Experimental Centric Pedagogy as Scaffolding for a Better Understanding of Calculus in the Mathematics Discipline

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Abstract

The field of calculus is critical to the success and advancement of many engineering and statistical systems. Calculus provides ways of analyzing transient quantities, including data collected from sensors, determining the area under a curve, fitting a line for predictive analytics, and price changes in the stock market. It is also core to the understanding of numerous probability distributions in statistics, hence, fundamental knowledge of this concept is crucial for a successful career in science, technology, engineering, and math (STEM). The proposed experiment will ease the complexities involved in the learning of calculus students by using experimental centric pedagogy (ECP), which entails providing simple yet relevant experiments that would boost the students' interest in this field. The concepts of differentiation and integration would be practically demonstrated to students using Hooke's law, velocity, acceleration with respect to time, and ruler experiment. The project would employ readily available utilities to demonstrate integration and differentiation to the students. These experiments will also enable the students to appreciate the relevance of these concepts in STEM fields.

Introduction

To prevent students from being required to review the same knowledge content on numerous topics, interdisciplinary education seeks to find knowledge content that has commonalities with two or more subjects. To avoid having to teach the other subjects again, it is possible to teach in that subject's program interdisciplinary knowledge with the dominant subject. For students, integrated instruction has several benefits. The lesson becomes more engaging, appealing to them, and not boring. It also inspires learners to think and produce in accordance with their preferred thinking processes. It dramatically reduces rote learning because students can rapidly use knowledge to solve an issue at hand while internalizing the minimal amount of essential and relevant information. Because they do not have to repeat the same material in several areas, integrated content also frees up students' time to study new information. This improves thinking speed and turns the brain into a programming machine rather than making learning dull. Apart from obtaining engagement for learners' interdisciplinary integration has some advantages for instructors as well. Teachers are familiar with interdisciplinary information in their subject areas, making it simple to synthesize and condense knowledge into primary ideas that are distinct from one another and are easy to visualize. Additionally, using this method, teachers self-organize, examine, assess, and orient learning for students both within and beyond the classroom. This goes beyond merely transmitting knowledge to students.

Calculus has many useful applications. This topic reveals itself in its numerous and significant applications in practice and in many branches of science, particularly physics, which has historically been most closely associated with analysis. According to Kleiner [1] for three centuries (18th, 19th, 20th), the primary quantitative instruments for analyzing scientific issues have been calculus, modern physics, and engineering. Calculus cannot, then, solely concentrate on solving problems of pure mathematics while ignoring the chance to show students the crucial role that calculus plays in other subjects.

Numerous studies have demonstrated that students have trouble using the calculus skills they gained in math classes to tackle physics problems. According to Edward et al. [2], while performing mathematical operations successfully in the context of a math problem, students could be unable to comprehend the same processes when they appear in physics problems. Jone's [3] results supported the notion that arithmetic skills had not been effectively engaged in science lectures. Lack of knowledge was not the issue. For instance, as in Bajracharya et al. [4] and Chau et al. [5], students have essential backgrounds in both mathematics and physics, and they still struggle to make connections; they interpret physics issues using a calculus tool. Many students did not understand how, when, or why the analytical skills they gained in physics were applied in those cases. Jone's [3] attributed this phenomenon to the fact that calculus classes effectively give students the information and skills they need to complete math class assignments.

From the study above, two important problems should be remembered. First and foremost, a teaching strategy that can completely enable students to comprehend the conceptual nature and skills to analyze methodologies is needed. Second, it is important to have students use their analytical skills in physics or comprehend the different calculus applications they encounter in the high school physics curriculum. What approach helps to accomplish these two objectives? To develop more effective teaching strategies, several educational scholars have examined the historical development and spread of calculus. The teaching strategy used is experimental centric pedagogy (ECP), which will be used to help students understand calculus using experiments for a better understanding of mathematics concepts such as Hooke's law, distance, etc. Calculus helps physics to solve many of its problems. Calculus and the dynamics of practice and the sciences have a close link, according to historical study. Particularly throughout history, there has been a strong connection between analysis and physics. The inception and development of analytical ideas have been largely influenced by the challenges that physics has raised. On the other hand, calculus tools enable physics to address many of its issues. In the history of human civilization, these two sciences' mutual support has led to important advancements. It was recommended by researchers that analytical knowledge be taught in classrooms today.

