Effects of Computer-Assisted Multiple-representations on Problem Solving and Experimentation Abilities in Learning General Physics at Arba Minch University

Mulugeta Habte Gebru

Department of Physics, Arba Minch University, Arba Minch, Ethiopia
Email: mulugeta1970@gmail.com

Abstract

This study aimed to test the efficiency of Computer-Assisted Multiple Representations (CAMR) in tutorial and laboratory classes. The experimental group consisted of 34 physics students, and the control group contained 45 chemistry students for design one (i.e. pre-test and post-test control group design) targeting the problem-solving ability as one dependent variable. In addition, the same 34 physics students were selected for design two (one group only pretest and posttest design) targeting experimentation ability as the other dependent variable. The results from Design One revealed a statistically significant difference in mean scores, favoring the experimental group, as determined by the performance test. The result was also indicated that male students performed better than the female students. Design two indicated a significant mean difference between the simulation performed by CAMR, and conventional physical experiments that were obtained based on the practical test. However, no significant difference was observed between male and female students with respect to CAMR and conventional physical experiments. With regard to correlation, performance tests and assessment scores were significantly correlated under design one, but not under design two. The quantitative results were also supported by the evidence from qualitative analysis. The study finding implies that teaching organized knowledge assisted by computers is essential for the effective performance of problem-solving and experimentation tasks and activities.

1. Introduction

Developing conceptual understanding and procedural fluency are two essential competencies in learning mathematics and science (Laswadi *et al*, 2016). However, students who learn to recite

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definitions and formulas that are common in traditional instruction (TI), show limited proficiency in solving problems and understanding situations in experimentation in which those concepts and procedures could be used. Recent research has increasingly focused on the transition from novice to expert problem solver, particularly in physics, emphasizing the development of competence in interpreting and integrating multiple representations, such as graphs, diagrams, illustrations, and formulas (Walsh et al., 2007; Cock, 2012). Students' ability to solve problems and engage in experiments is largely influenced by their prior knowledge, which is critical for building both conceptual understanding and procedural fluency (Heuvelen, 1991; Trumper, 2003).

Hestenes (1996) suggested that to address misconceptions directly models and models with multiple representations expose students with conceptual tools for diagnostic and eliciting purpose and create an environment of activities and discourse to think and reason critically about physical phenomena. According to Wetzels, Kester, & Van Merriënboer (2010) engaging the learner to actively build external representations might promote organization and integration processes that foster the development of mental models. Constructivist perspectives argue that students achieve the most effective learning when engaged in tasks that allow them to build understanding in connection with their own interests and prior knowledge (Rapp, 2005). Learning environments based on constructivist principles, such as CAMR, are structured to offer students opportunities to develop conceptual understanding and skills through problem-solving activities and experimental tasks.

The theoretical basis of the current research which tries to effectively change existing practices in physics classrooms is cognitive schema theory which receives special attention as an important theoretical perspective. Kotsaro & Smyrnaiou (2017) discussed such association between constructionism and modeling approaches through performing computer-assisted multiple representations. Finally, they recommended that it would be helpful to integrate other theoretical approaches of new technologies in teaching science starts from kindergarten and secondary schools, even in higher education. Beyzen et al. (2017) highlighted that physics is often perceived as a challenging subject, and teaching should align with constructivist principles. Additionally, students' prior knowledge and misconceptions acquired during instruction can lead to misunderstandings of key concepts (Kubsch et al., 2020). To foster meaningful and lasting learning, these preconceptions, including misconceptions, need to be actively identified, questioned, and addressed during instruction.

Regarding what is required for effective problem solving are beliefs centered on one's learning and knowledge (Reddy, 2019). As teachers, we should choose appropriate tools to fulfill the needs and interests of individual students. The use of computer applications in problem-solving and experimental activities through virtual reality enables the visualization of abstract phenomena, providing immersive visual experiences that stimulate students' imagination and foster creativity. This approach helps learners generate diverse, feasible, and novel ideas and concepts (Hu et al., 2016). In this context, Kaymakci (2016) examined the reasoning learning model and suggested increasing the use of analogies in textbooks to promote meaningful learning, particularly to support students' transition from concrete to abstract operational thinking.

