Study of Second-year Physics Students' Scientific Reasoning Ability and Knowledge of Simple Harmonic Motion through Guided Inquiry

Michael Gavriel de la Serna Reyes

A Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Physics (International Program)
Prince of Songkla University
2019

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I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

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Academic Year 2018

ABSTRACT

In the physics education literature, it has been reported that there is a disconnection between the progress of scientific reasoning skills and content knowledge. Scientific reasoning skills were not addressed with the content-rich pedagogical approach. This study is aimed at studying the effects of guided inquiry approach with the three-phase learning cycle to mitigate the problem. Design of the instructional intervention was targeted on the application of scientific thinking through class response system, lecture demonstration with a video, simulation, or experiment, as well as worksheet tasks and problems about simple harmonic motion. These activities were supported by the evaluation of one's own idea and small group or whole class discussions. The sample consisted of 26 participants in a vibrations and waves course at Prince of Songkla University. Lawson Classroom Test of Scientific Reasoning and standard simple harmonic motion problems were administered to them as pre- and posttests. Practically, no significant gain of overall scientific reasoning ability was observed. By model analysis, changes in mental models revealed that students moved toward better thinking pattern strategies on some subskills of scientific ability. Moreover, they developed to become better problem solvers in the context of simple harmonic motion.

ACKNOWLEDGEMENTS

This thesis cannot be achieved without the efforts of my adviser, Asst. Prof. Dr. Suttida Rakkapao. Thank you for always getting me back on track to fulfill my goals. Her warm disposition and genuine concern for others are worthy of emulation as an educator.

I am very grateful to my thesis committee, Dr. Thanida Sujarittham (Bansomdejchaopraya Rajabhat University) and Assoc. Prof. Dr. Sawasdee Yordkayhun (Prince of Songkla University) for their time and knowledge. My deep appreciation goes to Asst. Prof. Dr. Helmut Dürrast and Dr. Boonyarit Chatthong for their useful insights that helped me improve this work. My sincere gratitude also goes to the ajarns and experts who helped validate the instruments and allowed me to collect data.

To the second-year physics students of Prince of Songkla University (PSU), as well as to all the people who are part of the research, I am thankful for their keen participation. To the physics education group of PSU, Piten and Betavia for their valuable discussions with model analysis and item analysis. To Ahamad, Ardian, Chaw, Lae Lae, and Yuanxing, thank you for the amazing friendship and support.

I am indebted to the Thailand Center of Excellence in Physics, PSU Graduate School, and PSU Department of Physics for the grants to support my research. My honest appreciation for Thailand's Education Hub for ASEAN Countries scholarship that aided me financially throughout my study.

Lastly, my family to whom I dedicate my work. Although we are separated by the heavens or seas, you are always there to guide me.

CONTENTS

APPENDICES

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER 1

INTRODUCTION

1.1 Background of Study

It is often assumed that acquiring knowledge from a complicated subject such as physics would spontaneously help improve one’s scientific reasoning ability. To distinguish scientific reasoning ability from content knowledge, the former refers to domain-general skills or problem-solving strategies by applying the scientific method, while the latter involves the understanding of the concept about phenomena particular to a specific field (Zimmerman, 2000).

However, Bao and colleagues (2009) reported a disagreement of results between the development of physics content and scientific reasoning among university students. They used the Brief Electricity and Magnetism Assessment (BEMA) and Force Concept Inventory (FCI) to measure student understanding of physics concepts, while Lawson’s Test of Scientific Reasoning (LCTSR) was used to assess the level of students’ reasoning abilities. They found that Chinese students outperformed U.S. students in terms of BEMA and FCI scores, but both groups obtained similar LCTSR results. This advantage of Chinese students in learning content was ascribable to their rigid science and mathematics curriculum years before entering university. However, there was only a negligible effect on the development of Chinese students’ scientific reasoning abilities when they learned physics content from conventional teaching methods. Their research revealed that it is not the concepts learned that significantly promote higher order thinking skills, but rather how these concepts are taught to students.

Scientific reasoning as part of critical thinking can be transferred to students through direct instruction (L. Bao et al., 2009; Gerber, Cavallo, & Marek, 2001; Hanauer et al., 2006). For science majors, such as in physics, this skill is very important. Formal reasoning is a significant component of lifelong learning as well as in the future careers of these students. Formal operational reasoners can demonstrate abstract and rational thought. They have higher thinking skills which are integral to be able to devise reliable and well-grounded solutions to scientific problems (Fuller, Karplus, & Lawson, 1977). In addition, studies also presented a significant positive correlation between scientific reasoning and learning gains for interactive engagement classes (Coletta, Phillips, & Steinert, 2007; Nieminen, Savinainen, & Viiri, 2012). These classes consist of the active involvement of students, instead of the passive lectures and note-taking in conventional or traditional classes.

In the year 2017, the LCTSR was administered to sophomore physics students (N = 37) of Prince of Songkla University (PSU), Hat Yai. Results showed that the majority (86%) of the students were below the threshold of formal reasoning based on Piaget's theory of cognitive development (Anton E. Lawson, 1995). The data were consistent with literature which reported that students who were taught by instructions without explicit scientific reasoning have not reached the formal reasoning stage and lacked enough experience in applying appropriate logic to hypothetical situations in most contexts (Moore & Rubbo, 2012; Neimark, 1979).

Moreover, an achievement test related to simple harmonic motion (SHM) given after instruction to the same group of students who took the LCTSR was examined. The problem involved the standard oscillating mass on a horizontal spring and asked students to express basic physics quantities. It was found that many students held dominant and recurrent misconceptions associated with the direction of vectors, algebraic sign in equations, units of physical quantities, and phase. These findings contained similarities with other research studies concerned with students' ideas from courses in intermediate-level mechanics and vibrations and waves (Ambrose, 2004; Somroob & Wattanakasiwich, 2017; Tongnopparat, Poonyawatpornkul, & Wattanakasiwich, 2014).

These preliminary results demonstrated that the sample group (*N* = 37) in 2017 had low scientific reasoning abilities and held some difficulties in physics concepts after a common instruction. In addition to calls for reform in the literature as mentioned earlier, it suggests that a class intervention is necessary for the course and should demand students to practice their reasoning skills for them to improve it and develop their conceptual understanding in physics. At PSU, the vibrations and waves course offered for physics majors provided a convenient opportunity to conduct the present study. The guided inquiry approach was integrated with the three-phase learning cycle as it is known to stimulate attitudes toward scientific inquiry or habits of mind (Karplus, 1980; Anton E. Lawson & Karplus, 2002). The instructional intervention was applied to the cohort of students (*N* = 26) in 2018 and evaluated through statistical analysis, model analysis, and case observations from students' responses. This work will contribute to the understanding of the effect of the learning cycle in terms of scientific reasoning to second-year Thai physics majors, as well as their ideas about SHM.

1.2 Purpose of the Thesis

In response to the students’ general scientific reasoning abilities and difficulties with simple harmonic motion, the objectives of this research are as follows:

1) to study the scientific reasoning skills of students through guided inquiry;

2) to promote students’ content knowledge in the context of simple harmonic motion through guided inquiry.

1.3 Variables of the Study

The identification of variables was crucial for the quasi-experimental research design to ascertain the effectiveness of the study. As in any scientific method, three variable types were considered namely, independent, dependent, and control variable. The independent variable is often called explanatory and is the one manipulated by the researcher, whereas the dependent variable is called the response because it is the variable that is gauged for variations after the experiment. The hypothesis considers the association between the independent and dependent variables or whether the independent variable predicts the dependent variable (Field, 2011; Sheskin, 2011). Moreover, some variables had to be controlled or fixed constant to avoid confounding the experiment. These confounding variables may interfere with the independent variable which may also yield an effect on the dependent variable (Nolan & Heinzen, 2011).

In the current study, the independent variable was the instructional approach using the three-phase learning cycle through guided inquiry. This predictor was hypothesized to influence students’ reasoning and understanding. The dependent variables were the scientific reasoning skills and knowledge about SHM of second-year physics students. These outcomes can be assessed through their performance in the LCTSR and SHM problems. Control variables were the medium of instruction, instructor, and background information of students. Students had to be taught using the Thai language with the same instructor to ensure that the learning process came from the treatment. Pretests were also administered to determine their pre-existing abilities and what they already know.

CHAPTER 2

RELATED LITERATURE

2.1 Scientific Reasoning

Piaget’s theory of cognitive development made an impact to science educators. There was evidence that displayed the flaw of the educational system. It was found that a considerable student population progresses slowly throughout their education in terms of thinking in abstract and complex ways (Arnold B. Arons & Karplus, 1976). In the early years of physics education research, there were researchers who already recognized the need to address instruction through Piaget’s ideas (A. B. Arons, 1976; Karplus & Butts, 1977).

It is worth noting that formal thought depends on the field of interest and experience in the subject area (Shaffer & Kipp, 2014). For example, mean scores in a test for scientific reasoning varied among different college majors (Maloney, 1981). It becomes a predicament for the learner if this skill is a requisite in learning about the subject. Hence, scientific reasoning should be cultivated through practice and direct instruction in formal education.

Generally, scientific reasoning can be both viewed as a skill and ability. It is a skill associated with the human process of inquiry, experimentation, evidence evaluation, inference, and argumentation. Conclusions acquired from the process lie outside the limits of immediate experience. Its purpose is to construct or change ideas in the physical and social realms (Zimmerman, 2007). Furthermore, scientific reasoning is the ability to construct understanding, to recognize core ideas in science, and to influence others to do something related to those core ideas. In fact, some countries focus on the promotion of reasoning ability in educating citizens, especially in science and mathematics education. This strategy of thinking is a principal theme in scientific literacy (Antone E. Lawson, 2004). As described by the *National Science Education Standards* (1996), literacy encompasses personal decision making, participation in civic and cultural affairs, and economic productivity.

The two main approaches to studying scientific thinking are the domain-specific and domain-general approach. The former is engaged in the development of conceptual knowledge in content domains, while the latter is concerned with hypothesis generation, experimental design, and evidence evaluation (Zimmerman, 2000). Lawson (1978) developed a test, which assumes domain generality, based on the theoretical framework of Piaget. He defined conservation of mass, proportional reasoning, identifying and controlling variables, probabilistic reasoning, correlational reasoning, and hypothetico-deductive reasoning as measures of scientific reasoning ability.

Reasoning ability is considered as one of the predictors of success in education. Studies reported a statistically significant positive correlation between formal reasoning and academic achievement, as demonstrated by students' conceptual understanding and representational consistency (Coletta & Phillips, 2005; Moore & Rubbo, 2012; Nieminen et al., 2012). Results from the study of Ding (2014) further validate the causal model that reasoning skill is most likely a hidden variable behind students' learning gains. Moreover, Coletta and colleagues (2007) stressed the importance of assessing the scientific reasoning ability of students to properly evaluate the class and attend to the needs of low-achieving students.

Learning through inquiry can be adopted to help students appreciate the nature of science and deepen their understanding of the scientific method. Effective transfer of learning is achieved to mold students as proficient critical thinkers, which is useful for them even beyond school (Iyengar et al., 2008; Linn, 2006). These factors show how the advancement of scientific reasoning has far-reaching implications for teachers and learners alike.

2.2 Simple Harmonic Motion

The content domain of oscillatory motion, particularly simple harmonic motion (SHM), was the focus of this work. Oscillation, or frequently called vibration if applied to mechanical systems, is an example of motion which is periodic or characterized by a repetitive movement that exhibits a certain pattern. When the restoring force or the acceleration of the body is directly proportional to its displacement as it oscillates from the equilibrium point, the physical system is known to be in SHM.

Throughout history, SHM among other scientific endeavors has earned its place in stimulating the curiosity of the human mind. One of the earliest figures is Galileo Galilei who detected periodicity from the swinging motion of a simple pendulum probably in the cathedral at Pisa. His observation started a spurt of many areas of investigation (Baker & Blackburn, 2005). The significance of SHM is discernible through its prevalence from classical physics to modern physics, as well as in other fields of science, engineering, and technology.

In most standard textbooks for introductory algebra- and calculus-based physics courses (Walker, Resnick, & Halliday, 2014; H. D. Young, Freedman, Ford, & Sears, 2016), there are a wealth of practical problems inherently related to one of the most basic forms of oscillatory motion. This type of motion is fundamental in various areas. The study of oscillations and associated wave phenomena is grounded in a thorough understanding of SHM. So that even textbooks intended for an intermediate course about vibrations and waves commence with the exposition of the SHM topic (King, 2009; Pain, 2008).

SHM is commonly taught in university as part of introductory physics or in the sophomore-level vibrations and waves course. Most concepts in mechanics are combined and studied in greater detail as the student progresses. As a result, student difficulties are compounded in addition to their previous misconceptions.

The constructivist theory of learning posits that students have their own existing knowledge regarding natural phenomena and they use these ideas based from current and past experiences to modify their cognitive framework (Redish, 1994, 2003). Hence conceptions of students about SHM, which are contrary to scientifically accepted notions, should be considered as it is critical in their learning. These alternative conceptions were grouped according to the general understanding of the physics concept, ability to solve quantitative problems, and fluency in different representations, as summarized in Table 2.1. Conceptual understanding can be probed with the explanation or reasoning about the physical situation. Quantitative questions were also employed to assess the ability of students in problem-solving. These included numerical computation, manipulation of variables, and derivation of a physical parameter. Finally, representational fluency involved graphical analysis, interpreting diagrams, translating graphs to equations or vice versa.