To take advantage of the relationship between mathematics and physics in the teaching process for two disciplines, the researchers discovered a way to go beyond the two above challenges in learning and applying calculus principles. The pedagogical trend that results from this line of study is the interdisciplinary integration of math and science. Berlin and White [6] claim that this line of inquiry has been discussed since the early 20th century and has gained increased traction in recent years. Many models examining the relationship between mathematics and science topics have been constructed by researchers, as seen in the trend above. It frequently highlighted the two primary multidisciplinary linkages listed below:

i.) Mathematics - Science Context - Science offers contexts, concepts, and material that provide meaning to and explain the basis for the notion of mathematics.

ii.) Science - Apply Mathematics (Science - Apply Math) focuses on the use of mathematics as a tool to assist in the solution of scientific issues.

Numerous studies have revealed that students struggle to use derivatives in physics issues ([7], [8], [3]). Jones [3] cites the analytical training program's emphasis on the derivative's geometric interpretation as the primary factor (slope). Physics application settings mostly employ the rate of change understanding. The unequal connection caused a disconnect between knowledge of the derivative and knowledge of its practical uses in physics. Students were familiar with using derivatives in these physical situations. Therefore, the concept of the rate of change needs to be understood to understand derivatives. Many physical variables, such as velocity and acceleration, were directly tied to the interpretation of the fundamental calculus concepts, such as derivatives. As a result, prior exposure to and familiarity with these variables via real-world experiences or physics coursework may aid students in better understanding calculus's abstract ideas.

For most STEM subjects, a solid grasp of the subject matter and ideas depends on the usage and application of mathematics. Particularly in physics, a large portion of problem-solving is turning the issue into a mathematical model, sometimes with many representations, and then giving the acquired mathematical answer physical significance, such as Hooke’s law experiment. Mathematics and physics course performance is a key determinant of students' success in STEM careers [9]. A lack of conceptual calculus comprehension can have a negative impact on students' subsequent learning in STEM courses and eventually cause them to reevaluate a STEM major. Only a tiny portion of college students in the US who enroll in basic calculus and/or physics courses plan to continue their studies in math or physics beyond those courses. Most of these students only sign up for beginning calculus and/or physics classes to satisfy general education requirements or to finish the prerequisites for further study [9].

We argue that students' struggles with learning and comprehending numerous subjects and concepts in these courses may be one factor in their lack of interest in these courses. The major goal of this study is to find a calculus-based solution so that students may comprehend the idea and use of calculus in a circumstance or problem from real life. More precisely, we wanted to determine how students comprehend and use concepts such as problem-solving (e.g., Hooke's law, reaction time etc).

Literature Review

There are different approaches to motivate students in physics, electrical engineering, industrial engineering, and civil engineering, which have been developed by researchers who employ ECP (experimental-centric pedagogy) to help students understand how calculus is used in physics and other scientific courses. In this paper, the Hooke's law and the ruler experiment will be used to assist students in comprehending how calculus is applied in physics, industrial engineering, and civil engineering.

Chau et al. [5] fully explain derivatives to students while also demonstrating to them how crucially important derivatives are in many physics' issues, demonstrating to them the strong relationship between physics and mathematics. Only 30 Vietnamese students in grade 11 were included in the sample because this was a case study in Ho Chi Minh City. The test contained physics issues intended to demonstrate to pupils the derivative growth connected to various physics circumstances. Reliable data were gathered, including worksheets from students and instructor interactions, and they were qualitatively assessed to shed light on how well students understood derivative ideas and how to solve problems. The experimentally involved students reportedly understood the general importance of the derivative in estimating the instantaneous quantity change rate after the two-increase ratio border determined the derivative. The use of derivatives in several areas of research and practice, notably in mathematics and physics, was further encouraged by this multidisciplinary approach.

According to Jones [3], it is difficult for physics and engineering students to incorporate mathematics into their coursework. While various curriculum initiatives aim to improve students' calculus education, it is important to identify any gaps by examining the data and comprehending the information that students' access or do not access while adhering to directions.

López-Gay et al [10] explained how to mathematically represent physical phenomena using differential calculus, which necessitates comprehension of differentials in the context of physics. The value of four distinct concepts of the physics differential for the mathematization process is found and evaluated in their paper. They also offer empirical research to examine students' notions of the differential in physics as well as their judgments of how they should apply differential calculus. Their findings were consistent with the hypothesis that students have a nearly exclusive conception of the differential as an infinitesimal increment and that they believe their teachers only expect them to use differential calculus algorithmically, without a clear understanding of why they are doing it. These findings are connected to how little emphasis is placed on the mathematization process in traditional physics instruction.

Bingolbali et al. [8] examine how mechanical engineering students see mathematics, as well as how they understand the derivative and prefer to understand it. Pre, post, and delayed posttests, a preference test, student interviews, and a review of calculus courses are all sources of data. Students studying mechanical engineering are compared using data from mathematics students. Thier findings demonstrate that while mathematical students' conceptions and preferences for the derivative develop in the direction of tangent aspects, those of mechanical engineering students develop in the direction of the rate of change aspects. Mechanical engineering students also view mathematics as a tool and desire the application aspects in their course. Regarding instruction and departmental affiliation, students' evolving ideas, interests, and perspectives are considered, and educational consequences are proposed for the mathematical education of engineering students.