Park (2016) reported that involving learners in model-based learning using computer-assisted multiple representations can enhance scientific literacy by deepening their understanding through generating, evaluating, and revising their ideas. Similarly, Hakyolu & Bekiroglu (2016) highlighted the importance of collaborative interactions in linking knowledge construction with argumentation. The result of the investigation (Duran, 2016) about the student-centered approach made suggestions which become relevant for the current study. When students are provided with sufficient time and support, they are more likely to ask questions and attempt to answer those posed to them. Therefore, teachers should foster an environment that encourages questioning and allows adequate time for students to reflect on the questions. In student-centered learning, it is essential that all students have the opportunity to think critically and express their ideas. Their opinions should be respected, and when errors occur, teachers should provide constructive feedback to guide learning and understanding. There has been a growing shift toward student-centered learning; however, students often face challenges when transitioning abruptly from traditional, teacher-led practicals to fully student-centered learning activities (King *et al,* 2016).

Several researchers (McDermott, 1998; 2013; diSassa, 1998; Hammer, 1996; 2000; Minstrell, 1992; and Redish, 1994; 1999) indicated that in a teacher-centered approach, where instruction focuses primarily on presenting facts and skills, students rarely articulate their conceptual understanding during problem-solving and experimental activities. This approach assumes that learners will independently recognize the underlying structures within the content, which often limits active engagement and explicit demonstration of their knowledge.

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skills, students seldom articulate their conceptual understanding during problem-solving and experimental activities. This method assumes that learners will independently discern the underlying structures within the content, which often limits active engagement and explicit demonstration of their knowledge.

According to the research literature, Degene (2007) noted that traditional teaching methods and instructional strategies in science are not well-suited to achieving conceptual learning. It can be implied that cognitive skills such as problem-solving and experimentation will be affected in the same way. These setbacks in our classroom practices could be the reasons for lower achievement results obtained by students who sat for the Ethiopian secondary school leaving certificate examination administered and reported in 2022 by the Ministry of Education (MoE). Therefore, the problems to be addressed in this study were:

- unsuccessful association of physics concepts/principles in doing problem solving and experimentation, and
- Skill gaps in problem solving and experimentation (Heuvelen, 1991; Trumper, 2003) observed for the first year physics students as it also was evident in our existing instructional practice as a member of Arba Minch University.

Thus, the following research questions were posed to guide the study.

1. Will students being taught by CAMR score a statistically significant result in problem-solving and experimentation in mechanics compared to students being taught by TI?
2. Does the CAMR teaching method produce statistically significant improvements in problem-solving and experimentation performance for female students in a mechanics course compared to their peers?
3. Will formative assessment results of classroom activities correlate with achievement test results?

CAMR is a student-centered method that would be helpful to encourage students to practice problem-solving and experimentation based on basic models in mechanics through doing multiple representations for effective interactive engagement.

2. Methodology

This study employed a non-equivalent pre-test and post-test control group in design one targeting problem-solving as a dependent variable and within one group comparison in design two targeting

experimentation ability as the second dependent variable. Quantitative data were collected by performance tests for problem-solving and experimentation. Qualitative data were collected by conceptual test activities and focus group interviews.

The participants were first-year physics students (N = 34, M = 10, and F = 24) as experimental group, and first-year chemistry students (N = 45, M = 13 and F = 32) as control group were used in design one and the same experimental group was used in design two. It was unfortunate to get a second section in physics which was why I was forced to select chemistry students who were registered for the course. Two teachers for the experimental and control groups participated in design one and the researcher and laboratory assistant in design two.

The current study focuses on CAMR that was employed in teaching Newtonian mechanics courses along with distinct stage-by-stage cyclic learning episodes as shown in Fig 1.
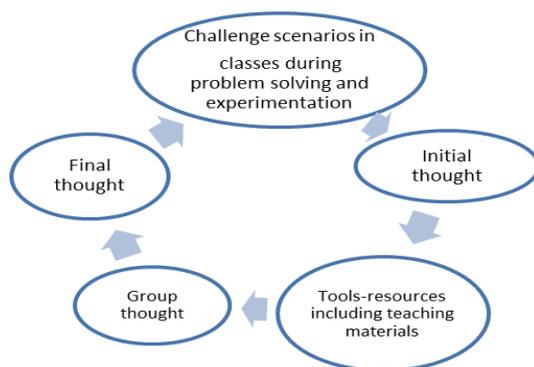

Figure 1: Stage-by-stage episodes of CAMR and each arrow corresponds with assessment and feedback

(Adopted and modified from Al-arfaj, 2011)

The illustration depicts stepwise or stage by stage instructional process.

