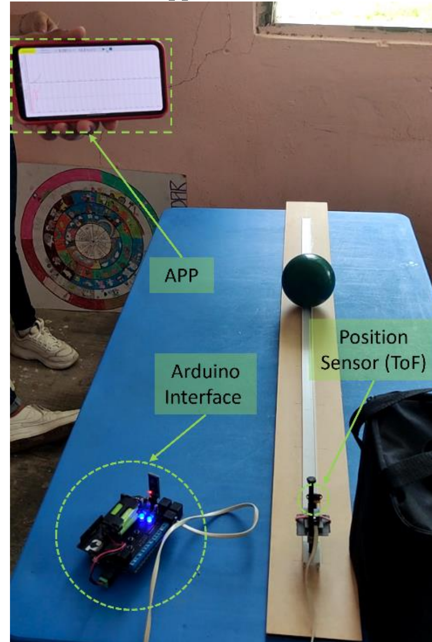


Fig. 1. Use Of the Real-Time Laboratory with Arduino in the Experimentation Stage.

The portability of the RTL allowed it to be easily moved to any location within the classroom—or even outside it (in the first activity, some teams worked outside the classroom)—as it did not require connection to an electrical outlet. Its compact size, the external noise tolerance of the ToF sensor, and the ability to visualize real-time data on the mobile phone screen facilitated its use in a variety of settings. A communication group was established using an instant messaging service (WhatsApp) among the participants who had the application installed and the instructor. This setup allowed participants to send screenshots of the obtained graphs (see Figure 2) and the CSV-format data tables for experiments that required them, thus streamlining the activities and facilitating the collection of evidence of the work performed.

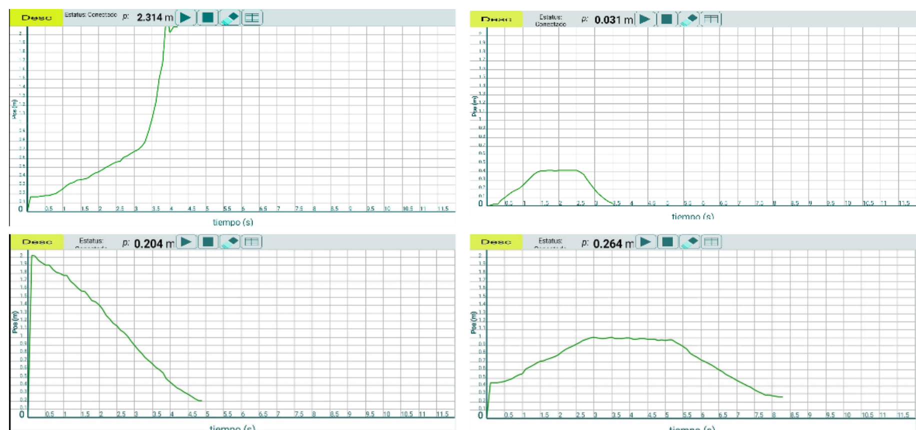


Fig. 2. Examples Of Graph Captures Obtained from Ardulab and Sent by The Teams.X − T

The worksheets were provided progressively. Activities that were to be completed individually were collected immediately after completion to prevent later modifications, while team-based activities were also collected at the end of each session. The instructor provided the necessary scaffolding to ensure successful completion of the activities. Teamwork sessions were recorded, with participants' consent, for subsequent analysis.

Research Questions

1. In what ways does the Real-Time Laboratory (RTL) with a STEM approach, implemented in the context of one-dimensional kinematics, contribute to: i) the conceptual gain of key concepts among upper secondary students; ii) the development of skills for interpreting kinematic graphs in these students; iii) the relationship between improvements in the understanding of kinematic concepts and the development of graph interpretation skills; iv) graphical competence, understood as the relationship between students' ability to interpret kinematic graphs and their ability to construct them?

2. What role does the RTL, as a semiotic resource, play in the conceptual learning and graphical competence of upper secondary students within the context of one-dimensional kinematics?

Hypotheses Corresponding to the first research question:

H1: Students who participate in the Real-Time Laboratory (RTL) with a STEM approach will show a significantly greater conceptual gain in key concepts of one-dimensional kinematics compared to those who receive traditional instruction.

H2: Students exposed to the Real-Time Laboratory with a STEM approach will develop significantly better skills for interpreting kinematic graphs than those in a traditional teaching environment.

H3: There will be a significant positive correlation between improvements in the understanding of kinematic concepts and the development of graph interpretation skills among students participating in the Real-Time Laboratory with a STEM approach.

H4: A positive relationship will be observed between students' ability to interpret kinematic graphs and their ability to construct them, indicating an overall improvement in graphical competence as a result of participation in the Real-Time Laboratory with a STEM approach.

Instruments

To address the first research question, three different instruments were used to evaluate the intervention. To measure students' understanding of kinematic concepts, the *Force and Motion Conceptual Evaluation* v99 (FMCE) by Thornton and Sokoloff (1998) was administered, using a subset of 16 out of the 47 original items, focusing exclusively on concepts related to one-dimensional kinematics. Although the full test was administered, the remaining questions were excluded from the analysis. To assess students' comprehension and interpretation of kinematic graphs, the *Test of Understanding Graphs in Kinematics* v4.0 (TUG-K) developed by Zavala et al. (2017) was used. Both instruments were applied in their Spanish-translated versions.

To assess students' graph construction skills, a rubric designed by the researchers was employed, called the *Rubric for Assessing Graphs in Kinematics* (RAGK). This instrument, based on previous works (Angra & Gardner, 2018; Stefanel, 2019; Vitale et al., 2014), was used to score students' graphical constructions in both the pretest and posttest phases.

The second research question was addressed through the analysis of classroom interactions documented in the instructor's observation guide, supported by video recordings of the team-based activities. This analysis was conducted through the lens of Social Semiotics (SS), focusing on how students interact with semiotic resources and engage in the core practices of this theoretical framework—namely, translations involving either transformations or transductions of semiotic resources.

Results

In conducting the hypothesis tests, it was essential to ascertain the type of distribution that characterized the scores at a given time point. Additionally, it was crucial to determine the type of distribution that governed the differences in pre-test and post-test scores within the same test and the same group. In order to address this issue, we present below a summary of the normality tests that were carried out for these tests.

In the hypothesis testing procedures we employed, it was necessary to determine either the type of distribution followed by the scores at a given time point or the distribution of the differences between pretest and posttest scores within the same test and group. To address this, we present below a summary of the normality tests conducted for these measures.

Group	Test	Time point	Statistical W	p-value
Experimental	TUG-K	Pre-test	0.9152	0.0697
		Post-test	0.9636	0.5920
		Difference	0.958	0.4767
Control	TUG-K	Pre-test	0.8293	*0.0012
		Post-test	0.9148	0.0516
		Difference	0.9058	*0.0334
Experimental	FCME	Pre-test	0.9613	0.5429
		Post-test	0.9599	0.5145
		Difference	0.9483	0.3166
Control	FCME	Pre-test	0.8842	*0.0121
		Post-test	0.9298	0.1084
		Difference	0.9028	*0.0288
Experimental	RAGK	Pre-test	0.9381	0.1994
		Post-test	0.9669	0.6643
		Difference	0.9861	0.9853

Table 1. Normality Analysis Results (Shapiro-Wilk) for the tests: TUG-K, FCME, and RAGK

From the table above, note that when the time point is labeled as "difference," it refers to the difference between pretest and posttest scores. Also note that an asterisk (*) indicates that the null hypothesis of normality is rejected.