Table 2.1. Students’ ideas with SHM based on literature.

	SHM Misconception	References
Conceptual understanding	Various physical quantities may evoke conflicting connotations with respect to its scientific definition.	(Parnafes, 2007, 2010)
	Oscillatory motion can be considered SHM if it exhibits periodicity even though the restoring force is not directly proportional with displacement.	(Allbaugh, 2003; Karamustafaoğlu, 2012, 2012; Meldawati, 2017; Parnafes, 2010; Somroob & Wattanakasiwich, 2017; Tongnopparat et al., 2014)
	Speed is constant within one period of oscillation.	
	Velocity is at a minimum where restoring force on the object is zero.	
	When velocity is highest, acceleration also has the highest value.	
	Acceleration is zero where the velocity is zero.	
	Acceleration is maximum at equilibrium position.	
	Restoring force and acceleration are constantly in the opposite direction throughout the motion.	
	Gravity contributes to the oscillation of a vertical spring-mass system.	

	Frequency is associated with amplitude. Period depends on amplitude.	(Ambrose, 2007; Frank, Kanim, & Gomez, 2008; Inhelder & Piaget, 2013; Parnafes, 2010; Somroob & Wattanakasiwich, 2017; Tongnopparat et al., 2014)
Quantitative ability	Force of gravity in the differential equation Parameter from the time-dependent functions Appropriate equation to use	(Meldawati, 2017; Tongnopparat et al., 2014; N. T. Young & Heckler, 2018)
Representational fluency	Relations among the graphs of displacement versus time, velocity versus time, and acceleration versus time Interpretation of phase from the harmonic equation Identifying physical quantities from the equation or graph Reading graphs as in period is half of one cycle.	(Doughty, 2013; Meldawati, 2017; Somroob & Wattanakasiwich, 2017; Tongnopparat et al., 2014; N. T. Young & Heckler, 2018)

2.3 Guided Inquiry

Learning that reflects the process of scientific inquiry engages students through an investigative process imitating the work of a scientist. It necessitates participants to appreciate the nature of inquiry and how it can be used to generate new knowledge in science. Educators should ensure the immersion of students into activities of scientific inquiry and their realization of its importance (*Inquiry and the National Science Education Standards*, 2000).

In guided inquiry (Colburn, 2000), students are supported by the facilitator by posing problems worthy of investigation. Then, they continue by themselves on how to conduct the investigation, which normally forwards into an open inquiry. However, the facilitator intervenes if an elaborate concept that is not easily observable is introduced. Students are induced to practice scientific reasoning and think critically about important physical concepts. Usually, they undergo a process of guided inquiry as they perform tasks in small groups together with a facilitator. The model is grounded on the constructivist learning theory where teachers act as facilitators to students who actively participate in the learning process.

A three-phase learning cycle shown in Figure 2.1 is essentially constructed onto the idea of guided inquiry. Thus, the guided inquiry approach is central to the learning cycle. These cycles are integrated into activities that stimulate scientific inquiry. The learning cycle was initiated by the Science Curriculum Improvement Study (Karplus & Butts, 1977). Its process involves three phases which are interconnected through a cycle. In the model, students' ideas are elicited as they perform tasks and confront known common mistakes (exploration phase). Students then invent new models to resolve the conflict between a new concept and their existing or previous knowledge (concept introduction phase). This newly built model is then applied across different contexts that pertain to the same physics concept (concept application) (Fuller, 2009; Anton E. Lawson & Karplus, 2002). Evaluation and discussion through the facilitator and peers can be integrated at any phase of the learning cycle.

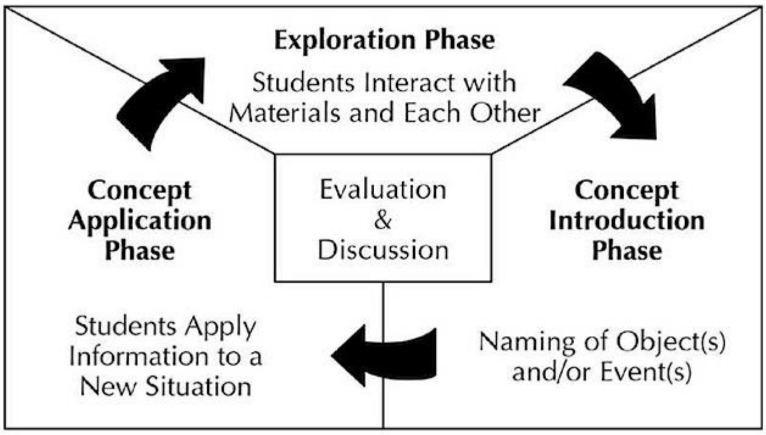


Figure 2.1. The 3-phase learning cycle (Karplus & Butts, 1977).

CHAPTER 3

METHODS

3.1 Sample Context

This study was conducted at Hat Yai campus, Prince of Songkla University, which is considered as the main university in southern Thailand. It is one of the national research universities of the country. Its physics department has a four-year Bachelor of Science in Physics program. Every year, there are around 20-40 freshmen students who register to the department as a physics major. The vibrations and waves course (code: 332-203) is part of its undergraduate curriculum and is offered in the first semester for second-year students. The present study was conducted on this course and a sample of students. It followed a quasi-experimental research design with a sample size of $N = 26$ physics majors for the academic year 2018. The group was effectively reduced to this number because of matched pre- and posttests.

3.2 Assessment Instruments

Pre- and posttests related to scientific reasoning and simple harmonic motion were utilized to evaluate the instructional intervention. In this section, a description of these instruments is presented, and their psychometric properties are also discussed.

3.2.1 Lawson Classroom Test of Scientific Reasoning

Lawson Classroom Test of Scientific Reasoning (LCTSR) is an assessment of scientific reasoning ability derived from Piagetian tasks (Anton E. Lawson, 1978). The former open-ended version that tests students’ formal reasoning was revised as a 24-

item instrument with a two-tier multiple-choice design (Anton E. Lawson, 2000), which can be found in Appendix A.. This test prompts students of their answer in the first tier and corresponding reason to their answer in the second tier. LCTSR measures students' scientific reasoning skills in six dimensions: 1) conservation of mass and volume, 2) proportional reasoning, 3) control of variables, 4) probabilistic reasoning, 5) correlational reasoning, and 6) hypothetico-deductive reasoning. Items were grouped together according to what subskill they assessed as shown in Appendix A. The validity of LCTSR was confirmed by Ding (2014) and Bao and colleagues (2018). In the present study, both individual and pair scoring in the data analysis were adopted. In the pair scoring scheme, students would receive one credit for responding to both tiers correctly. For this full score of 12, it was used to categorize students in terms of their level of scientific reasoning. There were three levels of scientific reasoning abilities that were identified as follows: 1) concrete operational (0-4), 2) transitional (5-8), and 3) formal operational (9-12) reasoners (Anton E. Lawson, 1995). On the other hand, each item was scored individually with 24 as the total score for statistical and model analyses to conveniently compare the results between the two investigations. Moreover, the current study emphasized the importance of taking into consideration the potential manifestations of intermediate learning from basic factual recall to insightful knowledge and reasoning.

The LCTSR was translated into Thai language and back-translated to English by a group of Thai physics professors. Inconsistent items were carefully checked and revised. Internal consistency reliability of the LCTSR was determined to be α = 0.82 from a cohort of students (N = 574) in another course. This measure indicated that the items were efficient in assessing scientific reasoning and no redundant questions were found. The result was found to be acceptable and comparable to the study of Bao and colleagues (2018). Based on these findings, we found it useful for the purpose of the present study, in which there were N = 26 students with matched pre- and posttest administrations of the same translated version.

3.2.2 Simple Harmonic Motion Problems

To measure students' content knowledge about simple harmonic motion (SHM), a set of related problems were used. The pretest problem was utilized for previous cohorts of students and the questions were refined to be readily understood by students. The posttest was modified carefully and detailed accordingly based on the pretest. As shown in Appendix B, pre- and posttest problems included the mass-spring system and bungee jumper, respectively. The set of items before and after the intervention were deliberately altered to prevent test-retest effects (Henderson, 2002; Otter, Mellenbergh, & Glopper, 1995) in a participant when answering the questions since these assessments were administered in a duration of fewer than five weeks. However, both pre- and post-assessments were equivalent with regards to the physics principles they pertain to.

Understanding of fundamental concepts is probed by the assessments namely, displacement, velocity, acceleration, period, angular frequency, amplitude, phase constant, potential energy, kinetic energy, and total energy in simple harmonic motion. Each test integrates six items through a given physical situation, that is the mass-spring system or bungee jumper. The scoring rubric created by McDaniel and colleagues (2016) shown in Table 3.1 was adopted. This rubric was slightly modified to suit the questions used in the assessment of students to the SHM problems. It has four components of problem-solving ability namely, translation, execution accuracy, evaluation, and planning coherence. The rating of each component ranges from 0 to 3 with a corresponding description when compared to a student's solution.

Table 3.1. Scoring rubric for SHM problems adopted from McDaniel and colleagues (2016).

Component	0	1	2	3
Translation	no diagram	major misinterpretations in diagram	minor misinterpretations in diagram	complete and fully accurate diagram
Execution accuracy	inappropriate or incomplete solution or did not arrive at a final solution	major mistakes in reasoning or application of physics principles	minor mistakes in reasoning or application of physics principles	completely correct and appropriate solution
Evaluation	no meaningful evaluation or no solution	evaluation was present but elements or reasoning was missing or incorrect	well thought out, meaningful, and accurate reflection on one of the three plausibility features	well thought out, meaningful, and accurate reflection on at least two of the three plausibility features
Planning coherence	plan of attack was missing or meaningless	plan of attack had major inconsistencies	plan of attack had minor inconsistencies	logical plan of attacking the problem

This rubric captures how expert-like an individual is in terms of problem-solving ability, which consequently affects their conceptual comprehension of the topic (Docktor, Strand, Mestre, & Ross, 2015; Heller & Hollabaugh, 1992). Inter-rater agreement of the scoring rubric used for the assessment of knowledge in simple harmonic motion was 0.99 according to McDaniel and colleagues (2016). In addition, its intra-rater reliability in the current study was found to be 0.97.

3.3 Overview of the Research Process

To effectively conduct research on students' reasoning ability and knowledge with SHM, the flowchart process shown in Figure 3.1 was followed. It commenced with the identification of the same issue in literature which was also found with second-year physics students' scientific reasoning at Prince of Songkla University and the drawback of the content-rich pedagogical method as backed up by L. Bao and his colleagues' (2009) study. In addition, difficulties with the SHM topic were examined in the literature, as well as in the Thai vibrations and waves context in the present study. More relevant information was acquired from literature to address the research problem. This part of the process was carried out throughout the investigation if necessary. It was then hypothesized that a designed intervention based on the three-phase learning cycle would improve students' reasoning ability and knowledge with SHM. The study focused on the cause and effect of the pedagogical intervention through observations such as assessments about scientific reasoning and understanding of SHM. The study approach is concerned with the conduct of scientific inquiry to address the hypothesis, whereas the guided inquiry instruction was designed to mitigate the problem. Moreover, data obtained from these observations were processed accordingly based on its form and the research plan. Then, data were collected using the instruments and applied to the sample context as discussed previously. The guided inquiry instruction detailed in the next section was implemented between the pre- and posttest administrations. Consequently, the intervention was evaluated through statistical analysis, model analysis, and narratives of students' solutions. Results of the study were then interpreted through hypothesis testing with Yes = accept and No = reject. Finally, results were reported to address the objectives of the study. It can be noted that symbols presented in Figure 3.1 denote the following meanings: ellipse = start/stop terminal, extended hexagon = preparation, rectangle = process, diamond = decision, and circle = decision indicator.