Stage 1: Challenging scenarios emphasize topics related to the fundamental principles of mechanics.

Stage 2: The initial stage emphasizes abstraction and the idealization of real-world phenomena through model building during problem-solving and experimentation. This process involves developing models in various forms, including (i) conceptual models, (ii) assumption-based propositions (which involve estimating quantities and making approximations), (iii) graphical representations, and (iv) mathematical formulations.

Stage 3: Tools (computer modeling), resources and teaching materials help to realize creating models;

Stage 4: The group thought focuses on generating hypothesis and generalizations. This process consists of model building with multiple representations in a small group discussion;

Stage 5: The final stage emphasizes using models to construct meaning. This process involves reflection and evaluation to validate explanations and predictions about real physical phenomena, as well as examining connections, revising hypotheses, and refining generalizations.
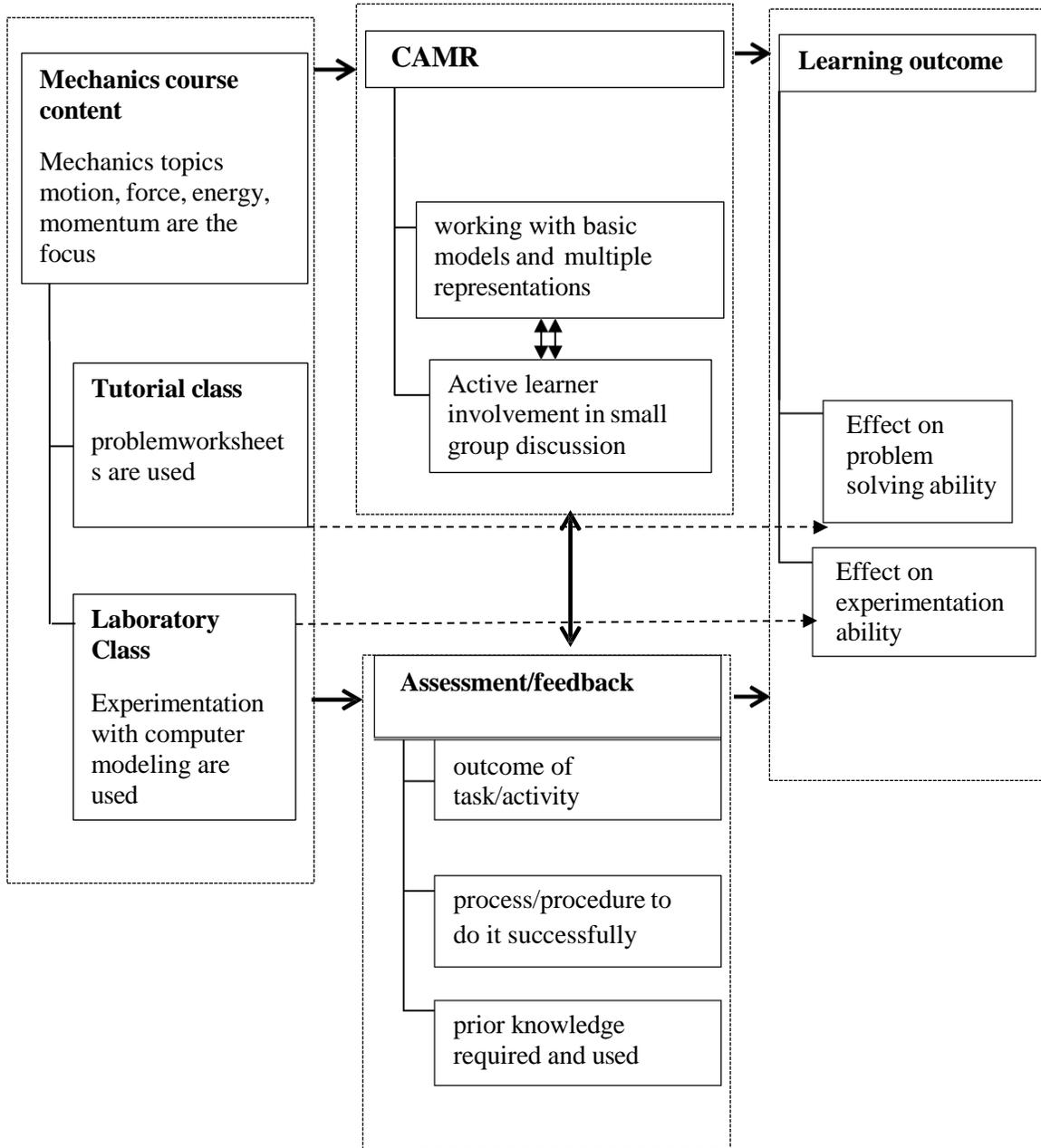