Reliability Analysis and Hake Gain

For the FCME and TUG-K tests, the Kuder–Richardson Formula 20 (KR-20) reliability analysis was used, as it is appropriate for tests with dichotomous responses (correct/incorrect) and has been previously reported in studies using the TUG-K. KR-20 coefficients were calculated for both tests using posttest scores, yielding values of 0.717 for the TUG-K and 0.702 for the FCME. These values indicate moderate reliability, which is considered acceptable in educational

contexts, and suggest that both instruments are consistent in measuring the intended concepts, thus supporting the reliability of the posttest results.

Building upon the reliability analysis, we decided to additionally report the Hake gain, which is an indicator of effectiveness widely used in educational interventions, particularly in physics education. The results show that the control group did not experience meaningful improvements, with a gain of 0.0 on the TUG-K and a slight decrease of -0.0373 on the FCME. In contrast, the experimental group achieved gains of 0.3980 on the TUG-K and 0.3004 on the FCME. These values reflect a significant and positive, though moderate, improvement in the experimental group, suggesting that the intervention contributed to enhanced understanding of kinematic concepts and graph comprehension. The Hake gain is especially relevant because it allows these changes to be contextualized within a learning scale, highlighting the effectiveness of interventions by measuring students' relative progress from their prior knowledge to post-intervention performance.

Concentration Factor Analysis

The concentration factor analysis, proposed by Bao and Redish (2001), is a valuable tool for understanding what occurs beyond whether a student answers correctly or not. This type of analysis provides insight into the presence or absence of mental models within a group for specific items, based on how students respond. For instance, if all students select the same answer on a given item, the concentration ($\mathbf{C}$) is maximal—equal to 1—indicating the existence of an associated mental model or schema (whether correct or incorrect). Conversely, if responses are evenly distributed across all options, the concentration is 0, suggesting that the group lacks a shared mental model for that question. Bao and Redish (2001) define the concentration factor as "a function that maps the response of a class on a multiple-choice question to the interval [0,1] with zero corresponding to students selecting a random distribution of answers and one corresponding to all students selecting the same answer" (p. 45).

The construction of the concentration factor graph allows for visualizing the relationship between the average item score $\mathbf{S}$ (horizontal axis) and its corresponding concentration $\mathbf{C}$ (vertical axis). The average score $\mathbf{S}$ for each item is normalized by dividing it by the total number of participants, such that the maximum average score per item ranges between 0 and 1. To calculate concentration as a dependent variable, a series of steps are followed (Eqs. 1–7 in Bao & Redish, 2001, p. 47), which enable $\mathbf{C}$ to be constructed as a measure of response concentration associated with a given score.

To calculate $\mathbf{C}$, we first need to compute the response distribution vector $|\vec{\boldsymbol{R}}|$ for each question. This value indicates how distributed (or concentrated) the responses are among all participants for a specific item. When all participants choose the same answer from among $\boldsymbol{m}$ possible options, $|\vec{\boldsymbol{R}}|$ reaches its maximum value, which is equal to the number of respondents. The next step is to obtain $\boldsymbol{r}$, which is the normalized response distribution vector. This normalization ensures that when $|\vec{\boldsymbol{R}}|$ reaches its maximum, $\boldsymbol{r}$ equals 1. To achieve this, $|\vec{\boldsymbol{R}}|$ is divided by the number of respondents. The last step is to calculate $\mathbf{C}$. It is important to note that while the minimum possible values of $|\vec{\boldsymbol{R}}|$ and $\boldsymbol{r}$ depend on $\boldsymbol{m}$ (and are therefore greater than 0), $\mathbf{C}$, by contrast, maps the minimum value of $\boldsymbol{r}$ —which occurs when all $\boldsymbol{m}$ options are chosen by an equal number of participants—to $\mathbf{C} = \mathbf{0}$, meaning there is no concentration but rather maximum distribution. Thus, computing $\mathbf{C}$ involves subtracting from $\boldsymbol{r}$ the algebraic term (in terms of $\boldsymbol{m}$)

that yields $\mathbf{C} = \mathbf{0}$, and then multiplying this difference by a scaling factor (also dependent on $\boldsymbol{m}$) that normalizes the result to 1. This factor ensures that when $\boldsymbol{r} = \mathbf{1}$ and the corresponding $\mathbf{C} = \mathbf{0}$ term is subtracted, the product yields $\mathbf{C} = \mathbf{1}$, thereby properly scaling the concentration values.

Having outlined the general relationship between ($\mathbf{S}$,$\mathbf{C}$), values, it is important to note that theoretical boundary curves for $\mathbf{C}$ must be plotted. This requires defining a function that, for each score $\mathbf{S}$, assigns a minimum concentration value, $\mathbf{C}_{min}$, when the remaining responses are evenly distributed, and a maximum concentration value, $\mathbf{C}_{max}$, when they are all concentrated in a single option. By incorporating these boundaries, the plotted ($\mathbf{S}$,$\mathbf{C}$), data become more interpretable, since an effective intervention (assuming the measurement instrument is valid) should yield higher $\mathbf{C}$ values irrespective of the score achieved. Such insight is not captured by conventional analyses, which typically focus solely on changes in student scores to assess instructional effectiveness.

A key feature of this analytic approach is its ability to reveal response patterns; to facilitate this, the authors propose a three-level coding scheme for both $\mathbf{S}$ and $\mathbf{C}$.

Score (S)	Level	Concentration (C)	Level
0–0.4	L	0–0.2	L
0.4–0.7	M	0.2–0.5	M
0.7–1.0	H	0.5–1.0	H

Table 2. Three-Level Coding Scheme for S And C (Bao & Redish, 2001, P. 47)

According to the authors, for this scheme, we can code the response patterns according to the models triggered in the students:

A model. Type HH indicating a correct model and LH a dominant incorrect model.

Two models. LM type indicating two possible incorrect models and MM two popular models.

No model. Type LL as an almost random situation (Bao & Redish, 2001).

The resulting graphs are presented below.

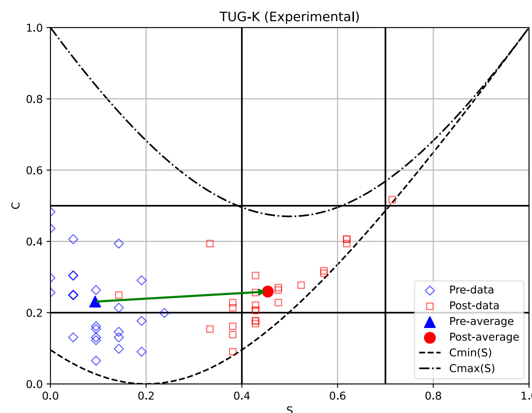


Fig. 3. Concentration Factor for the TUG-K Test in the Experimental Group

From the preceding TUG-K graph, we can observe the shift in students' states from pretest to posttest. The initial state corresponds to a low level, classified as LL and LM, which indicates that students activated two incorrect models for certain items and no model for the remaining ones. This suggests that, in terms of graphical understanding in kinematics, the related concepts were only beginning to be internalized. In contrast, after the intervention, an improvement is evident in both **S** and **C** dimensions, as indicated by the positive slope and direction of the arrow connecting the average (**S**, **C**) of the pretest to that of the posttest. This trajectory is desirable, as it reflects not only an increase in scores but also a progression from the lack of mental models toward the emergence of them.