Methodology

The goal of this study is to provide light on students' understanding of the integral and how it is used in physics and engineering fields. The Hookes law will mainly be implemented in mathematics, physics, and engineering classes where students will be motivated to see the application to calculus in real-life problems. Two major experiments are developed in mathematics so that students can understand the concepts of differentiation and integration. The two experiments are the ruler experiment that demonstrates the concept of calculus in traffic engineering and the Hooke’s law experiment. Twenty students from the departments of physics and civil engineering participated in this experiment, and the Motivated Strategies for learning Questionnaire (MLSQ) and Curiosity questionnaire were adopted for the purpose of collecting learners’ perceptions of the use of this pedagogy in the pre and post experimental design.

Equation of Motion

A moving vehicle was used to create the equation of motion model. A traffic stream's performance can be greatly impacted by the movement of a single vehicle. Understanding each vehicle type's features, capabilities, and movements enables us to simulate groupings of cars and assess the effectiveness of the traffic stream. The individual trajectories of individual vehicles in a time-space diagram show traffic flow. Parallel trajectories will exist between vehicles traveling in the same travel lane, and when one vehicle passes another, the trajectories will come together. Time-space diagrams are practical tools for assessing and showing the traffic flow characteristics of a particular route section over time (e.g., analyzing traffic flow congestion). However, the ruler experiment will be the one we pay the most attention to using the distance formula.

Now, using fundamental calculus knowledge, we can mathematically deduce the equation of motion. Acceleration, distance, and velocity are all related to time, as previously mentioned.

The velocity is the displacement that an object or particle experiences with respect to time. In the International System of Units (SI), the unit of velocity is meters per second (m/s)

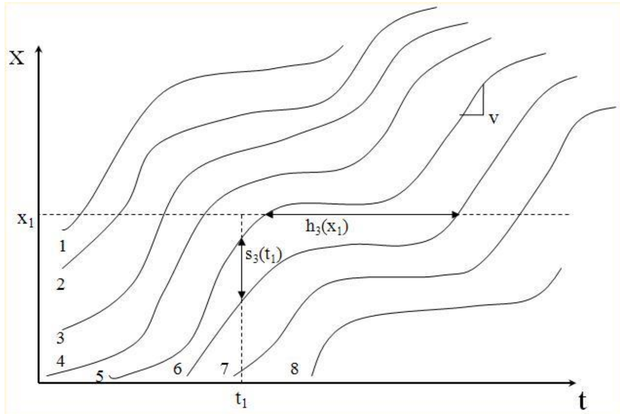

Figure 1 (Graph of an equation of motion where x is the distance and t is time)
Wikipedia

Velocity is written mathematically as:

$$v = \frac{dx}{dt} \qquad (i)$$

where x is the displacement/distance and t is time.

The term acceleration is the rate at which an object's velocity changes with respect to time. The expression of acceleration is given as

$$a = \frac{dv}{dt} \qquad (ii)$$

Note that acceleration is the second derivative of velocity and is written as:

$$\left(a = \frac{d^2x}{dt^2} = \frac{dv}{dt}\right)$$

The first equation of motion is modeled as

From Eq. (ii)

$$adt = \mathrm{dv} \qquad \text{(iii)}$$

Integrating both sides in (iii)

$$\int_{t_0}^{t} a\, dt = \int_{t_0}^{t} d\, v\,(t)$$

$$\int_{t_0}^{t} a\, dt = v(t) - v(t_0)$$

$$v(t) = \int_{t_0}^{t} a\, dt\ + v(t_0) \qquad (iv)$$

From Eq (i), we have

$$vdt = \mathrm{dx} \qquad (v)$$

Integrating both sides in Eq. (v)

$$\int_{t_0}^{t} v\ dt = \int_{t_0}^{t} dx$$

$$\int_{t_0}^{t} v\ dt = x(t) - x(t_0)$$

$$x(t_0) = \int_{t_0}^{t} v\ dt - x(t) \qquad (vi)$$

To derive the second equation of motion, substitute Eq. (iv) into Eq. (vi)

$$x(t_0) = \int_{t_0}^{t} [a(t\ -\ t_0)\ +\ v(t_0)]\, dt - x(t)$$

$$x(t_0) = \int_{t_0}^{t} [at\ dt\ -\ at_0\ dt\ +\ v(t_0)dt] - x(t)$$

$$x(t_0) = \frac{1}{2}[at^2 - at_0 t + tv(t_0)] - x(t)$$

Substituting in the intervals [t, t_0];

$$x(t) = \frac{1}{2}[a(t - t_0)^2 - at_0(t - t_0) + v(t_0)(t - t_0)] - x(t_0) \qquad (vii)$$

Assume a constant acceleration, which makes $a(t) = a,\ x(0) = 0, v(0) = 0,\ t_0 = 0$. From Eq. (vii), we have

$$x(t) = \frac{1}{2}\ at^2 \qquad (viii)$$

Having derived the distance equation, we can use it to carry out the ruler experiment by measuring the distance of the ruler measured in centimeters.