Figure 2: Conceptual framework

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The role of each component in the conceptual framework (Figure 2) is derived from the curriculum, although this study seeks greater integration and organization of these elements. The curriculum sequence begins with motion, followed by force, energy, momentum, and related topics, reflecting the learning progression in the mechanics course. Real-world phenomena in these areas can be represented using basic models, which can take multiple forms: scale models to illustrate spatial relationships, conceptual models that symbolically represent underlying structures, analogue models that use one physical system to model another, among others. Formative assessment and feedback support both teachers and students in monitoring learning progress, identifying errors, and implementing remedial measures. Misconceptions and mistakes are addressed through further clarification and explanation, ensuring deeper understanding and mastery of the concepts.

Sample lesson I

The lesson focuses on the given problem solving activity in the worksheet to be performed by CAMR stage-by-stage episodes. This activity was set for students to challenge their knowledge base on the first condition of equilibrium that they learned it in the lesson of Newton's first law. The problem-solving format (displayed in sample examples) guided the learner forward looking model-based strategies. Learners were guided to build models (predicted relations of variables) in different representations to describe events and processes in the context of the problem with the knowledge of basic models in mechanics.

The instructors of both the experimental and control groups set chapter-based problem worksheets. The problems for the treatment group were selected with the potential to engage the learner in a thoughtful course of actions through undertaking multiple representations based on basic models in mechanics.

Scientific argumentation and meaningful learning could be attained at the end of the CAMR cyclic stages. The assessment and feedback were practiced based on prescribed scoring procedures to come to the conclusion of the cyclic stages of CAMR.

Table 1: CAMR applied in problem solving activities

Question: For the systems to be in equilibrium, find the unknown tensions and masses.	**List of known information:**
	$F = 30N$
	$\theta = 60^0$
	Identify unknown: $T_1 = ?$; $T_2 = ?$ & m = ?
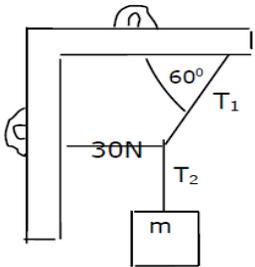
(1) Pictorial Representation
   Coordinate axes : x & y coordinate axes
   Symbols for quantities: T-tension; W-weight

(2) Physical representation:
2.1 object description
-The block can be represented by point mass (center of mass = C.M)
-The strings are ideal ones since they are massless & inexpensive
-The weight is a force vector through the C.M.
2.2 Force diagram: For the junction point of the three strings and for the block.

(i)   (ii)

(3) Conceptual model: The system under several forces model
Conceptual model was the system with balanced interaction forces. Students in small group applied 1st condition of equilibrium using force diagrams above where both $\sum F_x = 0$ and $\sum F_y = 0$ holds true for every part of the system.

(4) Mathematical Representations & Solution: Mathematical model was used as part of modeling in order to identify variables, formulate equations, and analyze possibilities.

Step 1 for the junction point, $\sum F_x = 0 \rightarrow 30N = T_1 \cos60^0 \rightarrow T_1 = 60N$,

$$\sum F_y = 0 \rightarrow T_2 = T_1 \sin60^0 = (60N)(0.87) = 52N$$

Step 2 for the block, $\sum F_y = 0 \rightarrow W = T_2 = 52N \rightarrow mg = 52N \rightarrow m = 5.2 \text{ kg}$

This was the solution for the first question and the same problem solving strategy was utilized for the rest two questions.

(5) Evaluation: Answer sheets of small group of students for these homework questions were assessed according to the scoring rubrics to check the correctness of the answers.

Sample lesson II

The lesson focuses on the given experiment on friction to be performed based on CAMR stage-by-stage episode. The lesson objective is for students to be able to: (i) mention the physical

principles used in the experiment; (ii) to deal with basic models; (iii) use physical principles and basic models to explain the experiment; and (iv) refine the modeling when it is needed.