For the FCME test, the concentration factors were displayed in separate graphs not because of the nature of the questions, but due to differences in the number of answer options across groups of items, that is, differing m values. Although the authors state that for $m > 6$, a ± 1 difference in response options is generally acceptable, in this case we had items with $m = 8$ and $m = 9$ (which fall into that category), as well as items with $m = 5$. Since the theoretical concentration boundaries depend on the value of m, different m values result in different limit curves for **C**. Therefore, to enhance visual clarity, we opted to display the results across three separate graphs instead of two.

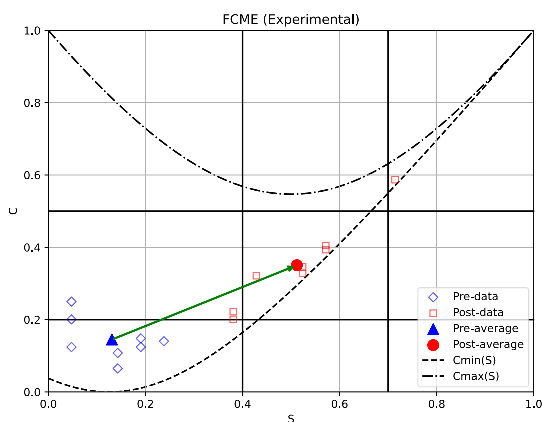


Fig. 4. Concentration Factor for the FCME Test in The Experimental Group (Questions 22-29 With M=8)

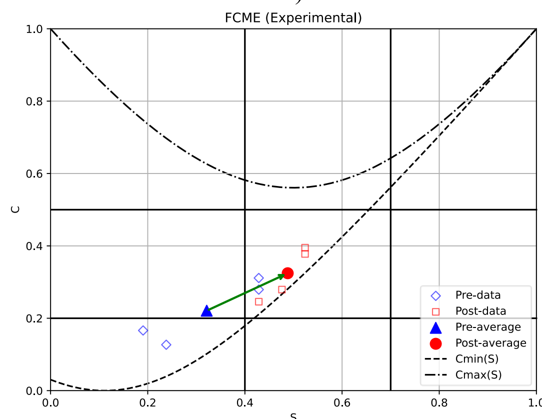


Fig. 5. Concentration Factor for the FCME Test in the Experimental Group (Questions 40-43 With M=9)

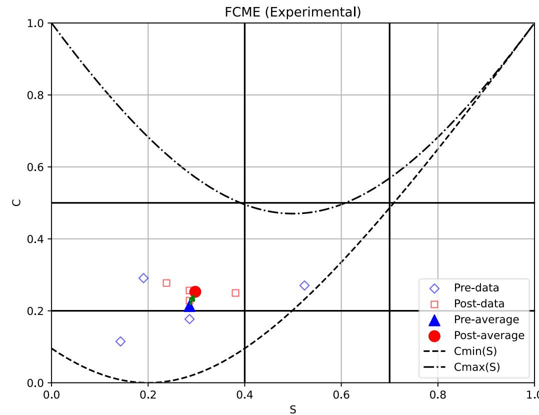


Fig. 6. Concentration Factor for the FCME Test in the Experimental Group (Questions 44-47 With M=5)

In general terms, an improvement in both **S** and **C** was observed across the three concentration graphs for the FCME test. This indicates that, following the intervention, students were able to construct mental models associated with the concepts of one-dimensional kinematics. Tables 3 and 4 present the different categories of response types at the pre-instruction and post-instruction stages for both tests.

	Types	LL	LM	LH	ML	MM	MH	HH
Pre-test	Questions	3, 7, 9, 10, 14, 15, 16, 18, 19, 21, 24, 26	1, 2, 4, 5, 6, 8, 11, 12, 13, 17, 20, 22, 23, 25					
Post-test	Questions	7, 11, 16, 24	1, 4, 5, 23		6, 15, 21	2, 3, 8, 9, 10, 12, 13, 14, 18, 19, 20, 22, 25, 26		17

Table 3. Comparison of Response Types in Pre- and Post-Intervention Stages for the TUGK Test

	Types	LL	LM	LH	ML	MM	MH	HH
Pre-test	Questions	22, 23, 24, 25, 26, 29, 41, 42, 46, 47	27, 28, 44			40, 43, 45		
Post-test	Questions		27, 29, 44, 45, 46, 47			23, 24, 25, 26, 28, 40, 41, 42, 43		22

Table 4. Comparison Of Response Types in Pre- and Post-Intervention Stages for the FCME Test

After analyzing the table, it becomes evident that students' progress in their ability to interpret graphs and understand the concepts related to one-dimensional kinematics evolved from displaying almost no mental models to reaching an MM level, which implies the presence of two models. This is significant, as the identification of persistent incorrect models—often associated with misconceptions—can be effectively addressed through targeted pedagogical interventions designed to confront these specific conceptual difficulties.

Hypothesis Testing

Hypothesis 1 (H1):

"Students who participate in the Real-Time Laboratory (RTL) with a STEM approach will show a significantly greater conceptual gain in key concepts of one-dimensional kinematics compared to those who receive traditional instruction."

To evaluate Hypothesis 1, a Linear Mixed Model (LMM) was employed instead of a repeated-measures ANOVA. This decision was based on the violation of key assumptions: the normality of score differences in the control group (see Table 1), and the homogeneity of variance in the difference scores between pretest and posttest across groups. This latter assumption is critical in repeated-measures ANOVA to ensure the validity of the results; its violation indicated the need for a more flexible model. The LMM was selected due to its robustness to such violations and its ability to model the interaction between Group (experimental vs. control) and Time (pretest vs. posttest), while also allowing the inclusion of random effects to capture individual variability.

Several assumptions were assessed to ensure the validity of the LMM:

- Normality of residuals: This assumption was satisfied, ensuring accurate confidence intervals and significance tests.
- Linearity between dependent and independent variables: This assumption was also met and found appropriate.
- Homoscedasticity of residuals: This assumption was violated, indicating heteroscedasticity in the residuals. To address this, robust standard errors (**RSE**) were calculated using a bootstrap procedure with 1000 samples, correcting for the heteroscedasticity and enhancing the reliability of the model.

The analysis included 88 observations (23 participants in the control group and 21 in the

experimental group, each evaluated at two time points: pretest and posttest). The results revealed a significant coefficient for the experimental group ($\boldsymbol{\beta}$ = 4.542, **RSE** = 0.733, 95% **CI** = [3.107, 5.978], $\boldsymbol{p}$ < .001), indicating that students in the experimental group achieved significantly higher posttest scores than those in the control group. The relatively small standard error compared to the coefficient supports the precision of this estimate.

Additionally, the interaction between the experimental group and the pretest ($\boldsymbol{\beta}$ = −4.240, **RSE** = 1.026, 95% **CI** = [−6.252, −2.229], $\boldsymbol{p}$ < .001) was significant. This suggests that although the experimental group started with lower scores in the pretest, they showed considerable improvement in the posttest as a result of the intervention, compared to the control group. Again, the ratio of the coefficient to its robust standard error supports the reliability of this interaction.