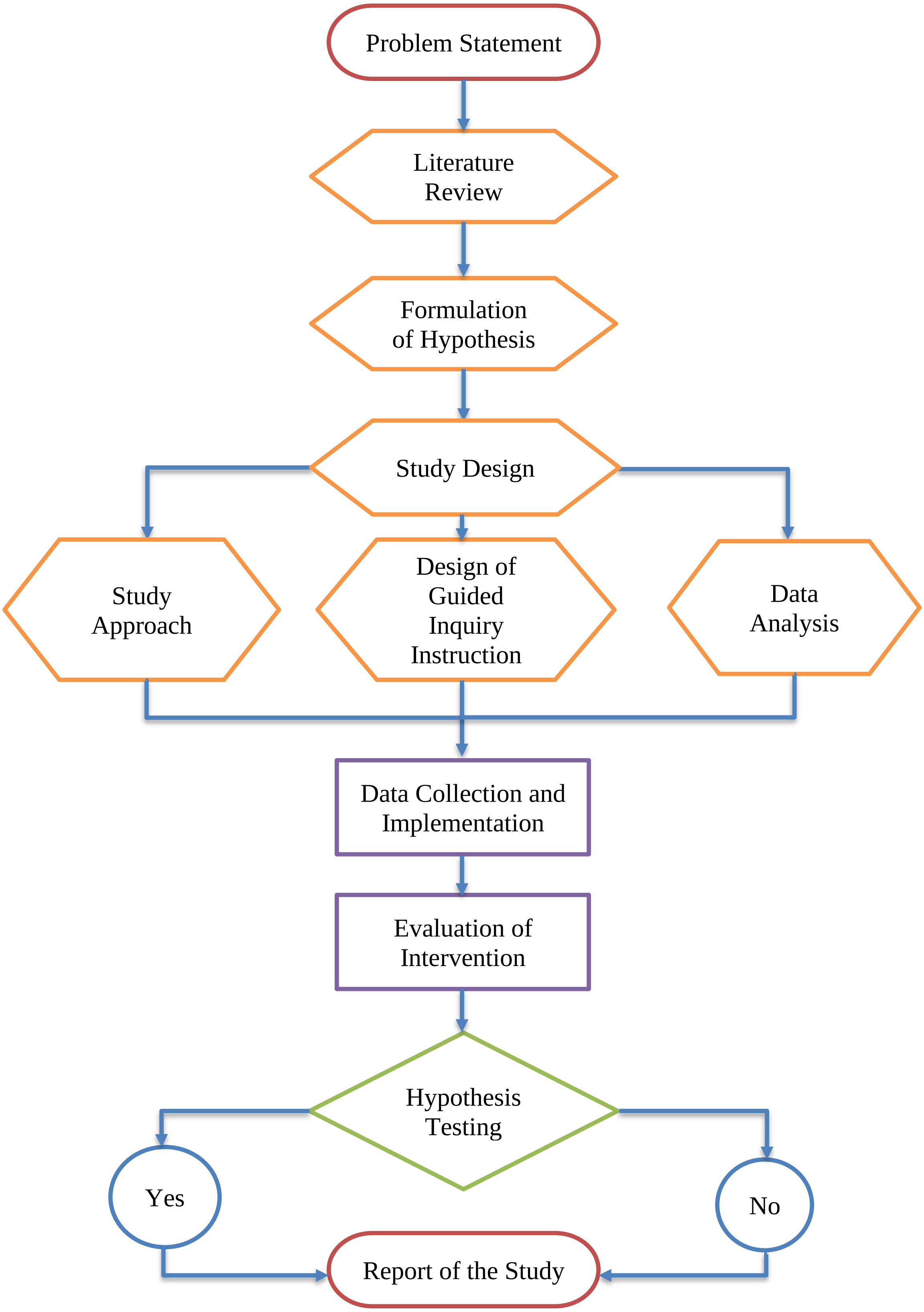


Figure 3.1. Flowchart of research methodology.

3.4 Design of Guided Inquiry Instruction

The course objectives of the unit of SHM for the vibrations and waves are shown in Figure 3.2. Lecture notes based on standard course texts (King, 2009; Pain, 2008; H. D. Young et al., 2016) were provided through the learning management system at the beginning of the semester.

Vibrations and Waves Course (332-203)

I. Topic: Simple Harmonic Motion

II. Learning Objectives

Students will be able to:

1. define and use the quantities and units involved in describing simple harmonic motion;
2. relate displacement, velocity, acceleration, and restoring force vectors to the physical phenomenon with an emphasis on direction and algebraic signs;
3. interpret displacement, velocity, and acceleration as functions of time;
4. illustrate and analyze displacement-time, velocity-time, acceleration-time graphs;
5. calculate angular frequency, amplitude, phase constant, and energy in simple harmonic motion;
6. apply scientific reasoning skills in learning about simple harmonic motion.

Figure 3.2. Objectives for the SHM topic.

As summarized in Table 3.2, class activities in the 2018 cohort can be compared with the previous 2017 cohort of the same vibrations and waves course. Phase 1, 2, and 3 correspond to the three phases of concept exploration, introduction, and application in the learning cycle. The intervention was incorporated into the lecture and consisted of four class periods in total with 90 minutes of allotted time per period. There was no specific seating arrangement for students to be comfortable to discuss with their peers when they are asked to form small groups. Activities intended to promote interactive engagement were fitted to the 3-phase learning cycle (Fuller, 2009; Karplus & Butts, 1977; Anton E. Lawson & Karplus, 2002) through the guided inquiry approach. The sessions which followed the 3-phase learning cycle were also targeted for the six dimensions of LCTSR. This strategy was purposely integrated into the course to develop both content knowledge in SHM and scientific reasoning skills of students. How the activities helped improved each scientific reasoning subskill and the effect of the intervention are explained in the succeeding chapter.

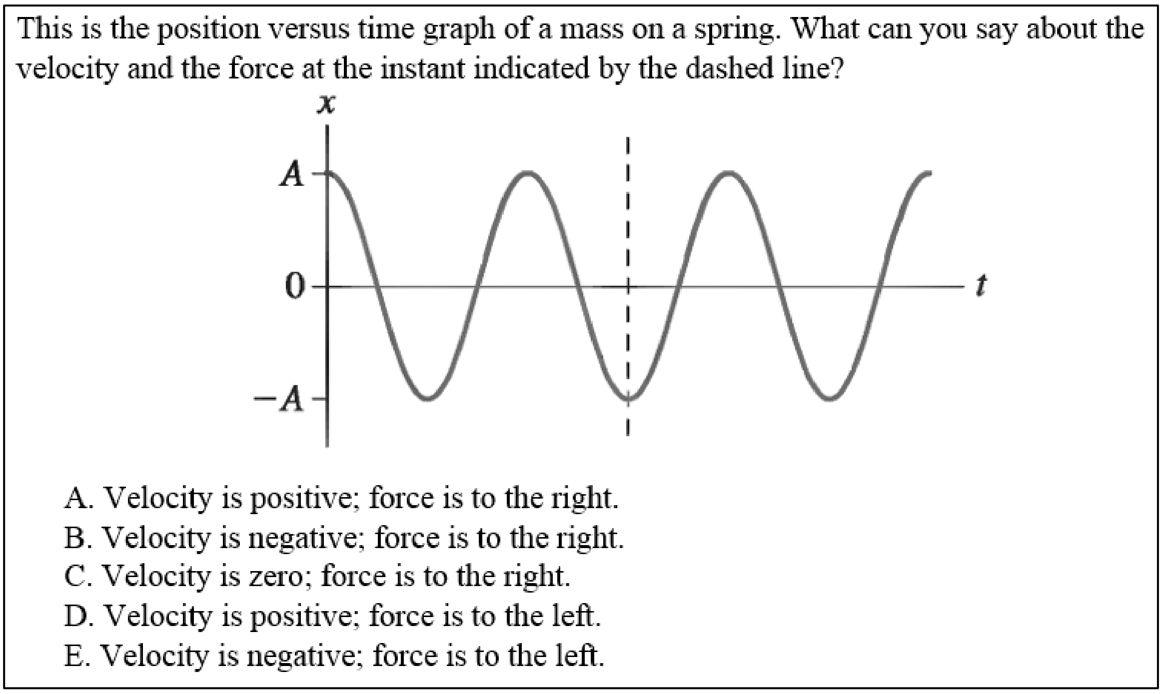
Table 3.2. Comparison of class activities between year 2017 and 2018.

	2017	2018
1st Period	- SHM video demonstration (periodic motion examples) [10 min.] - Interactive demonstrations and standard lecture led by two instructors about SHM properties and energy [80 min.] Demo 1: measure and calculate the frequency of a mass-spring system when regarding and disregarding the spring’s mass Demo 2: measure and calculate the frequency of a mass-spring system when the connection is in series and parallel with another spring	- SHM video demonstration (periodic motion examples) [10 min.] - standard lecture [80 min.]
2nd Period	- Interactive demonstrations and standard lecture led by two instructors about SHM properties and energy [90 min.]	- Session A: Qualitative analysis of motion [50 min.] Phase 1: worksheet task (stretched spring diagram)

	Demo 3: measure and calculate the frequency of a simple pendulum Demo 4: measure and calculate the frequency of a physical pendulum	Phase 2: uniform circular motion and SHM simulation Phase 3: follow-up question (compressed spring diagram) - Session B: Differential equation of motion [40 min.] Phase 1: worksheet task (simple pendulum) Phase 2: simple pendulum demonstration Phase 3: follow-up question (physical pendulum)
3rd Period	- solving challenge SHM problems by students who worked as a group and discussed to the whole class [90 min.]	- Session B (continuation) [50 min.] - Session C: Displacement, velocity, acceleration of SHM – Expressing position as a function of time & Velocity and acceleration of SHM [40 min.] Phase 1: worksheet task (expression to graph) Phase 2: student-led discussion of graphs Phase 3: follow-up question (graph to expression)
4th Period	- solving challenge SHM problems by students who worked as a group and discussed to the whole class [90 min.]	- Session D: Constant SHM parameters [50 min.] Phase 1: worksheet task (amplitude, period, angular frequency, phase constant, energy equations) Phase 2: student-led discussion of constant parameters and energy simulation Phase 3: follow-up question (initial speed and energy bar charts) - Session E: Factors affecting the vibration period [40 min.] Phase 1: worksheet task (period equations) Phase 2: simulation of parameters that influence period Phase 3: follow-up question (displacement versus time graphs)

The instructional method was specifically selected as it was suitable for the course and it is known to develop scientific reasoning ability while at the same time learning content knowledge (Carmel, Jessa, & Yezierski, 2015; Anton E. Lawson, 2001; Anton E. Lawson & Wollman, 1976). Implementation of the pedagogical approach, which demands interaction among the students and the instructor, is convenient because the class size was small, and it can be managed with minimal effort. Immediate feedback can be provided to the students while they are accomplishing the tasks. Moreover, the intervention does not require elaborate laboratory apparatus and it can easily be adopted with different classroom settings.

In the class, students were furnished with worksheets based on *Intermediate Mechanics Tutorials* (Ambrose & Wittmann, n.d.). The modified worksheets can be found in Appendix B. These worksheets pose questions related to SHM concepts in its task problems (concept exploration). Cognitive conflict occurs as they are presented with the concept through the student-led presentation to the problem solution or class demonstration in a form of video or simulation (concept introduction). The newly formed concept is tested with follow-up questions (concept application). These activities cause students to exercise their scientific reasoning skills through a series of cycles from one concept to another. Class response system was also used through *Kahoot* (https://kahoot.com/) as a formative assessment to students' understanding of the lesson. Figure 3.3 shows one example of the checkpoint question.



This is the position versus time graph of a mass on a spring. What can you say about the velocity and the force at the instant indicated by the dashed line?

A. Velocity is positive; force is to the right.
B. Velocity is negative; force is to the right.
C. Velocity is zero; force is to the right.
D. Velocity is positive; force is to the left.
E. Velocity is negative; force is to the left.

Figure 3.3. A *Kahoot* question related to graph.

3.5 Evaluation of Intervention

In line with the purpose of examining the effects of the designed instructional approach, data obtained from LCTSR and SHM problems were analyzed with statistics. Model analysis was applied for the LCTSR data in order to obtain a detailed investigation. Solutions to the SHM problems were also studied by case.

3.5.1 Statistical Analysis

Mean scores and corresponding standard deviations were computed for LCTSR and SHM problems. Standard deviations were shown as error bars in the graphs to indicate the typical difference between the scores and their average. In addition, it determined whether a score belonged within the typical spread of data. Conversion to percentages permitted convenient comparisons across scientific reasoning dimensions and problem-solving components. Usually, a dependent (paired) t-test is conducted to examine the difference between means, in which the same sample existed in two different experimental conditions such as in a pre- and posttest study design. However, this parametric test has the assumption that the sampling distribution is adequately normal, and data is at an interval measurement level. The distribution of score differences between pre- and posttest was assessed qualitatively with a histogram. Identification of measurement levels adhered to the classification of Stevens (1946). If it is found that the data disagree with either of the assumptions which are usually observed for small sized samples, the alternative Wilcoxon signed-rank test is used (Field, 2011). This test yields the probability that the difference between two conditions is caused by the randomness in sampling. However, statistical significance varies due to how big the sample is or the precision of the measurement (Wasserstein & Lazar, 2016). Thus, in addition to statistical significance, the effect size (also called magnitude of treatment effect) was reported as recommended also by Nissen and colleagues (2018). It shows the importance of the difference in scores and accounts for the influence of the number of students and their variation within the group. In the current study, the effect size estimate (Rosenthal, 1991) was given by

$$r = \frac{z}{\sqrt{N}} \tag{1}$$

where N is the number of participants and z is the z-score from the Wilcoxon signed-rank test. The magnitude of an effect is set as small ($r \approx |.10| - |.23|$), medium ($r \approx |.24| - |.36|$), and large ($r \geq |.37|$) based on Cohen (1992).

3.5.2 Model Analysis

Model estimation of the model analysis technique by Bao and Redish (2006) was applied to present the probabilities of students using the mental models related to scientific reasoning. The power of this method lies in its full use of students' answers (both right and wrong) in the analysis, as opposed to standard score-based analysis where the correct answer is only considered.

Due to the widely diverse solutions to the SHM problems, model analysis was only applied for the scientific reasoning assessment. Each dimension of the LCTSR constituted a set of common models with its corresponding item choices, which are presented and explained in the succeeding chapter. The construction of models was very similar to the procedure in another study (Reyes & Rakkapao, 2018). It was initially built upon false reasoning strategies of college students (Woolley et al., 2018) or obvious reasoning patterns based on a basic idea that is familiar among item choices. Choices of each question were classified into common mental models according to the following criteria: 1) find the most appropriate model for each choice in an item and 2) consider the most popular pair of choices in both pre- and posttest answers to decide which among the models the choice belongs to. These common student models are represented by orthonormal vectors in linear vector space and its size may vary for each scientific reasoning subskill.