For the first twenty minutes of the laboratory session, conceptual test activities were set to challenge students' knowledge base about friction in the work sheet. One of the conceptual questions was the following. A constant force (P) is applied to three identical boxes sliding across the floor, with each force acting in a different direction, as illustrated in the diagram below:
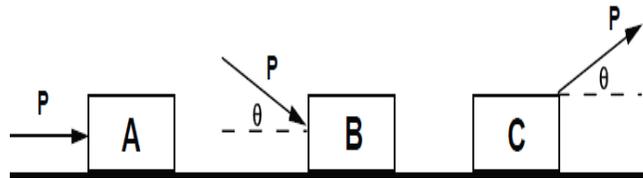

Figure 3: Forces in Different Directions

For the three boxes, which one experiences the greatest or least frictional force, or do they all experience the same? Explain your answer using appropriate free-body diagrams and Newton's second law. The instructor as well as the technical assistant has to give timely feedback on the performance of students and corrections are made based on the feedback until the conceptual understanding is up to the required level for them to perform the experiment effectively. Once again, CAMR is used to perform simulation experiments with the help of built-in instructions for computer simulations available in the software package and softcopy of the detail manual for the computer simulations was also available. Model building was the process in which the learner used a large number of different representations to describe events and processes in the simulated situations with the knowledge of basic models in mechanics.

The students in small groups were working interactively through discussion over the experimental investigation as part of the group thought activity. The degree of interactivity of the learner in simulation experimental activities was maximized through the available instruments and teaching materials such as written lab manuals, handouts, computers, and lab reporting format. The investigation was performed by doing multiple representations using computer software. Finally, they should check the value of the coefficient of static friction is greater than the coefficient of kinetic friction.
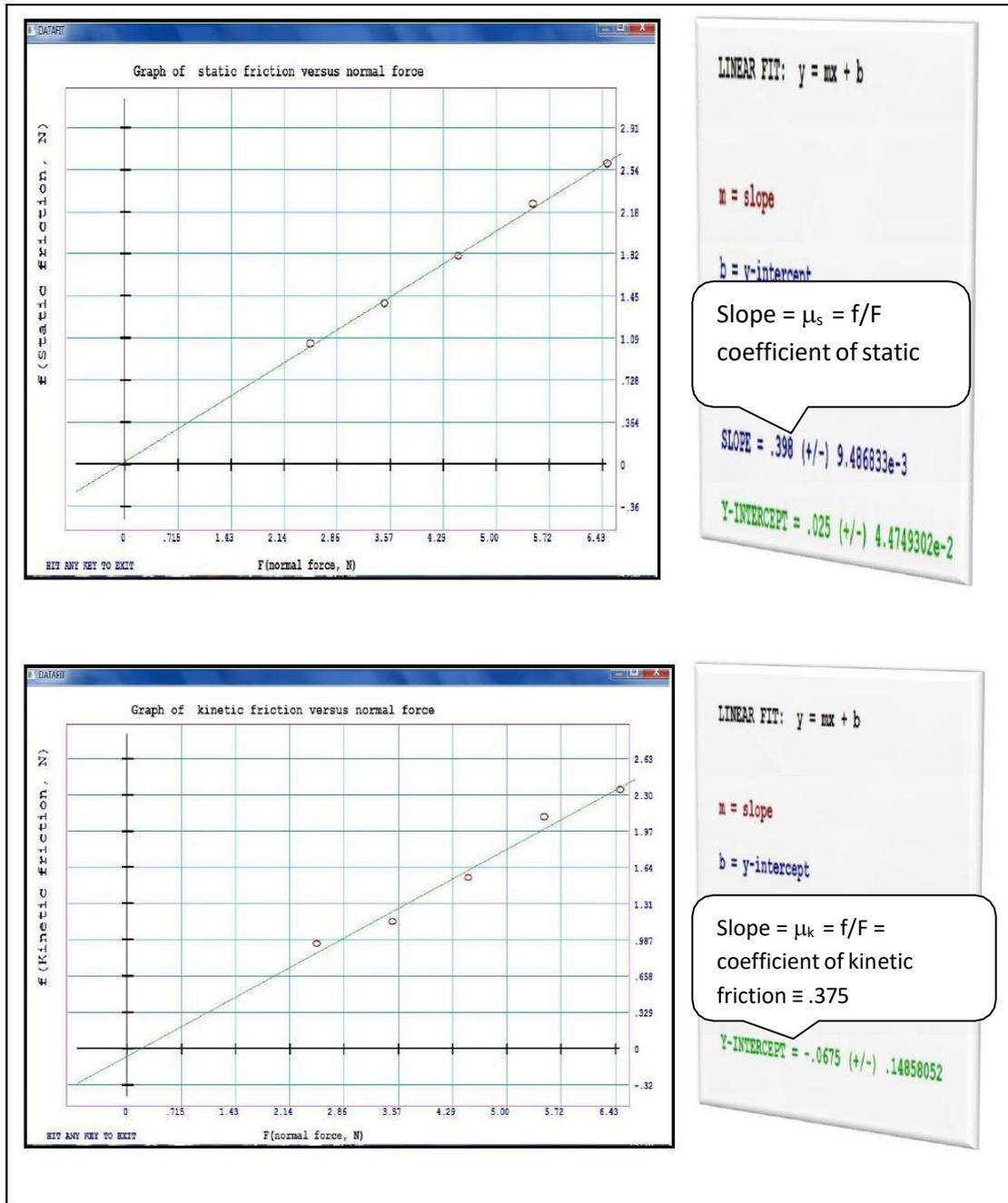
Figure 4: Graphical results for determination of coefficients of static & kinetic friction