The main effect of Time in the LMM was not statistically significant, indicating that there was no overall change from pretest to posttest across both groups. Likewise, the variance attributed to Group was not significant, suggesting that between-group variability did not substantially impact the results.

This model enabled the evaluation of both the general improvement in scores and the interaction between Group and Time, supporting Hypothesis 1. The statistical significance of the coefficients, along with 95% confidence intervals that exclude zero, reinforces the conclusion that the experimental group improved significantly more than the control group in key one-dimensional kinematics concepts. The low ratio of robust standard errors to the coefficients further supports the precision of these estimates, validating the effectiveness of the intervention.

Hypothesis 2 (H2):

"Students exposed to the Real-Time Laboratory with a STEM approach will develop significantly better skills for interpreting kinematic graphs than those in a traditional teaching environment "

To test Hypothesis 2, a mixed repeated-measures ANOVA was conducted to evaluate the interaction between Group (experimental vs. control) and Time (pretest vs. posttest) on the TUG-K test. As with the FCME test, a total of 44 participants were included (23 in the control group and 21 in the experimental group), resulting in 88 total observations. The Shapiro–Wilk normality test showed a slight violation of normality in the difference scores for the control group, but not for the experimental group (see Table 1). However, this violation was considered manageable in the context of repeated-measures ANOVA, since Levene’s test for homogeneity of variances did not reject the null hypothesis of homogeneity ($\boldsymbol{W}$ = 1.0004, $\boldsymbol{p}$ = 0.3229), and the group sizes were relatively balanced. This allowed the analysis to proceed. Descriptive statistics showed that, on average, students in the experimental group improved from 2.43 points in the pretest to 11.81 points in the posttest, while the control group remained virtually unchanged at around 3.39 points in both stages.

The mixed repeated-measures ANOVA revealed significant results for the effect of Group ($\mathbf{F}(1, 42)$ = 25.53, $\boldsymbol{p}$ < 0.001, $\boldsymbol{\eta}^2$ = 0.378), Time ($\mathbf{F}(1, 42)$ = 134.73, $\boldsymbol{p}$ < 0.001, $\boldsymbol{\eta}^2$ = 0.762), and the Group × Time interaction ($\mathbf{F}(1, 42)$ = 147.56, $\boldsymbol{p}$ < 0.001, $\boldsymbol{\eta}^2$ = 0.778). These results indicate that the experimental group not only showed a significant improvement over time, but that the improvement was substantially greater than that of the control group. The significant interaction suggests that the experimental group, which began with lower pretest scores, experienced a notable gain in the posttest, thus supporting Hypothesis 2. The magnitude of the effect ($\boldsymbol{\eta}^2$ = 0.778) indicates that a large proportion of the variance in posttest scores can be explained by the

intervention using the Real-Time Laboratorie with a STEM approach.

Hypothesis 3 (H3):

"There will be a significant positive correlation between improvements in the understanding of kinematic concepts and the development of graph interpretation skills among students participating in the Real-Time Laboratory with a STEM approach."

To test Hypothesis 3, a correlation analysis was conducted between the individual gains in scores from the FMCE (Force and Motion Conceptual Evaluation) and the TUG-K (Test of Understanding Graphs in Kinematics) assessments. Given that prior analyses identified two violations of normality in the control group—one in the TUG-K pretest and another in the FMCE pretest—Spearman's correlation coefficient was employed, as this non-parametric statistic is more robust to violations of normality assumptions than Pearson's correlation coefficient.

The analysis included pretest and posttest scores from 23 students in the control group and 21 in the experimental group. Individual improvements in both assessments were calculated. Spearman's correlation coefficient was selected for its suitability for non-normal distributions and monotonic relationships, making it better aligned with the characteristics of the observed data.

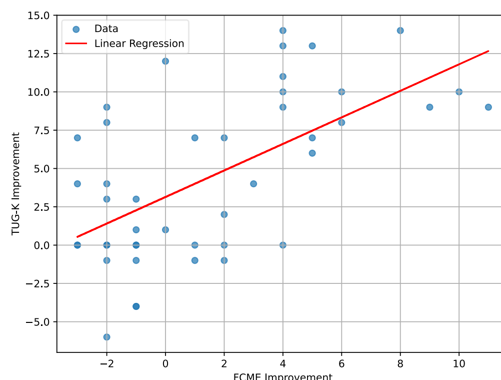


Fig. 7. Correlation of Score Improvements Between FCME and TUG-K Tests

The results of the analysis indicated a moderate-high positive correlation between improvements in FCME **and** TUG-K with a Spearman correlation coefficient **(**rho**)** of 0.5615 and a $\boldsymbol{p}< 0.001$, showing a indicating a significant correlation. This result suggests that, as students improve in their understanding of kinematic concepts, they also tend to improve in their ability to interpret graphs, supporting Hypothesis 3. The statistical significance ($\boldsymbol{p} <0.001$) reinforces the reliability of this correlation, indicating that the probability of this relationship being due to chance is extremely low. Therefore, the data confirm that the intervention based on the Real-Time Laboratory with a STEM approach had a positive impact on both conceptual development and the development of graphic skills, and that both improvements are significantly correlated.

Hypothesis 4 (H4):

"A positive relationship will be observed between students' ability to interpret kinematic graphs and their ability to construct them, indicating an overall improvement in graphical competence as a result of participation in the Real-Time Laboratory with a STEM approach"

To test Hypothesis 4, we began by evaluating whether the change in students' graph construction ability, as measured by the Rubric for Assessing Graphs in Kinematics (RAGK), was statistically significant. Based on the prior normality analysis (see Table 1), it was confirmed that the differences between pretest and posttest scores on the RAGK followed a normal distribution. This allowed the use of a paired Student's t-test to assess the significance of the change in the graph construction ability of the experimental group. As previously mentioned in the Instruments section, this rubric was based on previous works (Angra & Gardner, 2018; Stefanel, 2019; Vitale et al., 2014), particularly on the categories relevant to one-dimensional kinematics and the scoring criteria used by those authors. In the case of Stefanel, for example, we adapted the criteria he used to analyze participants' graphical constructions to our specific educational context. Below, we present the rubric we designed, which evaluates six graphical constructions. The first three graphs (G1, G2, and G3) are all related to position (x) graphs, while the last three (G4, G5, and G6) represent the same physical phenomenon, for which students were asked to construct the corresponding position (x), velocity (v), and acceleration (a) graphs that describe the motion.