Ruler Experiment Procedure.

The main apparatus needed is a ruler (Figure 2).

1. Have your subject rest their hand on the table.
2. Hold a ruler at the top edge.

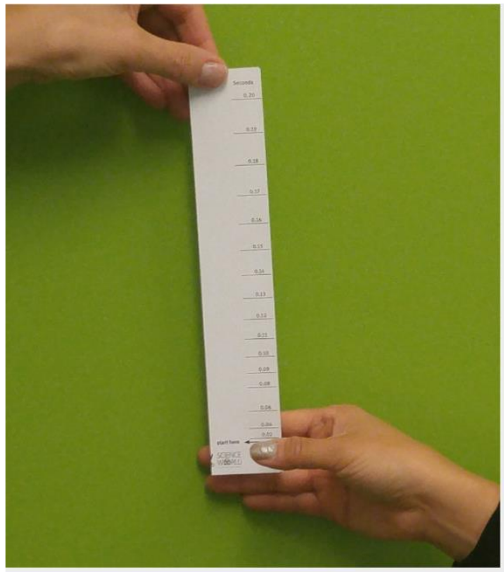

Figure 2 (Apparatus) ***Science world image***

3. Have the subject put their thumb on one side of the bottom of the ruler and their fingers on the other side. They should not grasp the ruler, however. It must be able to freely fall between his fingers.
4. Without warning the subject, let go of the ruler.
5. When the subject notices that the ruler is falling, they should try to grasp it by closing his thumb and fingers around it. They should not move their hand (Figure 3).

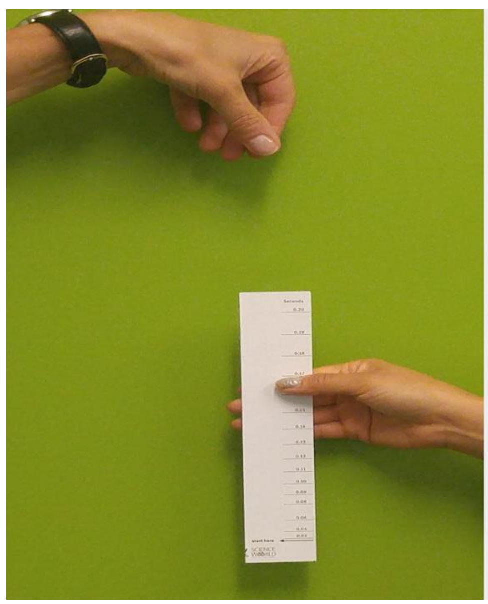

Figure 3 (Apparatus) ***Science world image***

6. Look at the ruler and see where the subject grasped it. Find the location in centimeters on the ruler where the hand is grasping the ruler. This should tell you how far the ruler fell before the subject reacted and grasped the ruler.
7. Record the location of the grasp on your sheet.
8. Repeat the whole procedure (steps 1 through 7)
9. Record your value in Table 1 calculating the time using Eq. (viii);

Table 1: Data Recoding Guide for Learners

Distance (cm)	Time (sec)

Hooke's Law Derivation.

A force acts to draw a spring back to its equilibrium length when it is stretched. The restoring force, which is directly proportional to the displacement from equilibrium, pulls the spring back toward equilibrium. The restoring force increases when the spring is stretched further. Hooke's law of elasticity is the equation for a restoring force and is as follows:

$$F = -kx$$

Using integral calculus, we can derive Hooke's law from work done. Let us consider a spring that is at initial rest, with no force applied on it. We assume that we apply a force F to the spring, which causes it to stretch by a distance x.

The work done by a force stretches the spring by a distance x, which can be calculated using an integral.

$$W = Fx$$

$$W = \int F\,dx \qquad (ix)$$

where the integral is taken over the distance x. The work done by the force is equal to the potential energy stored in the spring.