Suppose that η number of common models were identified, an individual model state vector u_k shows a student k whose responses to the m number of questions is given by

$$u_k = \frac{1}{\sqrt{m}}\begin{pmatrix}\sqrt{n_1^k} & \sqrt{n_2^k} & \sqrt{n_3^k} & \cdots & \sqrt{n_\eta^k}\end{pmatrix}^T \tag{2}$$

where n represents the frequency of using each model and the probability amplitude is $\sqrt{q_\eta^k}$. This single student model vector is used to obtain the model density matrix D_k for an individual student, where $D_k = u_k \otimes u_k^T$. Then, D_k is averaged with other students' matrices in the whole class sample N to create the class density matrix as shown below

$$D = \frac{1}{N}\sum_{k=1}^{N} D_k = \frac{1}{N\cdot m}\begin{bmatrix} n_1^k & \sqrt{n_1^k n_2^k} & \sqrt{n_1^k n_3^k} & \cdots & \sqrt{n_1^k n_\eta^k} \\ \sqrt{n_2^k n_1^k} & n_2^k & \sqrt{n_2^k n_3^k} & \cdots & \sqrt{n_2^k n_\eta^k} \\ \sqrt{n_3^k n_1^k} & \sqrt{n_3^k n_2^k} & n_3^k & \cdots & \sqrt{n_3^k n_\eta^k} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \sqrt{n_\eta^k n_1^k} & \sqrt{n_\eta^k n_2^k} & \sqrt{n_\eta^k n_3^k} & \cdots & n_\eta^k \end{bmatrix} = \begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \cdots & \rho_{1\eta} \\ \rho_{21} & \rho_{22} & \rho_{23} & \cdots & \rho_{2\eta} \\ \rho_{31} & \rho_{32} & \rho_{33} & \cdots & \rho_{3\eta} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \rho_{\eta 1} & \rho_{\eta 2} & \rho_{\eta 3} & \cdots & \rho_{\eta\eta} \end{bmatrix} \quad (3)$$

As illustrated in equation (3), the diagonal elements demonstrate the percentage of responses in corresponding models. These elements may not necessarily add up to 1 because of missing responses from the participants. The off-diagonal elements in the same density matrix D indicate the mixing of individual students' use of models. There is significant mixing if the result of dividing an off-diagonal element and the product of the square roots of the two relative diagonal elements is greater than 50%. By eigenvalue decomposition, the primary eigenvector which has the largest eigenvalue (>0.65) shows the dominant features of the class model states. This eigenvector represents the weighted average of students' mental states for the whole class.

The model state of the class can further be simplified by comparing the probability of using the correct model (vertical axis) and incorrect model (horizontal axis) which correspond to the two axes in a model plot. Movement of mental states can be conveniently seen in this graph. As shown in Figure 3.4, the coordinates $\left(P_2 = \sigma_\mu^2 \nu_{2\mu}^2,\ P_1 = \sigma_\mu^2 \nu_{1\mu}^2\right)$ of the model point B are obtained from the primary eigenvector $\nu_\mu = (\nu_{1\mu} \quad \nu_{2\mu} \quad \nu_{3\mu})^T$ and its eigenvalue σ_μ^2. In this case, model 1 is the correct model while model 2 is the incorrect model. Model point in the primary model region (model 1 or model 2 region) indicates that students' response patterns are similar in which a model (model 1 or model 2 depends on the location of the model point) is dominant. If the point is in the mixed region, there are inconsistencies of model use among individual students. If eigenvalues are less than 0.4, the model point is in the secondary model region and indicates less popular class response patterns.

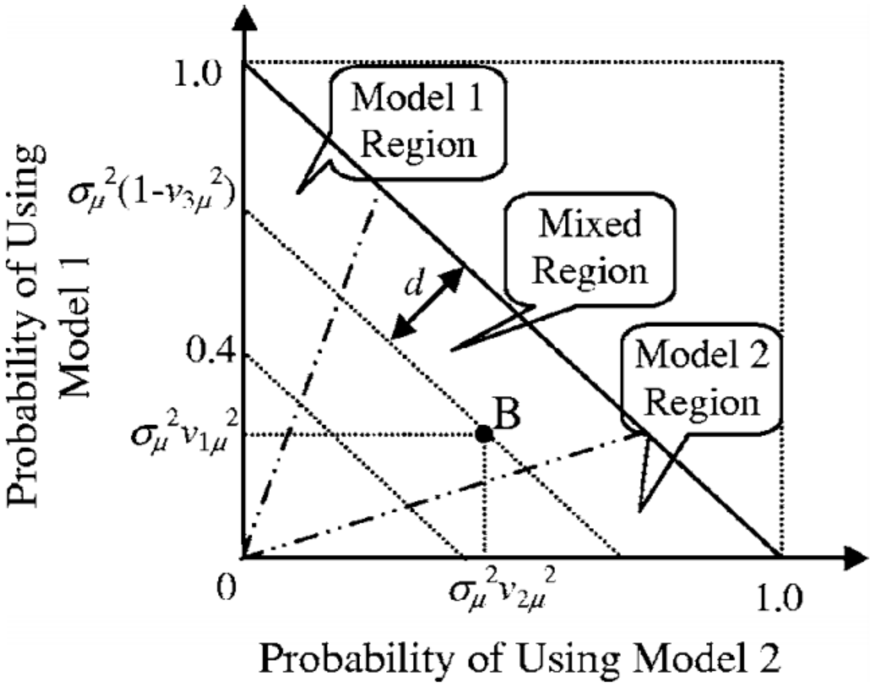


Figure 3.4. Sample model plot between 2 models (Lei Bao & Redish, 2006).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results of Scientific Reasoning Assessment

The maximum score for the Lawson Classroom Test of Scientific Reasoning (LCTSR) is 24 because the individual scoring method was utilized. The mean scores of 26 participants on the pretest were 10.69 (*SD* = 4.69), while on the posttest was 10.85 (*SD* = 6.35). Students' overall average scores were observed to be virtually the same. This result along with the scores of each scientific reasoning dimension before and after instruction is shown in Figure 4.1. The error bars indicated a wide dispersion among students' scores. Background knowledge of the sample in the pretest was found to be similar with the study of Piraksa and colleagues (2014), in which the most difficult dimensions were hypothetico-deductive reasoning, proportional thinking, and control of variables.

The number of students who were classified into the three levels of scientific reasoning skill was also determined by using the pair scoring method, as shown in Figure 4.2. There were 17 students grouped as concrete operational reasoners before instruction, but it decreased to 15 after the intervention. These reasoners need a reference to tangible objects or properties. The same number of 8 students was found in both pre- and post-instruction of the transitional reasoner's group. These reasoners,

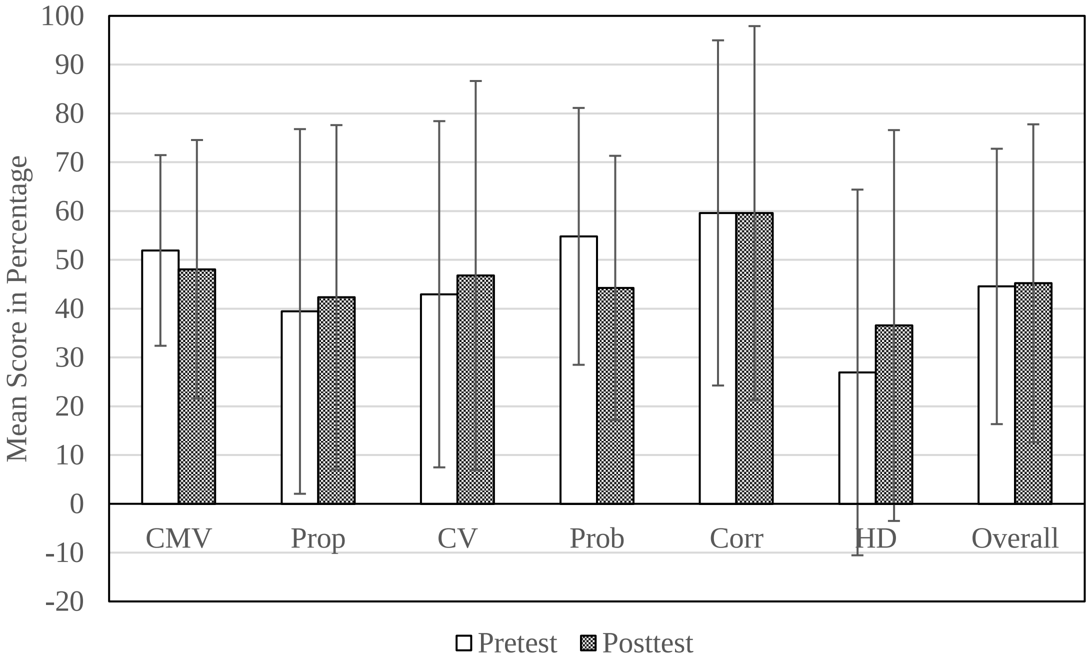


Figure 4.1. Average percentage scores of overall LCTSR and its dimensions (CMV = conservation of mass and volume, Prop = proportional reasoning, CV = control of variables, Prob = probabilistic reasoning, Corr = correlational reasoning, HD = hypothetico-deductive reasoning).

whose reasoning abilities are not fully developed, are in a stage intermediate between concrete and formal reasoners. Initially, only 1 student was a formal operational reasoner, after the intervention, 3 students were able to think in an abstract manner if given different contexts. These students thought in a logical manner, organized and well-planned strategies, as well as inconsistent ideas, were virtually absent. However, the majority of the 2018 cohort (*N* = 26) were still below the formal operational level of scientific reasoning. Comparison of the pretest with the 2017 cohort (*N* = 37) also indicated they had a lower initial background in terms of scientific reasoning ability. Posttest, however, was not administered for the 2017 cohort of students.

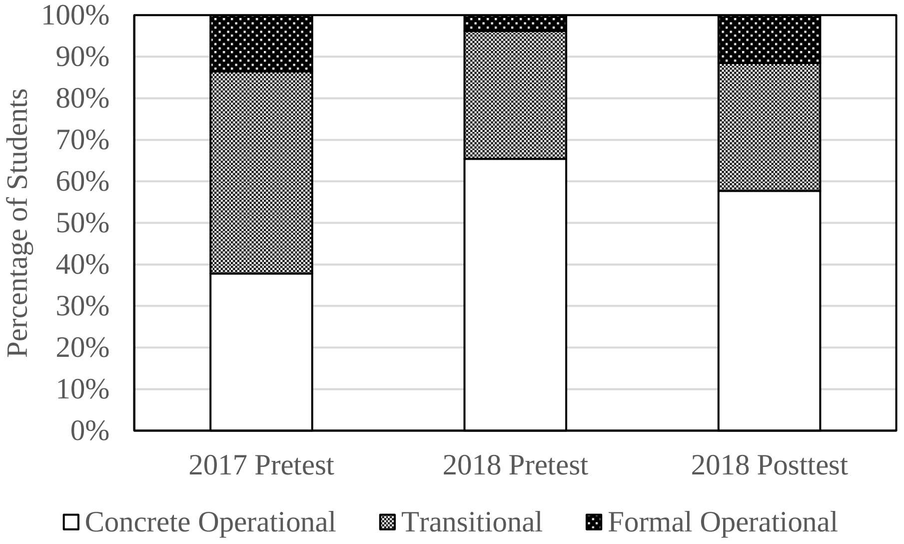


Figure 4.2. Classification of students based on scientific reasoning levels.

Based on the frequency of overall scores of individual students, it is apparent in Figure 4.3 that the sample is not normally distributed although total scores were at the interval measurement level. Hence, the Wilcoxon signed-rank test was conducted to match between two different conditions. Comparison between pretest and posttest total

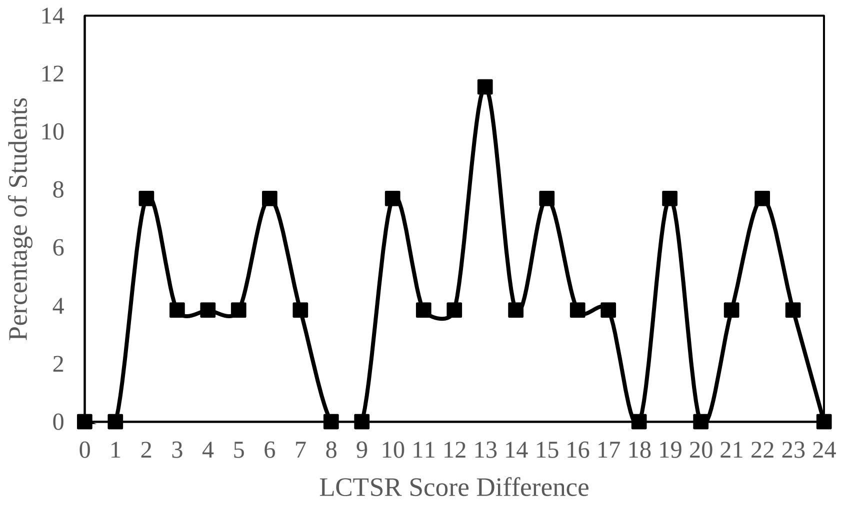


Figure 4.3. Distribution of students (*N* = 26) plotted against score difference between LCTSR pre- and posttests.

scores of the LCTSR showed no statistically significant difference ($z = -.18$, $p = .86$) with very small effect size ($r = -.03$). Moreover, the null hypothesis of no difference between pre- and postscores was retained for the conservation of mass and volume, proportional reasoning, control of variables, correlational reasoning, and hypothetico-deductive reasoning, as shown in Table 4.1. It can be noted however that these null results may be of value to physics education research (Conlin, Kuo, & Hallinen, 2019). The effect size (r) also revealed that the differences between pre- and posttest results were practically small. These findings suggest no substantial change after the intervention. In contrast, a statistically significant ($p < .05$) decrease with large effect size can be observed between pre- and posttest for *probabilistic reasoning*.