Category	*Type of Motion*	*Criterion*	*Different phenomena*			*Same phenomenon*		
			x			x	v	a
			G1	G2	G3	G4	G5	G6
Possible points (0-2)								
Communication	ALL	Title present						
		Axes labeled						
		Numbers present						
		Logical increments						
		Appropriate size						
		Clarity in presentation						
Possible points (0-3)								
Correspondence to the phenomenon	x *vs* t	Motion phases				-----	-----	-----
		Phase slopes				-----	-----	-----
		Initial and final position values						
		Concavity	-----	-----	-----			
	v vs t	Graph slope	-----	-----	-----			
		Time correspondence with x *vs* t graph	-----	-----	-----			
	a *vs* t	Graph shape	-----	-----	-----			
		Time correspondence with v *vs* t graph	-----	-----	-----			

Total per Graph						
TOTAL SCORE						

Table 5. Rubric for Assessing Graphs in Kinematics (RAGK)

Criterion		**Description in the score**
COMMUNICATION	Title Present	**2 points:** Provides an appropriate title that names the type of kinematic graph in accordance with the described phenomenon. **1 point:** Provides a vague or unclear title. **0 points:** No title is provided.
	Axes labeled	**2 points:** Clearly identifies both axes, labeling the kinematic quantity (variable) of time with its unit on the x-axis, and the corresponding kinematic quantity (position, velocity, or acceleration) with its symbol and unit on the y-axis. **1 point:** Only one axis is correctly labeled (either time and unit, or the kinematic quantity and unit). **0 points:** Incorrect labeling of kinematic quantities, missing units, or both quantities are misplaced.
	Numbers present	**2 points**: Complete and clear numerical scale on both axes. **1 point**: Numerical scale present but incomplete or unclear. **0 points**: No numerical scale is included.
	Logical increments	**2 points**: Consistent and appropriate increases on both axes. **1 point**: Appropriate increments on one axis or partially consistent. **0 points**: Illogical or inconsistent increments.
	Appropriate size	**2 points:** Makes optimal use of available space and facilitates readability. **1 point:** Graph is too small or too large to be easily read. **0 points:** Graph size hinders readability.
	Clarity in presentation	**2 points:** Clean, professional-looking graph with no unnecessary marks or distracting elements, and with clear and organized layout. **1 point:** Minor marks or distracting elements are present, but clarity and legibility are maintained. **0 points:** Multiple smudges, marks, or distracting elements that affect readability and organization.
x *vs* t	Motion phases	**3 points:** Accurately represents all the required phases of motion (e.g., moving away, stopping, returning) in a way that is consistent with the described phenomenon, ensuring alignment with the indicated time or position. **2 points:** Represents the phases partially correctly, but there is some inaccuracy in the duration of phases in G1 and G3, or in the position in G2. **1 point:** Represents one phase of the motion, but incompletely or with significant errors in time or position correspondence. **0 points:** Does not represent the phases of motion, or the graph does not match the described phenomenon.
	Phase slopes	**3 points:** Accurately represents the slope of all phases with correct

		qualitative meaning (correct sign and inclination) and numerical correspondence to the described phenomenon (if applicable). **2 points:** Represents qualitatively correct slopes for all phases, but the numerical value of the slope in one or more phases is incorrect (in applicable graphs). **1 point:** At least one phase has the correct slope, either qualitatively or numerically (if applicable). **0 points:** The slopes do not match the phenomenon, either qualitatively or numerically.
	Initial and final position values	**3 points:** Initial and final position values are correct and consistent with the described phenomenon. **2 points:** Approximate values, but with some interpretation error. **1 point:** Incorrect or misinterpreted values, but showing an attempt to represent the phenomenon. **0 points:** Values are unrelated or inconsistent with the phenomenon.
	Concavity	**3 points**: Adequate and smooth concavity, reflecting constant positive acceleration in a precise way. **2 points**: Correct concavity, but with minor irregularities or fluctuations in the curve. **1 point**: Incorrect concavity (convex instead of concave), suggesting deceleration or lack of understanding of acceleration. **0 points**: Linear or incorrect curve (without concavity), indicating lack of understanding of the acceleration phenomenon.
v vs t	Graph slope	**3 points**: Constant and adequate positive slope, correctly indicating constant acceleration. **2 points**: Positive slope, but with inaccuracies in magnitude or inclination, suggesting that the student understands acceleration, but without precision. **1 point**: Horizontal line at a positive value, interpreting the motion as uniform rectilinear (constant velocity) rather than accelerated. **0 points**: Horizontal line at 0, downward line, or negative slope, indicating a lack of understanding of the accelerated motion.
	Time correspondence with x vs t graph	**3 points**: Consistent and accurate relationship with the position graph, showing a constant change in velocity that corresponds to the slope on the position graph. **2 points**: Partially coherent relationship, with some error in the exact correspondence between the two graphs, but in general it represents the expected change. **1 point**: Incoherent relationship or with obvious errors, without exact correspondence with the change in speed in the position graph. **0 points:** No apparent relationship between the velocity graph and the position graph; the change in velocity does not correspond to the expected behavior based on the slope of the position graph.
	Graph shape	**3 points**: Horizontal line in a positive and constant value, indicating

a *vs* t		constant acceleration with correct magnitude and direction. **2 points**: Horizontal line in a positive value, but with some imprecision in the value that does not correspond exactly with the position and speed graphs. **1 point**: Positive slope (confusion with the velocity graph), indicating an error in the interpretation of constant acceleration. **0 points**: Negative slope or non-constant curve, suggesting a deceleration or change in acceleration, which is incorrect for the phenomenon described.
	Time correspondence with v vs t graph	**3 points**: Magnitude of acceleration correct and consistent with the other graphs, indicating a complete understanding of the phenomenon. **2 points**: Approximate but not precise magnitude, which reflects partial understanding in the quantitative value of acceleration. **1 point**: Incorrect magnitude, but indicative of acceleration in the correct direction. **0 points:** Magnitude unrelated to the phenomenon, indicating a lack of understanding of the constant acceleration quantity.

Table 6. Description of the Scoring Criteria in the Rubric

The results of the t-test yielded a test statistic of $\boldsymbol{t} = -11.1840$ and a $\boldsymbol{p} < 0.001$, indicating a statistically significant difference between the pretest and posttest scores. Additionally, Cohen's $\boldsymbol{d}$ was 2.44, indicating a large effect size, supported by the critical $\boldsymbol{t}$ value of ±2.086 for 20 degrees of freedom. This finding suggests a substantial improvement in graph construction ability within the experimental group following their participation in the Real-Time Laboratory (RTL) with a STEM approach.

With this improvement in construction ability established, we proceeded to analyze the correlation between this gain and graph interpretation ability, as measured by the TUG-K scores in the experimental group. Prior to conducting Pearson's correlation, we confirmed that both the differences in TUG-K scores and the RAGK posttest scores met the normality assumption, thereby ensuring the validity of the analysis.

The Pearson correlation analysis yielded a positive correlation coefficient of $\boldsymbol{r} = 0.6931$ with a $\boldsymbol{p} < 0.001$, indicating a significant correlation between improvements in graph interpretation and graph construction. These results support Hypothesis 4, suggesting that as students improve their ability to interpret kinematic graphs, they also tend to improve their ability to construct them—thus strengthening their overall graphical competence in the context of one-dimensional kinematics.