From the definition of Hooke's law, we can deduct from (ix) that,

$$W = \int -kx\,dx \qquad (ix)$$

Integrating we have

$$W = -\frac{1}{2}kx^2 + c \qquad (x)$$

where c is a constant. We can equate the constant c to zero since the spring is at rest in its equilibrium position. Then,

$$W = -\frac{1}{2}kx^2 \qquad (xi)$$

Equation (x) gives the work done on the spring as a function of its displacement. We can use equation (x) to find the potential energy stored in the spring, which is the negative of work done:

$$-W = \frac{1}{2}kx^2$$

$$U(x) = -W = \frac{1}{2}kx^2 \qquad (xii)$$

Equation (xi) shows that the potential energy increases quadratically with the displacement. We can also use the equation to find the force exerted by the spring as a function of its displacement, by taking the derivative of the potential energy in equation (xi) with respect to displacement x.

$$F(x) = \frac{dU(x)}{dx} = -kx \qquad (xiii)$$

The expression shows the definition of Hooke's law, showing that the force exerted by the spring is proportional to its displacement.

Experimental Procedures: Hooke's law

Some apparatuses are weight sets, rulers, springs, masses, strings, ratus stands, etc.

1. Gather the supplies necessary to perform the experiment, including the hanging masses, the spring, the ruler, and others.
2. Set up the apparatus as described in the kit manual (Figure 4).
3. The 0 cm mark of the ruler was aligned with the bottom of the coiled part of the spring and was mounted to the rod as shown below.

Figure 4 (Apparatus)

Experimental setup with measuring tape aligned with spring. The red arrow indicates the bottom of the spring coil (Figure 5).

Figure 5 (Spring with Mass)

4. Attach the hanging mass to the bottom loop of the spring and record the new position of the bottom of the coiled part of the spring to distance as the displacement in Data Table 2.

A wooden ruler was used as the straight edge. The bottom coil of the spring is marked with a red arrow and is located at 9.4 cm in this image.

5. Repeat step 4 for the remaining masses listed in Data Table 2.

Table 2: Data Recoding Guide for Learners Measuring the Spring Constant of a Spring

Mass(kg)	Distance(cm)	Weight(N)	K = Slope
0.1			
0.15			
0.5			
0.55			
0.66			
0.6			

Data Collection

The experiments described above were carried out in the two courses in Physics and Civil engineering during Spring 2021. The experimental design was described in the authors' preliminary findings in [11] and was carried out in a pre- and posttest method. Data collection was performed via an electronic survey using standard tools. The Motivated Strategies for Learning Questionnaire (MSLQ) and Curiosity questionnaire were adopted for the purpose of collecting learners' perception of the use of this pedagogy in the pre- and post-experimental design. The MSLQ has a 7-point Likert scale ranging from 1 (Not true of me) to 7 (Very true of me) and covers the three theoretical components of motivation, namely, value beliefs, expectancy, and affect [11], which were built into 8 subscales, namely, intrinsic goal orientation, extrinsic goal orientation, task value, expectancy component, test anxiety, metacognition, critical thinking, and peer learning collaboration. The curiosity questionnaire adopted in the present study had two 5-item subscales, namely, interest-type epistemic curiosity and deprivation-type epistemic curiosity. The assessment tool utilizes a 4-point Likert-type scale. These scales have undergone validation and exhibit acceptable internal reliability coefficients.

Interest-type epistemic curiosity is defined by an innate fascination or interest in a certain subject. It is frequently motivated by a sincere desire to learn more about a topic that is intellectually or personally interesting to the learner. This kind of curiosity is self-driven and frequently followed by the acquisition of new skills and knowledge. However, deprivation-type epistemic curiosity is motivated by a sense of ignorance or deprivation. It appears when there is a discrepancy between one's knowledge and what one desires to know. This kind of interest is frequently brought on by a sense of intellectual inadequacy or a perceived knowledge gap. It can be a strong learning motivator since it fosters a sense of urgency and a drive to fill in knowledge gaps.

The participants' total scores were classified into three levels of motivation: low, moderate, and high. A total obtainable score of 208 was possible, and using the categorization technique, learners with less than 50% were categorized as 'low', 51-70 % as 'moderate,' and above 70% as Scores less than or equal to 39 (below 50%) were considered low motivation, scores between 40% and 69% (40-69) were considered moderate motivation, scores between 70% and 88% (71-88) were considered high motivation, and scores between 89% and 98% (89-98) were considered very high motivation. The study conducted both descriptive (frequency, percentages, mean, and standard deviation) and inferential statistics (t test) to analyze the data. The parametric method was used because the data were normally distributed, and a 95% confidence level was set for the study. All data cleaning and data analysis activities were carried out using Statistical Package for the Social Sciences (SPSS IBM 25.0).