Table 4.1. Average scores of LCTSR in each dimension for pre- and posttest.

	Mean ± *SD*		(z, p)	r
	Pretest	Posttest		
Control of mass and volume	51.92 ± 37.37	48.08 ± 35.30	(-.95, .34)	-.19
Proportional reasoning	39.42 ± 35.48	42.31 ± 39.86	(-62, .54)	-.12
Control of variables	42.95 ± 26.32	46.79 ± 27.09	(-1.05, .30)	-.21
Probabilistic reasoning	54.81 ± 35.37	44.23 ± 38.28	(-2.07, .04)	-.41
Correlational reasoning	59.62 ± 37.47	59.62 ± 40.05	(0, 1)	0
Hypothetico-deductive reasoning	26.92 ± 28.22	36.54 ± 32.58	(-1.00, .32)	-.20

Items 15, 16, 17, and 18 are questions related to probabilistic reasoning in LCTSR. As shown in Figure 4.4, the greatest number of responses that increased for the incorrect choice in item 15 was 1 chance out of 6. The colors regardless of the piece of wood are red or yellow was not considered. The next question (item 16) reflected their reasoning that there is large inherent uncertainty with the problem. For item 17, the most probable incorrect choice that increased is “cannot be determined” because of the line of reasoning in the succeeding item. The corresponding reason stated that only 1 of the 21 pieces is picked out of the bag. These faulty scientific thinking of probabilistic reasoning were similar to the study of Woolley and colleagues (2018). Students’ responses seemed to exhibit lesser confidence than before with the manner of their answers. Nevertheless, the cause as to why students selected these incorrect ideas after instruction warrants further examination.

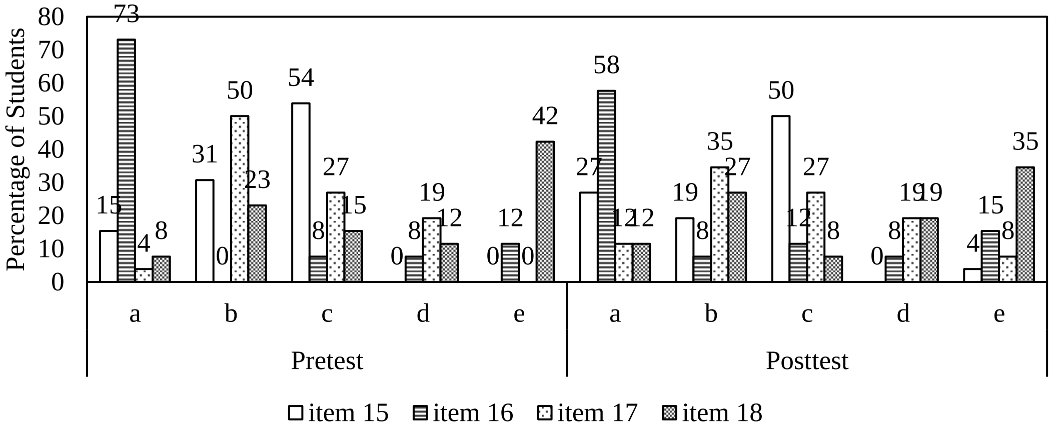


Figure 4.4. Percentage of responses in each choice of probabilistic reasoning between pre- and posttests.

However, these results in the overall and dimension scores considered only the correct answers of students. Despite very minimal changes from pre- to posttest, both correct and incorrect answer choices of students in the LCTSR were studied in more detail using the model analysis technique. Investigation of mental models of subskills was conducted to determine whether students’ ideas transitioned into lesser degrees of faulty scientific thinking. Each of the six dimensions of scientific reasoning ability was examined intently through its respective common mental models.

4.1.1 Control of Mass and Volume

Four questions included in the conservation of mass and volume prompted ideas about the effect on physical properties which remain constant although variations are introduced into the system. As shown in Table 4.2, common mental models identified were: mass and volume are the same because changes to the system did not influence either of the two quantities (model 1), a non-conservationist idea where the quantity increased due to differences in size or mass (model 2), and a non-conservationist idea where the quantity decreased due to differences in size or mass (model 3).

Table 4.2. Modelling of student responses for the conservation of mass and volume.

Question number	Model 1	Model 2	Model 3
1	b	a	c
2	d	a e	c, b
3	a	b	c
4	e	b, c	a, d

This dimension involves the understanding of quantities or properties that are to be preserved or remain unaffected with changes in certain conditions. In the LCTSR, mass and volume are fixed and does not change with the circumstances mentioned in the instrument. To enhance this subskill, students identified constant quantities in SHM (Constant SHM parameters session) namely, amplitude, period, angular frequency, and phase constant. These parameters remain fixed with respect to time provided the initial condition is the same. One student volunteer led a discussion of these constant parameters. Then, a follow-up question that prompted students about the calculation of the speed of a block helped reinforced their idea about the distinction between parameters that can be conserved and those which vary.

In Table 4.3, those participants who selected the correct model decreased by 4% after instruction. Mixed model states are evident in both testing conditions with respect to instruction. The distribution of student responses varied widely, especially in the pretest whose eigenvalue was in close proximity to the threshold of 0.65 (Lei Bao & Redish, 2006). As shown in Figure 4.5, *CMV Pre* and *CMV Post* refer to control of mass and volume for the pre- and posttest respectively. The model plot is characterized by a small shift of mental states in the mixed region of the correct model (model 1) and incorrect model (model 2). Students often alternate between conservationist and non-conservationist ideas. Thus, the intervention was not able to affect students into the scientific thinking of conservation of mass and volume.

Table 4.3. Model estimation values for the conservation of mass and volume.

	Pretest	Posttest
Class density matrix	$\begin{bmatrix} 0.52 & 0.17 & 0.08 \\ 0.17 & 0.33 & 0.12 \\ 0.08 & 0.12 & 0.15 \end{bmatrix}$	$\begin{bmatrix} 0.48 & 0.21 & 0.07 \\ 0.21 & 0.30 & 0.13 \\ 0.07 & 0.13 & 0.22 \end{bmatrix}$
Eigenvalue	0.65	0.66
Primary eigenvector	$(0.81 \quad 0.52 \quad 0.25)^T$	$(0.78 \quad 0.56 \quad 0.29)^T$

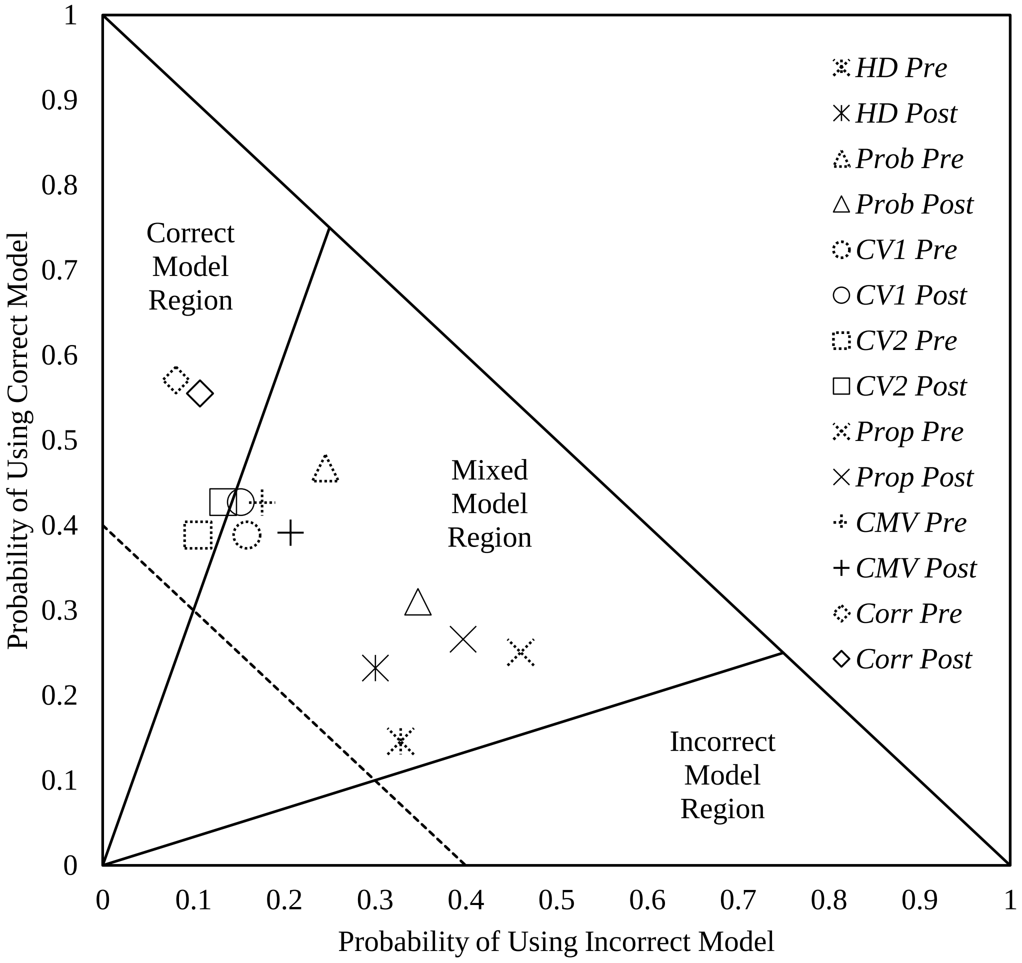


Figure 4.5. Model plot by LCTSR dimension.

4.1.2 Proportional Reasoning

There were four questions related to analyzing ratios by which an unknown value can be determined if the other terms are known. The item responses yielded to common mental models of appropriate calculation based on the relationship of ratios (model 1), ratios which are switched or answer which cannot be selected from the choices given (model 2), and unsuccessful in applying proportions (model 3). Each item choice was grouped according to its corresponding model as presented in Table 4.4.

Table 4.4. Modelling of student responses for proportional reasoning.

Question number	Model 1	Model 2	Model 3
5	b	e	a, c, d
6	c		a, b, d, e
7	d	e	a, b, c
8	a	b	c, d, e

In the intervention, proportional reasoning was explicitly taught in the Qualitative analysis of motion session. In this activity, students learned about the interactions between the restoring force of the spring and the kinematic quantities of motion. According to Newton's second law, this force is proportional to the acceleration of the block. This relation was inherently integrated into the task by understanding the behavior of the force and acceleration vectors of the oscillating mass on a spring at different locations with respect to the equilibrium, as shown in Appendix B. In addition, proportional reasoning can also be applied in the Factors affecting the vibration period session. By studying the relationship of the period with the length of the pendulum, students would better understand the concept of ratio and proportion.

After the intervention, selection of model 3 decreased while it increased for model 1 and 2 in Table 4.5. Preference in the use of model 2 over model 3 is seen as a positive outcome. Choices associated with model 3 is considered of lower value than model 2 because it fails to recognize primarily that the problem involves the mathematical relationship between numbers, albeit both models are still erroneous. Mixing of ρ_{13} = 0.52 between model 1 and model 3 was significant in the pretest. However, it was lessened to ρ_{13} = 0.44 through instructional intervention. Consistency in the use of either models 1 or 3 was more evident in the posttest, in which responses increased for model 1 and decreased for model 3. As shown in Figure 4.5, *Prop Pre* and *Prop Post* refer to proportional reasoning for pre- and posttest respectively. These points present the transition between mental states of model 1 (correct) and 3 (incorrect). Despite a more heterogeneous pattern of responses after instruction as shown by the eigenvalues, the intervention caused the students to favor towards the correct idea about ratios and proportions.

Table 4.5. Model estimation values for proportional reasoning.

	Pretest	Posttest
Class density matrix	$\begin{bmatrix} 0.39 & 0.03 & 0.24 \\ 0.03 & 0.07 & 0.06 \\ 0.24 & 0.06 & 0.54 \end{bmatrix}$	$\begin{bmatrix} 0.42 & 0.02 & 0.20 \\ 0.02 & 0.08 & 0.06 \\ 0.20 & 0.06 & 0.50 \end{bmatrix}$
Eigenvalue	0.72	0.67
Primary eigenvector	$(0.59 \quad 0.10 \quad 0.80)^T$	$(0.63 \quad 0.10 \quad 0.77)^T$

4.1.3 Control of Variables

Six items were related to a focus variable in an experiment where other variables may or may not impact an event on the system. Students ideas for this subskill were grouped in Table 4.6 as follows: manipulation of pertinent independent variables to produce a causal effect on a target variable (model 1), test all variables even those that are not necessary (model 2), test opposite variables (model 3), unsuccessful to maintain fixed variables (model 4), narrow down on a single variable or trial (model 5), and depend on previous knowledge (model 6).

Table 4.6. Modelling of student responses for control of variables.