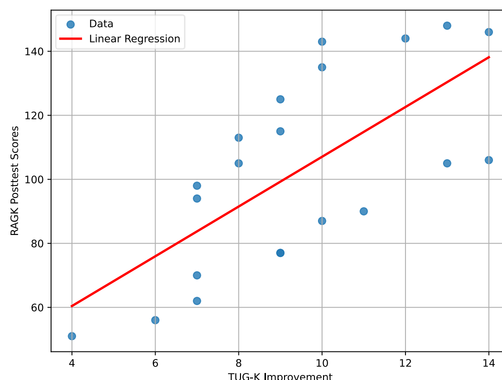


Fig. 7. Correlation of Score Improvement in the TUG-K Test and the Post-Test Score of The RAGK Rubric

Second Research Question: Analysis of Rtl from Social Semiotics

We present an analysis grounded in Social Semiotics, focusing on the interactions that emerged during the phases of the RTL methodology (Prediction, Experimentation, Comparison, Data Analysis). The names of the participants have been changed; Ana, Brenda, Carlos, Daniel, and Ema represent members of different teams. If we refer to two students from the same team, we will use the same initial letter (e.g., Ana and Aldo would belong to the same group). The interactions presented here are extracted and summarized from the observation guide used by the instructor to monitor team-based activities, in conjunction with video recordings of the sessions. In the corresponding tables, each interaction is accompanied by the activity (column A) and the phase (column M) in which it occurred, according to the RTL methodology. (Note: The letter M stands for "momento" in Spanish, referring to the specific phase of the RTL cycle.)

A	M	Description of the Interaction	Analysis
1	P	During the discussion on Situation 1 (S1), Ana expressed to the team her idea about what the position vs. time graph should look like. He explained that, by moving away slowly for 3 seconds and then at twice the speed for the next 3 seconds, the graph should start with a gentle slope and then become steeper from the third second onwards. As he explained, he drew a graph on the sheet that showed a gently sloping line for the first 3 seconds and a steeper slope for the next 3 seconds.	In this interaction, Ana performed a transduction from the spoken system to the graphics system. He turned his spoken description of movement into a visual representation by drawing lines according to her interpretation.
1	E	Observing that the graph showed irregularities due to sudden movements, Aldo proposed to Ana that she try to walk with more uniform and smooth	Here there was a transduction from the experimental system to the graphic system. They adjusted the way they performed physical movement to obtain

		steps. The team agreed and repeated the S2 experiment trying to perform one step per second, focusing on maintaining a constant speed and controlled movements. As a result, the graph obtained was more linear and representative of the expected movement.	the desired graphical representation.
1	E	While performing Situation 2 (S2), Carlos observed the real-time graph in Ardulab and noticed that the line line was descending uniformly. He told the team that this descending line represented that they were approaching the sensor at a constant speed.	Carlos carried out a transduction from the graphic system to the verbal system. He interpreted the graph generated in Ardulab and communicated it verbally to the team, translating the graphical representation with the conceptual explanation.
1	E	During the S3 experiment, Brenda noticed that when she stopped for 3 seconds, the graph in the app showed an almost horizontal line. She interpreted this horizontal phase to indicate that the velocity should be zero during that interval. On the worksheet, she drew that phase of the graph with " $v = 0$" to represent the resting state.	Brenda performed a transduction from the graphical system to the mathematical system by translating a specific part of the graph provided by the application, adding a mathematical notation to represent zero velocity.
2	E	During the team experiment, Daniel observed the position-time and velocity-time graphs in Ardulab as they hit the ball with moderate force. He noticed that the position vs. time graph generated a small curve. He told the team that this indicated that he was slowing down and not moving constantly. Diana suggested that the table might not be completely level and with a bubble leveler they made adjustments to the height of the table.	Transduction from the graphic system to the experimental one when they relate that the curve observed in the graph is due to a deceleration produced by a slightly greater inclination of the side of the table opposite the sensor.
2	D	The teams downloaded the position and time data of both experiments to the computer, although they observed a clear trend of the graph according to what was expected, they performed a cleaning eliminating the first and last data in order to correctly perform the curve adjustment.	They turned the experimental data into a mathematical model, connecting the graphical representation to an equation and extracting significant physical parameters.
3	D		

Table 8. Identification of transformations from Social Semiotics

A	M	Description of the Interaction	Analysis
1	P	Ana's team modifies the inclination of the graph predicted for S2 after discussing the time according to which slow movement was required and not as fast as they had at the beginning	It is a transformation within the graphi adjusting the representation without ch semiotic system.
1	P	The team initially drew a straight descending line for the S2 graph, without considering the exact position values. Brenda pointed out that since they were approaching the sensor from 2 meters to 0.25 meters at constant speed, the graph should reflect these values on the axes. Carlos proposed adjusting the graph so that it would start at 2 meters in the abscissa and end at 0.25 meters. The team corrected the graph, adjusting the scales and redrawing the downline correctly.	Here a transformation occurred within th system. The team modified their predict more accurately represent the positi refining the representation without semiotic systems.
1	C	Daniel's team corrects errors in the final hand-drawn graph of situation 1, adjusting scales and data points. The team argues that it obtained the average velocity of the first segment to ensure that the second segment of the graph would was accurate.	Transformation within the graphica improving the accuracy of the representa
2	P	One of the teams correctly predicts what the graph will be like through the graph they draw, but they also add in the initial and final stage of the movement a noise that the team mentions is due to the initial impact while the system stabilizes and at the end of the path where the ball falls.	Here a transformation of the graphic sys by adding the observed experimental no
2	P	Ema argues with her team that friction would affect the ball's movement and slow it down. This led the team to adjust the graphs of $p-t$, $v-t$ and $a-t$.	Although in the experimental setup the negligible for the requested distanc transformation occurs in the graphical sy
2	E	During the experiment, Daniel's team noticed that the ball did not reach 0.7 meters due to the lack of force in the hit. The team discussed whether it was due to friction, Diana commented that it was not friction as the ball was smooth and heavy enough for the short distance and that this could be due to the table not being completely level. With the help of a bubble leveler they verified that the small inclination was the problem, they leveled with coins under the table and once that was corrected the ball reached the end, even if little force was applied.	They made a transformation w experimental system. They modified th experiment was executed to obtain th shape.
2	D	Carlos adjusted the scale of the $v-t$ graph axes in Excel to better visualize the acceleration trend.	Carlos made a transformation within graphic system. He modified the present

		Changed the y-axis interval to highlight changes in velocity to make it easier to read values.	graph to facilitate its interpretatio changing the semiotic system.
3	P	During the design phase of the experiment, Carlos suggested that, in order to generate a movement with constant acceleration, they could slightly tilt the table by placing books underneath and use the cable channel and ball from the previous activity to form an inclined plane	The transformation occurs when they mo the experimental system, the experim previous activity so that it behave phenomenon described.
3	E	When reviewing the graphs in the app, Ana's team noticed that the data had some noise. They decided to repeat the experiment, this time they cleaned both the ball and the cable channel with a damp cloth and obtained more accurate data, the instructor questioned why they believed that this improved the reading, and the team generally thought that it was due to the fact that the water eliminated part of the friction between the cable channel and the ball.	They performed a transformation experimental system. They adjusted th conditions of the experiment to improve of the data, without changing the semiot
3	D	Carlos and his team adjusted the scales of the axes on the velocity vs. time graphs for both experiments, with the same scale for both axes for ease of comparison. In addition, it changed the limits of the axes and added legends and labels.	The team made a transformation within graphical system. He modified the pres the graphs to facilitate their interpre comparison, without changing the semic

Table 7. Identification of Transductions from Social Semiotics

Semiotic Resources and Disciplinary Relevant Aspects (DRAs)

A Disciplinary Relevant Aspect (DRA) refers to a conceptually important element within a discipline that warrants students' attention—such as position, velocity, acceleration, time, and the relationships among them. Svensson and Campos (2022) emphasize that semiotic resources are selected based on their ability to provide access to these disciplinary relevant aspects (DRAs). To help direct students' attention toward these aspects, we drew upon the theoretical framework of variation. During the experimental phases, student teams were instructed to vary position, velocity, and acceleration within the same experimental context, while keeping the same semiotic resource: the real-time generated graph. This strategy was also applied to hand-drawn graphs used for both prediction and comparison tasks. The concept of slope emerged as the most effective analytical tool for students to identify and understand the underlying physical relationships. Table 9 presents the results of the disciplinary discernment analysis, including the identified DRAs and their associated semiotic resources.