Findings and Discussion

The categorization of the subscale results of the students is presented in Figures 4a-j. In Figure 4a, there was an improvement in the percentage of learners who had moderate intrinsic goal orientation from 33.3% to 58.3%, and those with high scores remained unchanged. There was also an increase in learners with a high level of extrinsic motivation from 8.30% to 33.30% (Figure 4b). The results further revealed an improvement in the percentage of students with high-level scores in task value (TV), expectancy component, critical thinking (CT), and metacognition (MC) (Figure 4c, 4d, 4f, and 4g, respectively) and an increase in the percentage of learners with moderate scores under peer learning and collaboration (PLC), interest-type epistemic curiosity and deprivation-type epistemic curiosity (Figure 4h, 4i, and 4j, respectively). The number of students who scored low on test anxiety increased as expected because of the questions were in reverse sequence (as seen in Figure 4e), i.e., the proportion of students with low test anxiety scores increased. The posttest saw a slight increase in low levels of test anxiety, which brought attention to the benefits of experiential learning for students. The result in Figure 4i and 4j reveal an increase in the percentage of learners with a moderate level of curiosity. Yui et al. [12] findings support this study's conclusion that hands-on learning is linked to both types of curiosity.

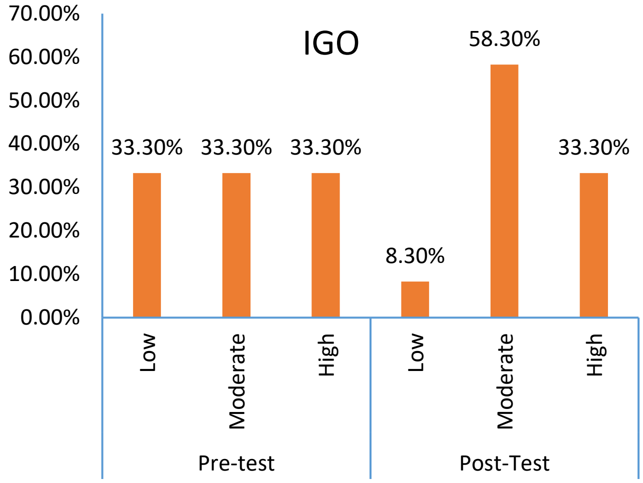

Fig 4a: Intrinsic goal orientation

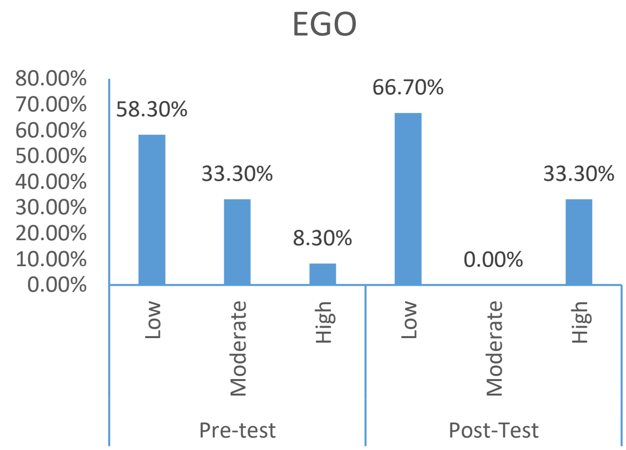

Fig 4b: Extrinsic goal orientation

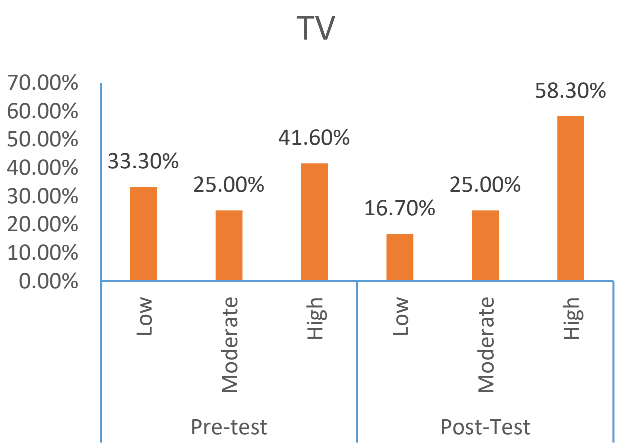

Fig 4c: Task value

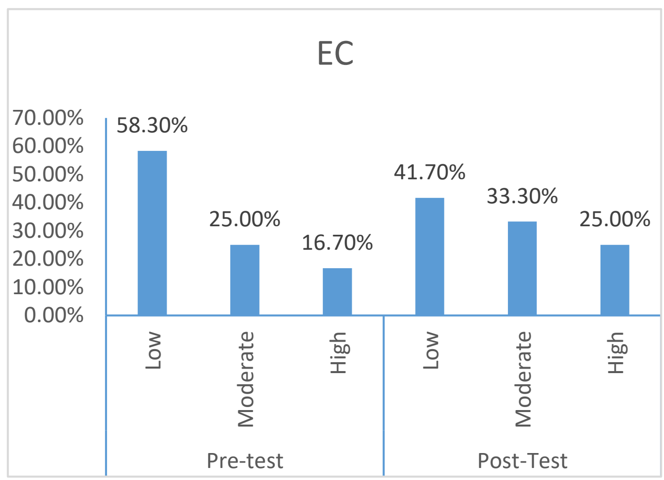

Fig 4d: Expectancy component

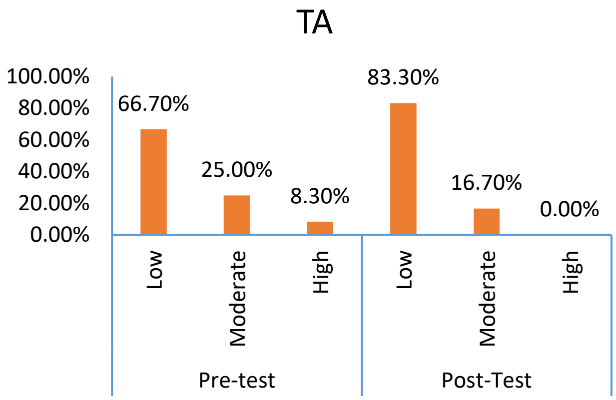

Fig 4e: Test Anxiety

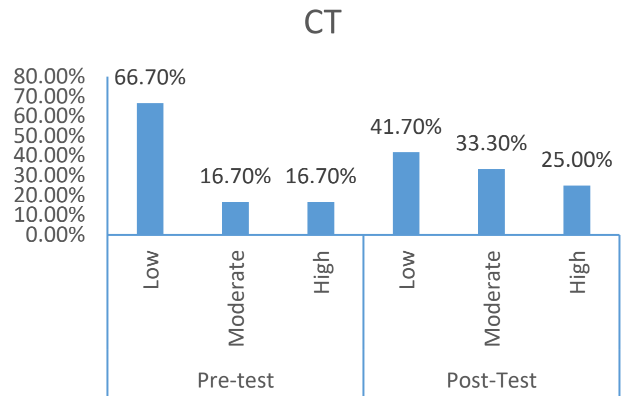

Fig 4f: Critical Thinking