Question number	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
9	e	b	d	c	a	
10	c	d, e	b		a	
11	b			a, d		c
12	a			b, d	e	c
13	c			a, d		b
14	d			e	a, c	b

Control of variables was the target dimension in the Factors affecting vibration period session. The worksheet task involved the variables that influence the period of an oscillating system. In this activity, students had to explore how length changes the vibration period of a simple pendulum. By setting the gravitational acceleration constant and all other variables, the effect of changing the length of a pendulum on its period of oscillation can be determined. Both masses of the bob and amplitude, if changed, would not affect period. Likewise, these changes or absence thereof is also reflected in the displacement versus time graphs.

As shown in Table 4.7, the most popular model was model 1 which increased from 43% to 47%. However, there were also observed gains in the proportion of participants using model 4 and 6. About 23-24% of responses from students neglected to acknowledge confounding variables in a system. These variables tend to impact independent and dependent variables resulting in spurious outcomes. *CV1 Pre* and *CV1 Post* correspond to the control of variables dimension for the respective pre- and posttests, as depicted in Figure 4.5. In this figure, it shows that the chance of students' choosing between model 1 (correct) and 4 (incorrect) moved near the boundary of the model 1 region. There were 16-21% of responses that manifested the idea of relying on prior knowledge. Moreover, *CV2 Pre* and *CV2 Post* refer to control of variables between pre- and posttest respectively. Both points of model 1 (correct) and 6 (incorrect) of pre- and posttests are in the model 1 region as shown in this figure. In this area, participants' responses are comparable, and the correct model is the dominant choice. The transition towards the correct model region also agrees with a higher mean percentage score in the posttest (46.79%) than the pretest (42.95%), as shown in Figure 4.1. The increase in eigenvalue also indicated a more similar pattern of responses derived from individual model state vectors. Higher probabilities of choosing the correct model with respect to models 4 and 6 were observed.

Table 4.7. Model estimation values for control of variables.

	Pretest	Posttest
Class density matrix	$\begin{bmatrix} 0.43 & 0.04 & 0.03 & 0.21 & 0.09 & 0.18 \\ 0.04 & 0.06 & 0.01 & 0.07 & 0.02 & 0.05 \\ 0.03 & 0.01 & 0.05 & 0.04 & 0.02 & 0.04 \\ 0.21 & 0.07 & 0.04 & 0.23 & 0.05 & 0.11 \\ 0.09 & 0.02 & 0.02 & 0.05 & 0.06 & 0.05 \\ 0.18 & 0.05 & 0.04 & 0.11 & 0.05 & 0.16 \end{bmatrix}$	$\begin{bmatrix} 0.47 & 0.02 & 0.03 & 0.21 & 0.04 & 0.21 \\ 0.02 & 0.03 & 0 & 0.03 & 0 & 0.02 \\ 0.03 & 0 & 0.03 & 0.03 & 0.01 & 0.04 \\ 0.21 & 0.03 & 0.03 & 0.24 & 0.03 & 0.12 \\ 0.04 & 0 & 0.01 & 0.03 & 0.03 & 0.03 \\ 0.21 & 0.02 & 0.04 & 0.12 & 0.03 & 0.21 \end{bmatrix}$
Eigenvalue	0.69	0.72
Primary eigenvector	$(0.75 \quad 0.14 \quad 0.10 \quad 0.48 \quad 0.19 \quad 0.39)^T$	$(0.77 \quad 0.05 \quad 0.07 \quad 0.46 \quad 0.08 \quad 0.43)^T$

4.1.4 Probabilistic Reasoning

Four items included in probabilistic thinking pertain to how likely an occurrence will happen based on mathematical rules. Mental models of students were identified in Table 4.8 as follows: reasoning grounded on a priori probability (model 1), ignore some factors that influence probability (model 2), and insufficient data provided (model 3).

Table 4.8. Modelling of student responses for probabilistic reasoning.

Question number	Model 1	Model 2	Model 3
15	c	a, b, d	e
16	a	c, e	b, d
17	b	c, d, e	a
18	e	a, b, d	c

In the Differential equation of motion session, the concept introduction phase involved a hands-on activity with the simple pendulum. Students timed the period of a pendulum and compared it with their computed period $\boldsymbol{T}$ based on the length $\boldsymbol{L}$ from the pivot of rotation to the center of mass of the pendulum bob. This calculation was given by the expression $\boldsymbol{T = 2\pi\sqrt{\frac{L}{g}}}$, where $\boldsymbol{g}$ is the acceleration due to gravity. When doing an experiment, it is important to consider the probability of measurement error. Thus, students were able to practice probabilistic thinking by conducting several experimental trials to lessen uncertainty and obtain the true measurement value for period.

Percentage of students' use of model 2 increased, whereas it decreased in model 1 and 3 in Table 4.9. Significant mixing ($\boldsymbol{\rho_{12}}$ = 0.52) between model 1 and 2 was identified before instruction. As shown in Figure 4.5, both points of *Prob Pre* (probabilistic reasoning of pretest) and *Prob Post* (probabilistic reasoning of posttest) in the model plot are in the mixed model region in which response patterns among students differ and there is no dominant model being employed. These two points depict the model plot between model 1 (correct) and 2 (incorrect). The shift towards the model 2 region is consistent with the result in Figure 4.1. Average percentage scores decreased from 54.81% to 44.23%. These findings suggest that the implemented pedagogical strategy did not support students in probabilistic reasoning.

Table 4.9. Model estimation values for probabilistic reasoning.

	Pretest	Posttest
Class density matrix	$\begin{bmatrix} 0.55 & 0.24 & 0.06 \\ 0.24 & 0.39 & 0.05 \\ 0.06 & 0.05 & 0.07 \end{bmatrix}$	$\begin{bmatrix} 0.44 & 0.21 & 0.05 \\ 0.21 & 0.46 & 0.06 \\ 0.05 & 0.06 & 0.10 \end{bmatrix}$
Eigenvalue	0.73	0.67
Primary eigenvector	$(0.80 \quad 0.58 \quad 0.11)^T$	$(0.68 \quad 0.72 \quad 0.13)^T$

4.1.5 Correlational Reasoning

Correlational thinking was tested using two items that measure the ability of a person to decide the degree of dependence between variables. Common models were classified in Table 4.10 as correctly identifying the association of variables (model 1), insufficient data provided (model 2), and dependence on previous knowledge (model 3).

Table 4.10. Modelling of student responses for correlational reasoning.

Question number	Model 1	Model 2	Model 3
19	a	b, c	
20	d	a, c	b, e

With the Constant SHM parameters session, there is an improved comprehension of the correlation among the energies in SHM. If students are aware of the principle of conservation of energy required for the problem, then the associations among potential, kinetic, and total energy of a system can be correctly identified. This understanding can be transferred and readily visualized through the energy bar charts. Through the charts, the energy conservation principle holds regardless of the different conditions of the oscillating system as provided in Appendix B.

The use of model 1 from pretest to posttest remained constant to 60% in Table 4.11. It can also be noted in the class density matrix that virtually no inconsistencies between the use of model 1 and 2 were found after the intervention. Hence, there was no confusion between the use of either model 1 or 2. From a large mixing of ρ_{13} = 0.50 between models 1 and 3, it also reduced to ρ_{13} = 0.42**.** This finding indicates that students were more consistent with their answers to the two questions in the posttest. Moreover, individual model states were comparable and the probability of selecting the correct model was highly likely, as shown in Figure 4.5. This figure shows the respective pre- (*Corr Pre*) and posttest (*Corr Post*) for correlational reasoning between model 1 (correct) and 3 (incorrect). Participants were also more coherent with their use of either the correct model or the incorrect models in answering the questions.

Table 4.11. Model estimation values for correlational reasoning.

	Pretest	Posttest
Class density matrix	$\begin{bmatrix}0.60 & 0.04 & 0.17\\ 0.04 & 0.19 & 0.02\\ 0.17 & 0.02 & 0.19\end{bmatrix}$	$\begin{bmatrix}0.60 & 0 & 0.17\\ 0 & 0.10 & 0.08\\ 0.17 & 0.08 & 0.27\end{bmatrix}$
Eigenvalue	0.66	0.67
Primary eigenvector	$(0.93 \quad 0.09 \quad 0.35)^T$	$(0.91 \quad 0.05 \quad 0.40)^T$

4.1.6 Hypothetico-deductive Reasoning

Four questions were associated with hypothetico-deductive reasoning. This subskill involves finding out a logical conclusion by testing inferences. Students' ideas were classified as carefully designing an experiment or objectively and accurately comparing the hypothesis with experimental data (model 1), designed experiment or results that are inadequate to support the hypothesis (model 2), and designed experiment or results that mismatch the hypothesis (model 3). These models included item choices as shown in Table 4.12.

Table 4.12. Modelling of student responses for hypothetico-deductive reasoning.

Question number	Model 1	Model 2	Model 3
21	a	b, e	c, d
22	a	b	c, d
23	a	c	b
24	b	c	a

For hypothetico-deductive reasoning, the Displacement, velocity, acceleration of SHM session included both expressing positions as a function of time as well as velocity and acceleration of SHM. This reasoning subskill is built within the three-phase learning cycle. In the concept exploration phase, students identify the problem. Then, they formulate a hypothesis in the concept introduction phase based on the presented model and their previous idea. Lastly, the hypothesis they constructed along with the new model derived from the cognitive conflict between the two ideas can be applied in another context to test the veracity of their hypothesis.

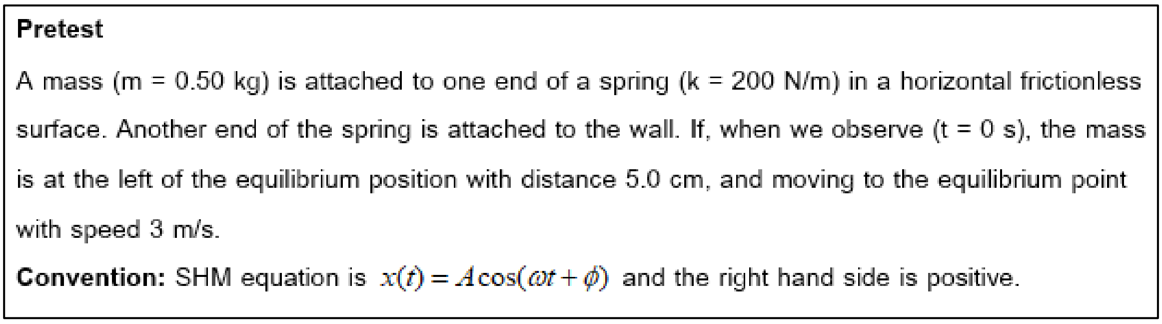
As shown in Table 4.13, the correct model was employed frequently by more students as it increased by 10% following the intervention. The other two incorrect models either decreased or remained the same in terms of the number of responses in each model. Although mixing between models 1 and 3 were still significant, it reduced before (ρ_{13} = 0.59) and after (ρ_{13} = 0.53) instruction. This result means lesser confusion between the correct and incorrect model, in which model 1 increased while model 3 remained the same in the posttest. Figure 4.5 shows that participants were more likely to select model 1 (correct) than model 3 (incorrect) after instruction. In this figure, *HD Pre* and *HD Post* refer to the pre- and posttest of hypothetico-deductive reasoning respectively. This finding is supported by the respective mean percentage scores of the pre- and posttests which were 26.92% and 36.54%, as shown in Figure 4.1.

Table 4.13. Model estimation values for hypothetico-deductive reasoning.

	Pretest	Posttest
Class density matrix	$\begin{bmatrix}0.27 & 0.11 & 0.19\\ 0.11 & 0.30 & 0.24\\ 0.19 & 0.24 & 0.38\end{bmatrix}$	$\begin{bmatrix}0.37 & 0.13 & 0.20\\ 0.13 & 0.25 & 0.21\\ 0.20 & 0.21 & 0.38\end{bmatrix}$
Eigenvalue	0.69	0.69
Primary eigenvector	$(0.46 \quad 0.55 \quad 0.69)^T$	$(0.58 \quad 0.47 \quad 0.66)^T$

4.2 Results of Assessment about Simple Harmonic Motion

The simple harmonic motion (SHM) problems of the pre- and posttest in Figure 4.6 and Figure 4.7 was rated and modeled after the scoring rubric in Table 3.1. Total problem-solving score with a maximum of 9 comprised of the translation, execution accuracy, and evaluation components. The highest rating of each component of problem-solving was 3. Planning coherence is also considered a component however it was scored separately from the other components. Novices, when presented with different contexts of the same concept, will tend to answer inconsistently. These cases are well-documented in the physics education literature (Bao & Redish, 2006; Maloney & Siegler, 1993; Steinberg & Sabella, 1997).