The instruments for data collection are: (i) performance test to measure both dependent variables, namely problem-solving and experimentation. The performance test for problem-solving contained items scored out of 48 points of experimental performance on six simulation and physics experiments, separately each scored out of 18 points in line with scoring rubrics prepared for such purpose. (ii) conceptual questions (with 4 items) during problem-solving (iii) follow-up interview

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during experimentation was recorded (iv) written documents for certain worksheet questions and laboratory reports as part of the assessment and feedback were considered.

During the first week of the intervention period, inter-rater correlation coefficients were calculated in order to establish the reliability of the scoring rubrics for problem-solving and experimental performance. Based on scores from two assessors, the researcher, and an experienced staff member, the problem-solving had a calculated value of Kandull's tau .64, and the experimental got a calculated value of Kandull's tau .741. Both turned out to be significant at p=0.01 level indicating stability of the scoring rubrics. The performance tests for both problem-solving and experimentation were administered at post-test. Content validity as an indicator of the relevance of performance assessment tests in problem-solving and experimentation was established through decisions made together with subject instructors. Basically, the problems were taken from standard books and the experiments were standard experiments known worldwide. The researcher and the experienced teacher rated the test and there were inter-rater reliability between the two scores with calculated values of Pearson's correlation (r) equal to .78 and .809, respectively. Conceptual test activities were also used to collect data during tutorial and experimentation laboratory classes which were also taken from the text book. Moreover, focus group interview was also used to obtain qualitative data.

3. Results of the study

The teaching method and gender, as independent variables, along with their interaction, were found to have a statistically significant effect on the dependent variable, which is the problem-solving performance measured by the post-test ($\alpha = .05$).

Table 2: Two-Way Analysis of Variance (Two-Way ANOVA) on problem solving performance test

Source	Sum of squares	df	Mean Square	F	Sig.	η^2
Method	809.649	1	809.649	22.271	.000	.236
Gender	540.067	1	540.067	14.856	.000	.171
Interaction	307.243	1	307.243	8.451	.005	.105
Error	2617.507	72	36.354			

The ANOVA results presented in Table 2 show a statistically significant main effect for the teaching method, $F(1,72) = 22.27$, $p < .05$, indicating that the intervention was effective. The difference in mean

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scores between groups was substantial, with a partial eta-squared of .236, meaning that 23.6% of the variability in problem-solving performance scores could be attributed to the teaching method. Specifically, the CAMR method led to greater learning gains (M = 8.47) compared to the traditional lecture method (M = 3.66). A statistically significant main effect was also found for gender, $F(1,72) = 14.86$, $p < .05$, with a large effect size (partial eta-squared = .171), indicating that 17.1% of the variability in problem-solving performance was explained by gender. Besides, the teaching method and gender interaction was significant, $F(1,72) = 8.45$, $p < .05$, with a medium effect size (partial eta-squared = .105), suggesting that the impact of the teaching method differed for male and female students. Further analysis using an independent t-test revealed a significant difference in performance within the CAMR group: male students (M = 17.8) outperformed female students (M = 6.3), t = 3.39, df = 30, p = .002 < .05, indicating that gender moderated the effect of the CAMR teaching method on problem-solving performance.