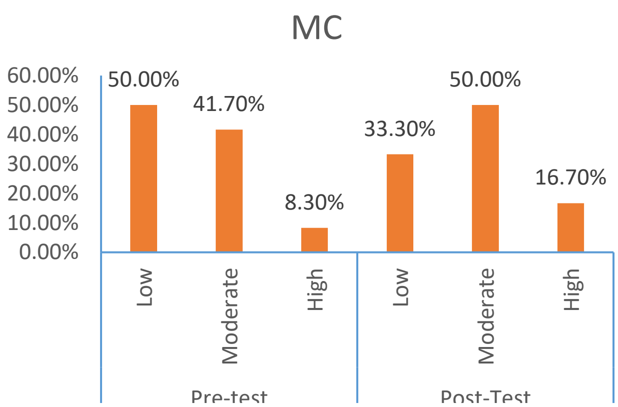

Fig 4g: Metacognition

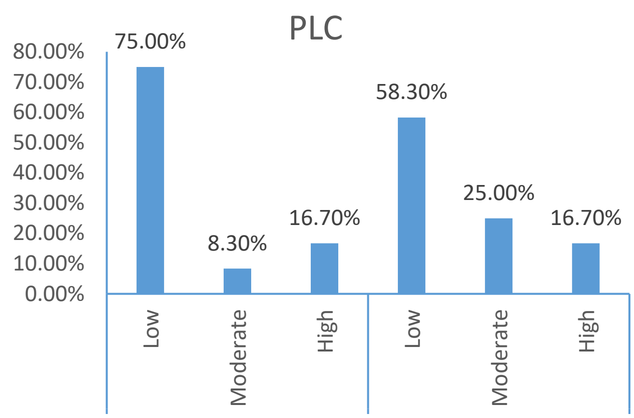

Fig 4h: Peer Learning and Collaboration

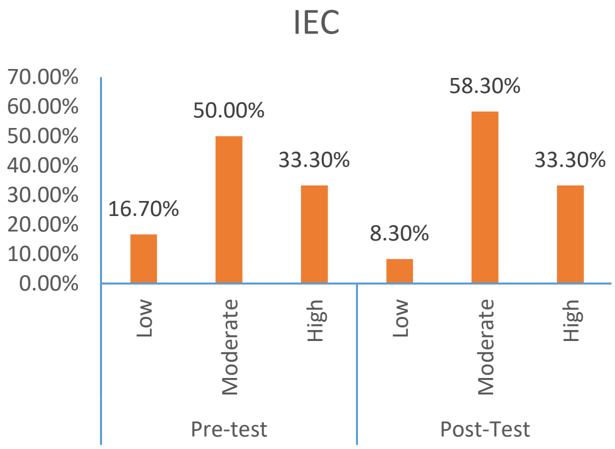

Fig 4i: Interest-type Epistemic Curiosity

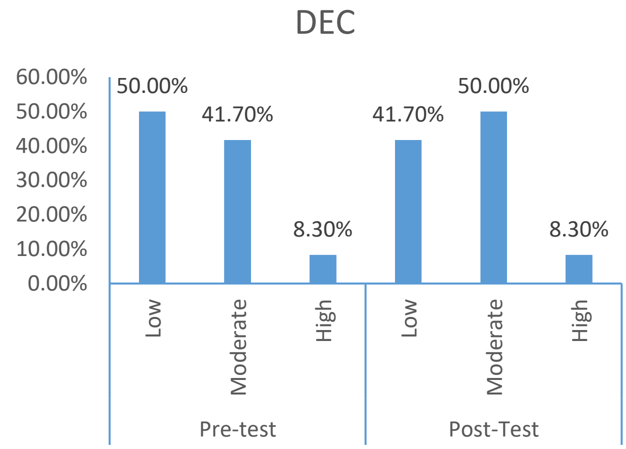

Fig 4j: Deprivation-type Epistemic Curiosity

The mean MSLQ score of learners in the present study is presented in Table 3 below. The results showed a positive mean difference for most of the subscales except for text anxiety, which was expected to be lowered (reverse questions). The p value of the t test revealed that there was no significant change in most subscales (p>0.050). Although the literature posited the significance of hands-on learning in STEM education, it can be observed here that the different subscales of the learners were not significantly improved.

Table 3: Mean comparison of MSLQ Subscale scores

Subscales	Pretest	Posttest	Mean difference	t test p value
Intrinsic goal orientation (IGO)[1]	5.31±1.4	5.89±0.74	0.58	0.22
Extrinsic goal orientation (EGO) [1]	3.53±2.14	3.69±2.54	0.16	0.80
Task value (TV)[1]	5.31±1.57	5.97±1.12	0.66	0.31
Expectancy component (EC)[1]	4.83±1.4	5.42±1.06	0.59	0.26
Test anxiety (TA) [1]	3.88±1.8	3.63±1.43	-0.25	0.74
Critical thinking (CT) [1]	4.5±1.58	4.97±1.36	0.47	0.44
Metacognition (MC)	4.92±1.46	5.38±0.91	0.46	0.43
Peer learning and collaboration (PLC) [1]	4.14±1.62	4.83±1.21	0.69	0.20
Interest-type epistemic curiosity (IEC) [2]	3.18±0.64	3.22±0.57	0.04	0.85
Deprivation-type epistemic curiosity (DEC) [2]	2.6±0.56	2.63±0.68	0.03	0.90

* Significant difference between pretest and posttest scores.

[1] 1-7 Likert Scale

[2] 1-4 Likert Scale

Conclusion