A	M	Description of the Interaction	Analysis
1	P	In general, most teams agree on how the tilt of the graph represents velocity and relate this to slope and physical movement.	The teams demonstrate a generalized disciplinary explanation by connecting the graphical representation with the DRA of velocity by observing how its slope change, this with the support of the Real-time graph resource provided

			by Ardulab.
1	P	When developing the predicted graph for S2, Brenda identified that, when approaching the sensor from 2 meters to 0.25 meters at constant velocity, the position vs. time graph should be a straight descending line. She explained to the team that the negative slope of the line represented a uniform decrease in position over time.	Brenda showed a disciplinary explanation. He recognized the proper shape of the graph and justified his reasoning based on kinematic concepts.
1	E	During the execution of S3, Diego observed that the phase of the graph corresponding to the period of detention was not completely horizontal but presented small variations. He concluded that this could be because the sensor could vary the readings due to the irregularities of the body. He proposed repeating the experiment, but this time with a cardboard he was holding so that the sensor would measure the distance to the cardboard and not to his body.	Diego showed disciplinary evaluation by identifying a discrepancy between the graphic representation and the expected movement. His proposal of how to repeat the experiment to correct the error reflects a good conceptual understanding and of the importance of precision in experimentation.
1	C	Carlos asked the team if in S1 the slope of the second section of the graph should be exactly double that of the first section, given that the speed doubled. He proposed that, mathematically, by doubling the velocity, the slope should also be doubled. The team discussed this idea and adjusted the predicted graph to reflect this proportional change in slope.	Carlos showed disciplinary appreciation by assessing the relationship between velocity and slope in a graph of position vs. time. Their analysis led the team to a deeper understanding and to adjust their representation according to kinematic concepts.
1	C	Daniel reflected on the observed differences between the predictions and the experimental results. He noted that factors such as difficulty maintaining constant velocities and making instantaneous changes affected the accuracy of their representations.	Daniel demonstrated disciplinary assessment by integrating his conceptual understanding with practical experiences. His reflection on limitations and how they influence outcomes confirms this.
3	P	Ana's team identified that, when tilting the table, the ball would experience a constant acceleration due to the effect of gravity. She drew on the graph $a - t$ a horizontal line with constant value. She explained that, in the absence of friction, acceleration should remain	Ana showed a disciplinary explanation by recognizing the effect of inclination on acceleration and how this should be constant when represented correctly in the acceleration graph.

		constant throughout the path.	
1	P	Carlos, upon reviewing the verbal description of S1 in the worksheet, decided to include numerical values for the velocities. He wrote that for the slow phase v_1= 0.5 m/s (3s), v_2= 1 m/s (3s)", providing more specific details on the velocities in each section. This modification helped the team to visualize better what the corresponding graph should look like.	A disciplinary appreciation is observed when Carlos relates the concept of velocity to a magnitude that enables his team to build a more accurate graph.
1	C	When comparing the predicted graph with the one obtained experimentally for S1, Ema pointed out to her team that her prediction of the transition from slow to fast motion was exaggerated (referring to the slope of the drawn line), while in the experimental graph the change in slope was not as large. Eduardo commented, when the instructor questioned the reason for that statement, that it was because it is not possible to change the velocity that much without running.	We observe a disciplinary explanation when the team is able to relate the concepts of velocity and slope in the context of the phenomenon.
2	E	While conducting the second experiment with a greater force, Ema noticed that the position vs. time graph had a steeper slope than in the first experiment. He explained to the team that this meant the ball had a higher initial velocity.	We observe a disciplinary explanation when the team is able to relate the concepts of velocity and slope in the context of the phenomenon. The DRA is velocity in connection with the Semiotic Resource of the real-time graph.
2	D	Ema pointed out that the first parameter indicated that the velocity was zero and that this was because there were no changes in speed. In another of the teams, Brenda also pointed out that the acceleration should be zero since the velocity was not changing, and therefore there was no acceleration.	Here we note a disciplinary appreciation in recognizing the equation as adequate for representing the phenomenon, the DRAs are velocity and acceleration in the semiotic resource of the obtained equation.
3	E	During the first experiment with the table slightly inclined, Daniel observed in the Ardulab app that the $v - t$ graph showed an upward straight line. He commented that this meant that the acceleration was constant.	Daniel demonstrates at least a disciplinary appreciation, as he correctly interprets the phenomenon through the graph, relating the DRA of velocity to acceleration and in turn to the phenomenon itself, using the experimental semiotic resources and the real-time graph.

3	E	When the inclination of the table was increased for the second experiment, Brenda noticed that the velocity vs. time graph had a steeper slope. When the team was asked why it happened, they concluded that the graph showing a greater increase in velocity indicated a greater constant acceleration.	Brenda and her team demonstrate at least one instance of disciplinary appreciation by connecting the experimental and graphic components with the DRAs of acceleration and velocity through the use of experimental semiotic resources and the real-time graph.

Table 9. Disciplinary Discernment from Social Semiotics

The RTL as a Semiotic Resource

In our social semiotics analysis, we observed common transductions among teams during their interaction with the Real-Time Laboratory (RTL). For example, students adjusted their physical movement based on how the graph changed in the real-time application. We also noted transformations within the experimental system when students improved the setup without switching semiotic systems: they modified the position of the ToF sensor to enhance measurement precision (see Figure 8), left space on the sides to prevent the sensor from detecting other objects, used a bubble level to align the ramp horizontally, and even reduced friction by moistening both the duct and the ball.

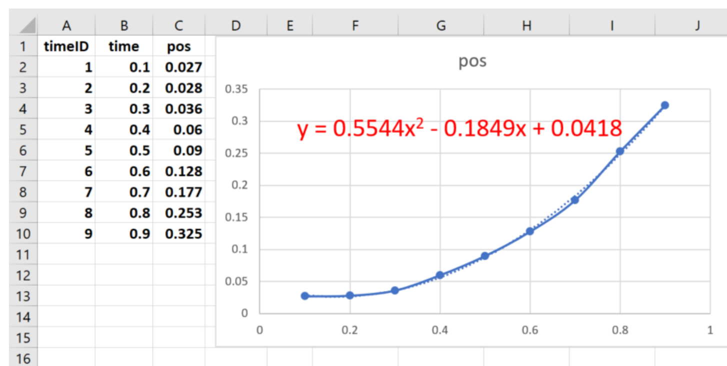
Additionally, we observed transformations when teams performed data cleaning on the computer to achieve a better curve fit, or when they adjusted graph scales to compare different experiments (see Figure 9). We attribute these transformations and transductions, especially those involving experimental modifications based on graph interpretation, to the rapid feedback provided by the RTL.

Although these changes occur within the same semiotic system—namely, the experimental setup—they are triggered by the interpretation of what the real-time graph indicates. This interpretation can be understood as a cognitive activity, a transduction that then results in adjustments to the experimental setup.