Table 3: Two-Way Analysis of Variance (Two-Way ANOVA) on experimentation performance test scores

Source	Sum of Squares	df	Mean Square	F	Sig.	η^2
Method	40.33	1	40.33	10.89	.002	.266
Gender	1.8×10^5	1	1.8×10^5	.00	.998	.000
Interaction	.075	1	.075	.02	.89	.001
Error	111	30	3.7			

Similarly, for design two, the *ANOVA* analysis result in Table 3 indicated the main effect of the teaching method which was statistically significant $F(1,30) = 10.89$, *p*< .05. Thus, the CAMR teaching method applied to simulation experiments produced more learning advantage (M= 16.41) than traditional lecture method applied on the conventional physics experiments (M = 13.76). Partial η^2-eta squared was .266 (26.6 % of the variability of the subjects' scores in the experiment can be accounted for teaching method and considered large in magnitude). Gender was not the main effect, $F(1,30) = .00$, p > .05 and the interaction effect was not statistically significant, $F(1, 30) = .02$, *p*> .05. Thus, there was no statistically significant difference observed by gender for experimentation ability which could be due to the application in the small groups.

As presented in Table 3, there was no significant correlation between problem-solving activity scores and post-test scores, r = -.256, p = .156 > .05, indicating that performance in problem-solving activities was not consistently linked to post-test outcomes. This may be attributed to the fact that problem-solving activities were not always accompanied by timely formative assessment and feedback. In contrast, there was a statistically significant correlation between experimentation performance test scores and the assessment of experimentation activities, p = .028 < .05. This suggests a positive relationship: as scores on lab reports increased, corresponding experimentation post-test scores also tended to increase, indicating that performance in experimental tasks was influenced by engagement and assessment in related activities.

The correlation coefficients between the post-test scores and formative assessment scores of problem-solving and experimental activities were also calculated. Correlations between the post-test and scores of problem-solving activities were found as r = -.256 and p-value .156. On the other hand, the correlations between post-test and scores of experimentation activities were found as r = .531* and p-value .028.

When we see the excerpt of the record of a small group of students, who were engaged to solve the following question taken from the textbook, we describe constant-acceleration motion with the variables and parameters v_{xi}, v_{xf}, a_x, t and $x_f - x_i$ of the equations:

$$\text{(i) } v_{xf} = v_{xi} + a_x t$$

$$\text{(ii) } x_f - x_i = \frac{1}{2}(v_{xi} + v)$$

$$\text{(iii) } x_f - x_i = v_{xi}t + \frac{1}{2}a_x t^2$$

$$\text{(iv) } v^2_{xf} = v^2_{xi} + 2a_x(x_f - x_i)$$

The first doesn't involve $x_f - x_i$, the second does not contain a_x, the third omits v_{xf}, and the last leaves out t. So to complete the set there should be an equation not involving v_{xi}, but it is derived from the others. Students of the small group were engaged to solve the problem. They searched the set of equations from (i) to (iv) as mentioned in the question somewhere in the textbook. According to the records of the discussions which were going on among students along with the teacher, students finally understood the problem and acquired more equations that were not considering v_{xi}.

$$x_f - x_i = v_{xf}t - \frac{1}{2}at^2 \qquad (1)$$

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This new equation proved useful for enabling students to solve the previous problem more efficiently. To reinforce the knowledge gained, homework problems were assigned to small student groups, aligned with the problem-solving strategy. The structured format guided them to follow the steps of a forward-looking, model-based approach. Additionally, students were instructed to prepare for the upcoming discussion on projectile motion in the next tutorial session.

Consider the work of a small student group measuring acceleration along an air track, following detailed procedures provided in both the manual and built-in instructions. They recorded the collected data in a table and then analyzed it to calculate g, the acceleration due to gravity. The graph was drawn with a slope = m = 1/2 a = 1/2 g sinθ. The students had used data analysis software in the software package to obtain the graphs indicated in figure 5.

Figure 5: Example of graphs drawn by students that show x-t and x-t2 graphs

The software can easily calculate the slope of x vs t^2 graph and equate it with 1/2 a = 1/2 g sinθ. The slope of the graph was calculated to be 487 cm/s^2 or the same to say 9.74m/s^2 = g sinθ which

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helped them to estimate the value of g. The students were also encouraged to use a standardized laboratory reporting format in computer-based experiments.