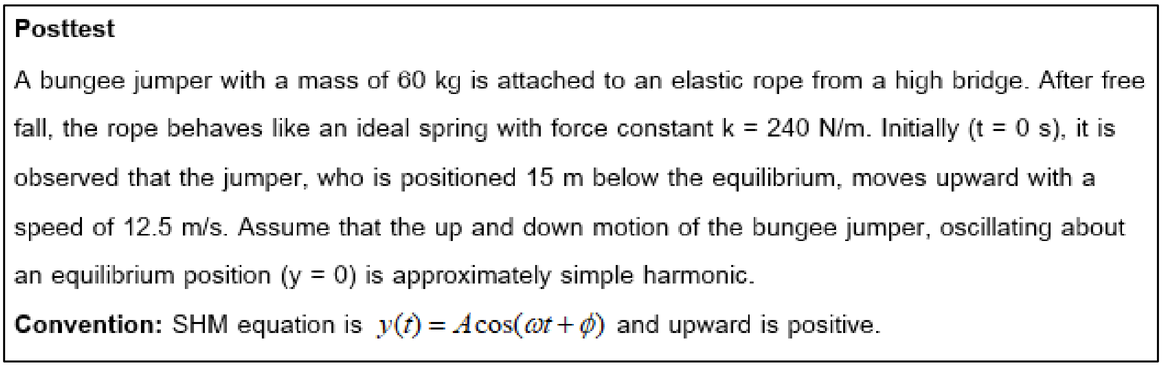


Pretest

A mass (m = 0.50 kg) is attached to one end of a spring (k = 200 N/m) in a horizontal frictionless surface. Another end of the spring is attached to the wall. If, when we observe (t = 0 s), the mass is at the left of the equilibrium position with distance 5.0 cm, and moving to the equilibrium point with speed 3 m/s.

Convention: SHM equation is $x(t) = A\cos(\omega t + \phi)$ and the right hand side is positive.

Figure 4.6. Mass-spring system problem for pretest.



Posttest

A bungee jumper with a mass of 60 kg is attached to an elastic rope from a high bridge. After free fall, the rope behaves like an ideal spring with force constant k = 240 N/m. Initially (t = 0 s), it is observed that the jumper, who is positioned 15 m below the equilibrium, moves upward with a speed of 12.5 m/s. Assume that the up and down motion of the bungee jumper, oscillating about an equilibrium position (y = 0) is approximately simple harmonic.

Convention: SHM equation is $y(t) = A\cos(\omega t + \phi)$ and upward is positive.

Figure 4.7. Bungee jumper problem for posttest.

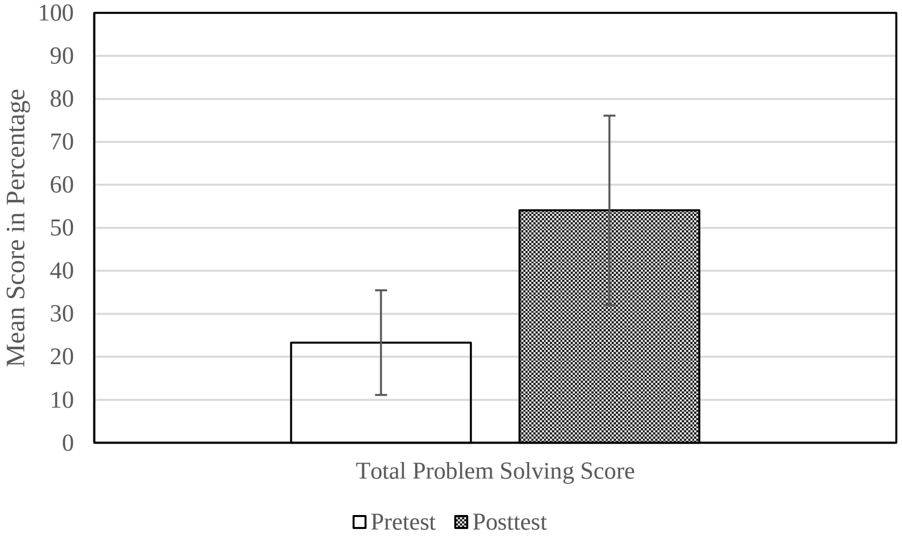


Figure 4.8. Average percentage of total problem solving score related to SHM.

Moreover, the scores were measured at the ordinal level and Table 4.14 showed that by the Wilcoxon signed-rank test there was no statistically significant difference with small effect size between pre- and posttests in the translation component. This result is opposite to other components and the overall problem-solving score, which showed significantly higher ratings in the posttest than the pretest. The total problem-solving score in Figure 4.8 increased from 23.29% to 54.06%. Problem-solving ability in the topic of SHM developed generally due to the instructional intervention. In the next subsections, a deeper investigation is presented to better understand students' knowledge through their written answers to the test problems. This approach complemented the ratings that were obtained from the scoring rubric. In addition, problem-solving component scores are presented.

Table 4.14. SHM problem-solving total and component scores for pre- and posttest.

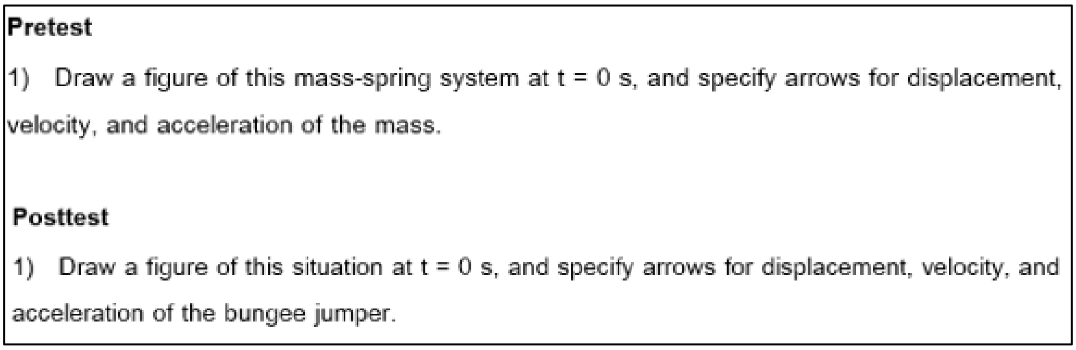
	Mean ± *SD*		(z, p)	r
	Pretest	Posttest		
Translation	35.90 ± 13.07	41.03 ± 35.66	(-.88, .38)	-.23
Execution Accuracy	18.59 ± 16.72	55.13 ± 24.60	(-4.20, <.001)	-.88
Evaluation	15.38 ± 30.58	66.03 ± 33.33	(-4.46, <.001)	-.87
Problem Solving Score	23.29 ± 12.17	54.06 ± 22.03	(-4.43, <.001)	-.87
Coherence	5.13 ± 13.96	46.15 ± 33.10	(-4.01, <.001)	-.88

4.2.1 Students' Understanding of the Physical Situation

The mass-spring system problem in the pretest can be interpreted in two ways. It could refer to a compressed spring due to the block being displaced towards the wall located at the left of the block or a stretched spring in which the wall is located at the right of the block, which is moved away from the wall. On the other hand, the bungee jumper problem in the posttest can be thought of to be similar to the mass-spring system, albeit oriented in the vertical direction. Both questions correspond to item 1 in Figure 4.9 of the pre- and posttests, respectively. The rubric used to grade students in this item is shown in Table 4.15. In Figure 4.10, the translation component which involved item 1 increased from 36% to 41%.

Table 4.15. Scoring rubric for SHM problem item 1.

Component	0	1	2	3
Translation	no drawing and vectors are shown	major misinterpretations in figure and vector representation	minor misinterpretations in figure and vector representation	complete figure and vector representation



Pretest

1) Draw a figure of this mass-spring system at t = 0 s, and specify arrows for displacement, velocity, and acceleration of the mass.

Posttest

1) Draw a figure of this situation at t = 0 s, and specify arrows for displacement, velocity, and acceleration of the bungee jumper.

Figure 4.9. Item 1 of pre- and posttest.

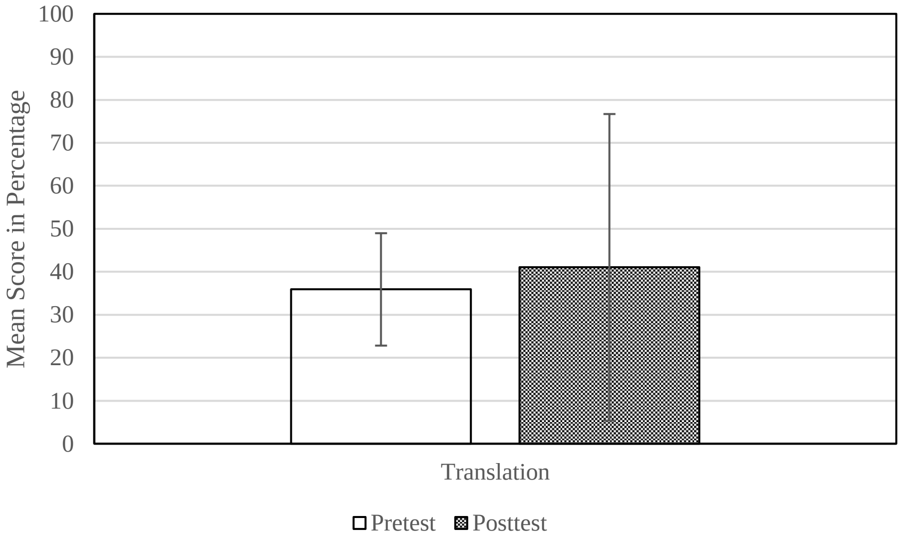


Figure 4.10. Average percentage of translation problem component related to SHM.

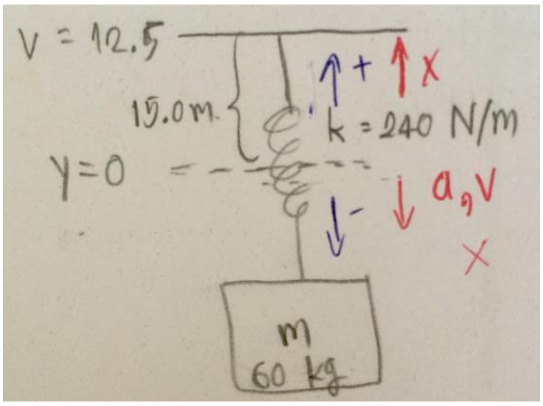


Figure 4.11. Student’s drawing to the bungee jumper question.

There were three students who indicated the equilibrium position only after instruction, but not in the pretest. Two of whom correctly identified the placement of the equilibrium position. However, the third one thought that 15 m is the distance between the bridge and the equilibrium position as shown in Figure 4.11. This misunderstanding may mean that this displacement is interpreted as the amplitude of the physical system since this is the greatest possible extent at which the mass can move from equilibrium based on the figure.

Two students also misinterpreted the bungee problem to be a simple pendulum, which was given as an example in instruction. This finding indicated that they might just be accessing what they can recall from memory instead of discerning about the problem. Moreover, it seemed that translation in solving the problems found in Figure 4.6 and Figure 4.7 was unimportant for respondents and asking them to draw a diagram affected their problem-solving strategy (Heckler, 2010).

After the intervention, better conceptions were observed with the direction of vectors such as two cases for velocity, one for the restoring force and another one for acceleration. However, only a few of these improvements were found in students' pictorial representations of the physical situation. In addition, misconceptions such as Figure 4.11 were still prevalent after instruction. These findings agree with the insignificant mean difference of ratings of the translation component for item 1 between pre- and posttest as shown in Table 4.14.

4.2.2 Simple Harmonic Motion Quantities

SHM quantities referred to in the current study were amplitude A, angular frequency ω, and phase constant ϕ in item 2 of Figure 4.12. The item can also be solved using the principle of conservation of energy, but none of the participants were reported to apply such an approach in either pre- or post-testing. Table 4.16 was used to rate students with their solutions in item 2. This item assesses the execution accuracy of students. Figure 4.13 shows the overall improved execution accuracy of students, which also is assessed by item 5, from 18.59% to 55.13%.


2) Find the angular frequency (ω), amplitude (A), and phase constant (ϕ) of this oscillation.

Figure 4.12. Same question for item 2 of pre- and posttest.

Table 4.16. Scoring rubric for SHM problem item 2.

Component	0	1	2	3
Execution accuracy	inappropriate or no solution for SHM constant parameters	major mistakes in reasoning or application when calculating for SHM constant parameters	minor mistakes in reasoning or application when calculating for SHM constant parameters	completely correct and appropriate solution when calculating for SHM constant parameters
Evaluation	no meaningful evaluation or no solution for SHM constant parameters	evaluation was present but elements or reasoning was missing or incorrect for SHM constant parameters	well thought out, meaningful, and accurate reflection on one of the three plausibility features for SHM constant parameters	well thought out, meaningful, and accurate reflection on at least two of the three plausibility features for SHM constant parameters

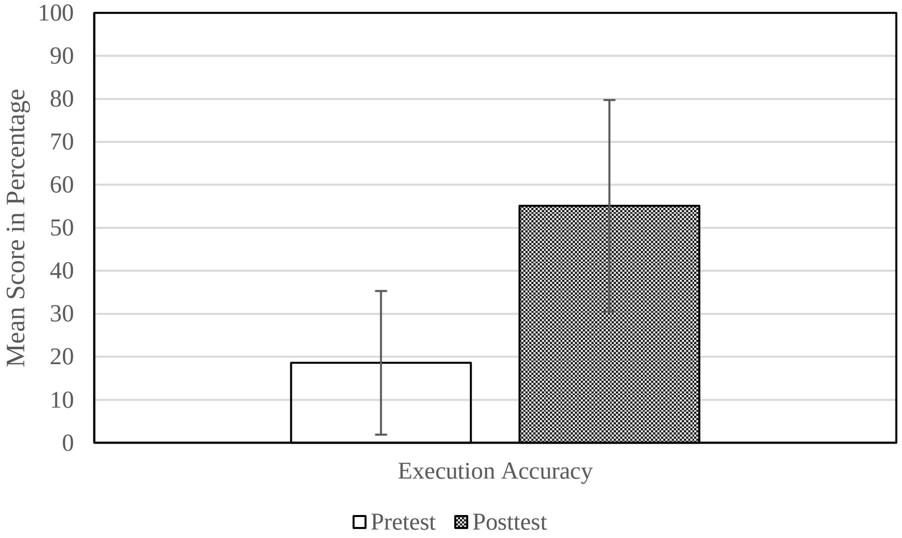


Figure 4.13. Average percentage of execution accuracy problem component related to SHM.