Two experiments were developed using the ECP: Hooke's law, a ruler experiment, and deflection, which will be further developed. The ruler experiment was successfully customized and integrated using mathematics, and we also integrated calculus in Hooke's law, where we have the initial and final length. These data are for Fall 2021 and Spring 2022, and details are presented. The Hooke's law experiment was integrated in Spring 2021 and Fall 2022. The implementation of hands-on learning has a positive impact on reducing test anxiety among learners. This suggests that hands-on learning could be a useful teaching strategy for educators to consider when designing instructional materials to help alleviate students' test anxiety. These study findings suggest that hands-on learning is linked to both types of curiosity - interest and deprivation. Thus, hands-on learning could potentially enhance students' curiosity in both areas and promote a deeper level of engagement and interest in the learning process. In conclusion, it is hoped that future experiments will be conducted in various STEM fields to expose learners to a more diverse range of mathematical concepts. This would enable students to develop a more comprehensive understanding of mathematics, which is a fundamental subject for many fields of study and careers. Students studying physics and engineering will want to learn more about how derivatives and integrals are used in their fields, as they already have a basic understanding of calculus. The student will be inspired and desire to study more about calculus, specifically the rate of change, if this is employed. Additionally, some students may find calculus difficult and difficult to understand, leading them to conduct additional research without prior knowledge. However, this research has made it possible for those without a background in calculus to understand calculus by performing hands-on experiments, as shown in the methodology, which will motivate them to learn more about and conduct additional research on calculus application due to their interest.

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