The RTL also enables broader transductions. For instance, during the prediction phase of each activity, students must translate the phenomenon—expressed in spoken language using kinematic terms—into a graphical representation. In some cases, this process is supported by gestures or hand movements to indicate slope and velocity.

Fig. 8. Students Modifying the Experimental Setup by Adjusting the Height of the ToF Sensor

During experimentation, the RTL automatically transduces the real phenomenon into a graph or a table of values. Subsequently, the table of values allows students, through a new transduction (data fitting), to obtain the mathematical function of the phenomenon. This dialogue between the systems of experimentation (measurements, movements), the real-time graph, the table, and the mathematical model is made possible because the RTL acts as a key transductive link that facilitates these representational changes.



timeID	time	pos
1	0.1	0.027
2	0.2	0.028
3	0.3	0.036
4	0.4	0.06
5	0.5	0.09
6	0.6	0.128
7	0.7	0.177
8	0.8	0.253
9	0.9	0.325

Fig. 9. Data Cleaning and Curve Fitting in A Spreadsheet Provided by One of the Teams During the UARM Activity.

As we have noted, the RTL takes on the role of a powerful transductive link by enabling shifts between semiotic systems. By classifying the RTL as a laboratory tool, we can consider it a complex semiotic resource, as it provides access to multiple representations. Therefore, a more appropriate definition for the RTL would be that of a transductive link with high potential for meaning-making.

Another relevant aspect of the RTL is that, through the semiotic resource of the value table, they allow students to engage in engineering practices, such as data cleaning—removing initial and final noise from the experiment—and curve fitting to obtain a mathematical model. Moreover, this value table allows the graph to be recreated, thus becoming a transductive link in its own right.

The reference frame is another important feature of the RTL. It is often intuitive for students when they agree that the ToF position sensor defines the reference point at y = 0. However, we also observed that if the sensor moves along with the student toward a wall, the reference point y = 0 shifts accordingly. During the graph construction stages, we investigated this phenomenon and found that students often associate specific types of movement previously observed in the RTL with their own graphical constructions. In other words, students consider both the position of the sensor and their own position as part of the reasoning behind their graphical representations.

All the above leads us to conclude, in response to the second research question, that the RTL plays a central role in students' conceptual development and graphical competence. The interpretation and construction skills within this competence improved following the intervention, as supported by previous quantitative analyses. Moreover, Social Semiotics provided us with insight into why this process is relevant and how social interaction plays a key role in its development.

Discussion

So far, our objective has been to provide insights into the impact of our educational intervention on students' conceptual understanding of one-dimensional kinematics and their graphical competence. We believe it was important to contribute quantitative data on student learning at the high school level, where this type of intervention using RTL methodology has been reported less frequently. Additionally, while the STEM approach has shown to align well with RTL methodology, we found no evidence of its application in combination with RTL at the high school level to generate quantitative insights into students' graphical competence. In our view, this symbiosis between the STEM approach and RTL—particularly through its incorporation of data analysis—offers greater flexibility than STEM implementations that appear to be anchored solely in project-based learning. We believe that engaging students in such activities may help spark their interest in STEM-related career

Another important point—also noted in previous studies (Stefanel, 2019)—is that students who were able to identify and associate motions involving constant velocity and constant acceleration with their corresponding linear and quadratic equations, as well as explain the meaning of the involved parameters (as evidenced in specific questions from both the pretest and posttest graph construction tasks), generally performed better across all assessments. This suggests that prior mathematical knowledge is relevant in this context for accurately discerning key concepts in kinematics.

When examining students' responses in light of the concentration factor analysis—which helped us identify a pattern in their answers—we found that the difficulties were related to questions involving negative values for position and velocity. This may be attributed to two factors: first, previous literature has documented that students commonly struggle with such cases; and second, our RTL's position sensor does not register negative positions. This aspect warrants further investigation to determine whether, for instance, reprogramming the RTL so that distance

values become positive only after a certain threshold (e.g., x centimeters) would help address this issue. In this regard, we consider this a limitation of our study.

We recognize that achieving expert-level graphical competence in one-dimensional kinematics requires extended practice across a range of graphical forms. Volkwyn and colleagues (2020), through what they refer to as a *disciplinary semiotic audit*, identified eight types of curves that students should be able to master. These curves appear in quadrants I and IV, while quadrants II and III are excluded because, as the authors note, negative time generally lacks physical meaning. If we consider the eight curve types in both quadrants I and IV, this results in 16 meaning-making possibilities. Since these forms can appear in the three main types of graphs of interest $x-t$, $v-t$, and $a-t$, there are 48 potential combinations that students should be able to interpret and construct. Furthermore, if we take into account axis crossings between quadrants and combinations of the eight forms for a single phenomenon, the number of possible graphical configurations increases substantially. Based on our results and the instructional time invested, we argue that the use of the RTL fosters a strong foundational level of graphical competence.

Considering the range of possible graph shapes and the physical scenarios that could produce them—including axis crossings between quadrants I and IV and the potential combination of the eight canonical curve forms—we propose a future line of research: the development of an artificial intelligence model trained to automatically assess kinematic graphs and provide personalized feedback. In this regard, the automated evaluation system in WISE (Vitale et al., 2015) and the GraphSmarts platform (Meir et al., 2023) have demonstrated the feasibility of implementing automated assessments based on interaction patterns with graphing tools in science education. Although a recent study using the ChatGPT-4 language model (Polverini & Gregorcic, 2024) examined the model's performance on the TUG-K test and found limitations in the general interpretation of kinematic graphs, it also suggested that a specialized, domain-trained model could be more effective. A model focused specifically on one-dimensional kinematics should be capable of evaluating how students interact with graphing tools—such as adjusting scales, labeling axes, or selecting curve types—and providing targeted feedback on areas for improvement. We believe that construction patterns differ between novice and more expert students. Such automation could, on the one hand, reveal a subset of graphical forms that most effectively enhance graphical competence, and on the other, enable the assessment of a larger student population while improving the accuracy of evaluations, thereby supporting the development of graphical competence after initial instruction.

We employed the social semiotics framework because of its capacity to reveal, through analysis, which types of relevant disciplinary concepts are made accessible through the use of a specific semiotic resource. In other words, it can provide qualitative insight into how effective a semiotic resource is in supporting the intended student learning. This is particularly important because it is within the interactions prompted by the resource—rather than solely in the statistical outcomes—where we seek evidence of its educational relevance.

Finally, we wish to clarify that the use of Arduino was not driven by a personal preference for open-source technologies or by an ideological stance, but rather by the recognition that in many marginalized social contexts—and in schools where budgets do not allow for the use of commercial data acquisition equipment (such as products from Pasco®, Vernier®, CMA®, etc.)—and, in some cases, where there is a complete lack of physical infrastructure for experimentation, these challenges can be overcome with low-cost technology. We believe that both educators working in similar contexts and those in more resourced environments can benefit

from implementing this type of tool. In this context, the formation of teacher learning communities can facilitate the development of new pedagogical strategies and the adaptation of effective practices (Carli & Pantano, 2019). For us, collaboration among educators is essential to addressing challenges and maximizing the educational impact of emerging technologies, as well as fostering the development of scientifically engaged citizens.

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