The lesson concluded with reflections from both students and instructors to validate the outcomes of the problem-solving and experimental activities. This process aimed to promote meaning-making and ensure meaningful learning as students worked to understand and apply scientific models. The computer-based model was designed to engage students interactively, encouraging them to think critically and justify their reasoning using basic models. While not every model fits every phenomenon, the discussions and debates that arose provided students with opportunities to develop models appropriate for specific situations. The final evaluation stage served to verify the accuracy of step-by-step progress in experimentation and problem-solving, often through group discussions and oral presentations, supported by ongoing assessment and feedback.

There was, therefore, valid evidence that the CAMR teaching method was important. The result of focus group discussions indicated what students experienced in group work, weekly activities, and peer assistance were helpful in bringing learning gains in the course. A significant percentage of the students replied that they had a better understanding of basic models, laws, principles, and multiple representations in mechanics they used in problem-solving. The instructor was interviewed to cross-check the importance of CAMR for the reported learning gains and the response attuned to the report obtained from the students.

The content analysis indicated that students made significant progress in problem-solving performance. Every time the students strictly followed the CAMR, they understood the problem by searching the basic model in mechanics. The basic models were used to make multiple representations. Students in significant numbers thought that group work, laboratory reports, computer utility, weekly activities, and peer assistance as features of CAMR were helpful in learning the course. It was also revealed that due to the implementation of CAMR in teaching, students responded as they obtained a considerable understanding of laws and principles, basic models, and multiple representations in mechanics. They also responded that they gained practical skills in designing laboratory experiments, finding trends in data, working cooperatively, and oral presentations.

4. Discussion

Lin & Singh (2015) found that for quantitative problems involving strong alternative conceptions, merely guiding students to solve an analogous problem was insufficient to support most students in understanding the solution. However, additional scaffolding supports directly helped students examine and repair their knowledge elements involving alternative conceptions. The reason is that misconceptions, unless treated with appropriate teaching methods, could limit students' performance in problem-solving and experimentation as demonstrated in this study. Thus, active learner involvement in small group discussion through working with basic models and multiple representations, as elements of CAMR, can bring students' conceptual understanding to the level they can perform problem-solving and experimentation for better results.

The result obtained based on design one showed CAMR teaching method brought about better performance scores in problem-solving which is consistent with prior research works (Ornek, 2009; Vesenka et al., 2002). The application of CAMR in design two also brought a significant experimental performance for the effectiveness of CAMR and for students' conceptual development gains as well. Computer simulation in-line with the assessment methods is effective in both computer-based and hands-on activities (Ekmekci & Gulacar, 2015). Similarly, learners who are taught using computer simulation were happy with the approach used by Kibirige & Tsamago (2019).

Duran (2016) argues that the inquiry-based learning approach as a constructivist learning approach can contribute to students' use and development of critical thinking skills in problem-solving and experimentation activities. In addition, Raiz, Marcinkowski, & Faisal (2020) reported the effect of discovery learning on students' conceptual understanding and they found that the new approach significantly improved their conceptual understanding during laboratory activities. Brewe, Kramer & O'Brein (2009) pointed modeling instruction impacts students in a significant, positive manner in learning introductory physics courses. There is therefore supportive evidence about the effectiveness of CAMR when it is applied in problem-solving and experimentation that is revealed in this study. The overall impact of the intervention was reported as positive by both students and the teacher, with conceptual test results and focus group interviews indicating that it effectively supported student learning.

5. Conclusion

This study confirmed that the CAMR teaching method is both practical and effective in improving problem-solving and experimentation performance in mechanics courses. It also found that male students outperformed female students in problem-solving, while no significant gender difference was observed in experimentation performance. Additionally, a significant correlation was found between experimentation performance test scores and formative assessment scores of experimentation activities, whereas no significant correlation was observed for problem-solving activities.

6. Implications

The finding of the study implies that teaching organized knowledge is essential for the effective performance of problem-solving and experimentation tasks and activities. Overall, there is no single teaching strategy that works best in every classroom situation; therefore, future research should focus on testing and identifying new, effective instructional approaches.

Declaration of competing interest

The author declare that there is no conflict of interest in this study.

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