For amplitude, six students used 5.0 cm as their basis for calculating the amplitude of the mass-spring system. This misunderstanding assumed that this distance is the amplitude of oscillation. In the posttest, these students at least calculated the correct magnitude for amplitude, but some still obtained negative signs. There were also three students who assigned length units for amplitude in the posttest compared with no units found in the pretest.

Initially, two respondents wrote the equation $v = \omega r$, where v = velocity, ω = angular velocity, and r = radius of motion. They were perplexed by the fact that this relationship between linear velocity and angular velocity cannot be applied to such a problem. After the intervention, this relation was not present in any of the students' solutions. This observation means that the misconception was corrected. In addition, seven students reported the unit of radians per second for angular frequency after instruction, as opposed to an incorrect or no unit before instruction.

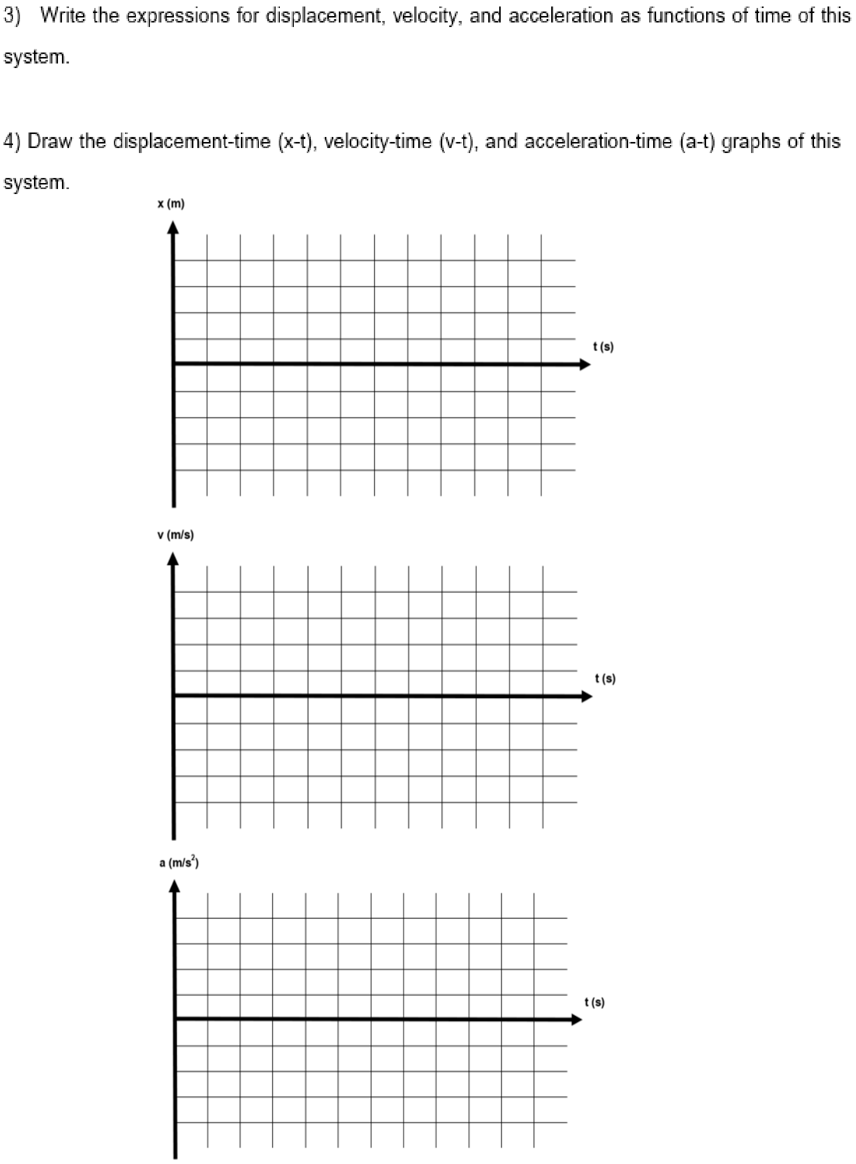
For the phase constant, it was the most difficult SHM quantity for students to solve even after the intervention. Both problems that they were prompted to solve have initial displacement and velocity at time t = 0 s. Thus, phase constant must not be zero to take into consideration these initial conditions. Not accounting for which quadrant, the phase constant is located and its radian unit when calculating with trigonometric functions were the most common mistakes. However, the majority of students did better overall after instruction in terms of execution accuracy and evaluation when solving for the SHM quantities.

4.2.3 Time-dependent Expressions and Graphs

Item 3 and 4 are two related task questions, as shown in Figure 4.14. SHM quantities embedded in the time-dependent expressions from the former item are transferred into the displacement-time, velocity-time, and acceleration-time graphs in the latter item. Basically, item 3 is just a “plug and chug” task for the student based on the values calculated from item 2 and given that they knew the right equations. However, it is essential that the time-dependent expressions be consistent with the graphs. This caveat is assumed to represent the planning coherence component of the problem-solving ability rubric regardless of errors with the computed SHM quantities in the earlier task. Table 4.17 was used to grade students’ coherence between item 3 and 4. Coherence between item 3 and 4 was assessed. Overall, planning coherence, which included item 5 and 6, increased from 5.13% to 46.15% in Figure 4.15.

Table 4.17. Scoring rubric for SHM problem in item 3 and 4.

Component	0	1	2	3
Planning coherence	no connection between expressions and graphs	major inconsistencies between expressions and graphs	minor inconsistencies between expressions and graphs	clear and consistent association between expressions and graphs



3) Write the expressions for displacement, velocity, and acceleration as functions of time of this system.

4) Draw the displacement-time (x-t), velocity-time (v-t), and acceleration-time (a-t) graphs of this system.

Figure 4.14. Same question for item 3 and 4 of pre- and posttest.

Note: Displacement of posttest is denoted as y.

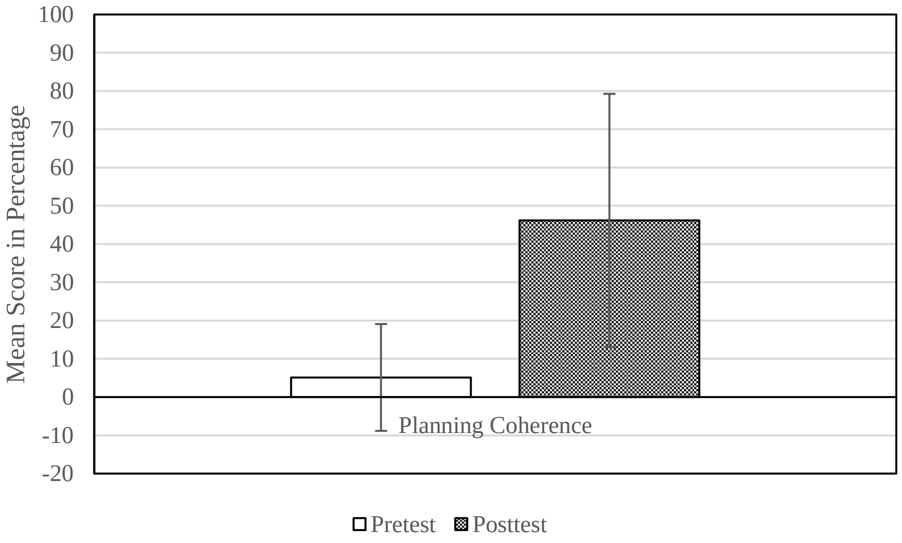


Figure 4.15. Average percentage of planning coherence problem component related to SHM.

There were five respondents who indicated the amplitude in the graph after instruction while it was nonexistent before instruction as shown in Figure 4.16. It can also be noted that a misconception was found in the posttest for amplitude. Maximum and minimum values for the quantities of the velocity and acceleration graphs were the same with the amplitude that referred to the maximum displacement as shown in Figure 4.17. This result revealed that the amplitude was generally interpreted by students as the distance of the crests and troughs of the sinusoidal wave with respect to the horizontal axis in a graph. Secondly, four students showed the value of the period in the graph just after the intervention. Period T is associated with the angular frequency ω in the expression by $T = 2\pi/\omega$. Recognition of the connection between the expressions and graphs for amplitude and angular frequency is a manifestation of the planning coherence component of problem solving. For phase constant, it may be shown implicitly by only presenting the plots as a function of time after the phase shift from the original graph where $\phi = 0$. It was difficult to identify coherence with the phase constant because it depends on the horizontal axis scales which most students did not clearly indicate on the graph.

It was also noticed that eight of the participants disclosed an improved understanding of the relationships among displacement, velocity, and acceleration through the graphs in item 4. Although these students may know by definition and in the equations that velocity is the time derivative of displacement and acceleration is the time derivative of velocity, it can be seen in Figure 4.16 that it is not consistent with the graphical representations. This occurrence can be explained by the lack of comprehension with the concept of differentiation in mathematics (Christensen & Thompson, 2012). After the intervention, it was clear that the graphs of displacement, velocity, and acceleration as functions of time were shown to be interrelated in Figure 4.17. Nevertheless, errors with amplitude, angular frequency, and phase constant persisted.

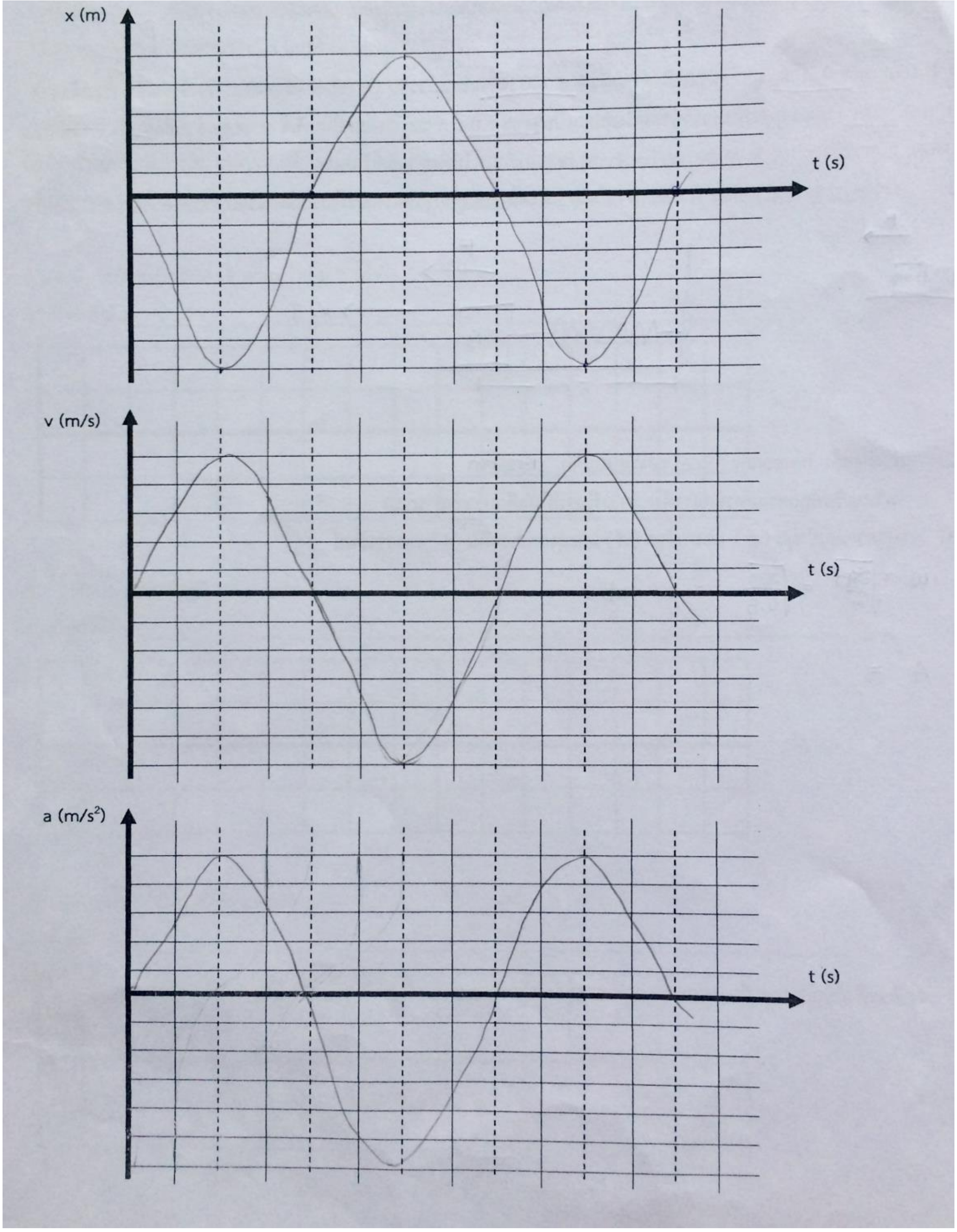


Figure 4.16. Pretest plots of displacement (x), velocity (v), and acceleration (a) as a function of time (t) of a student.

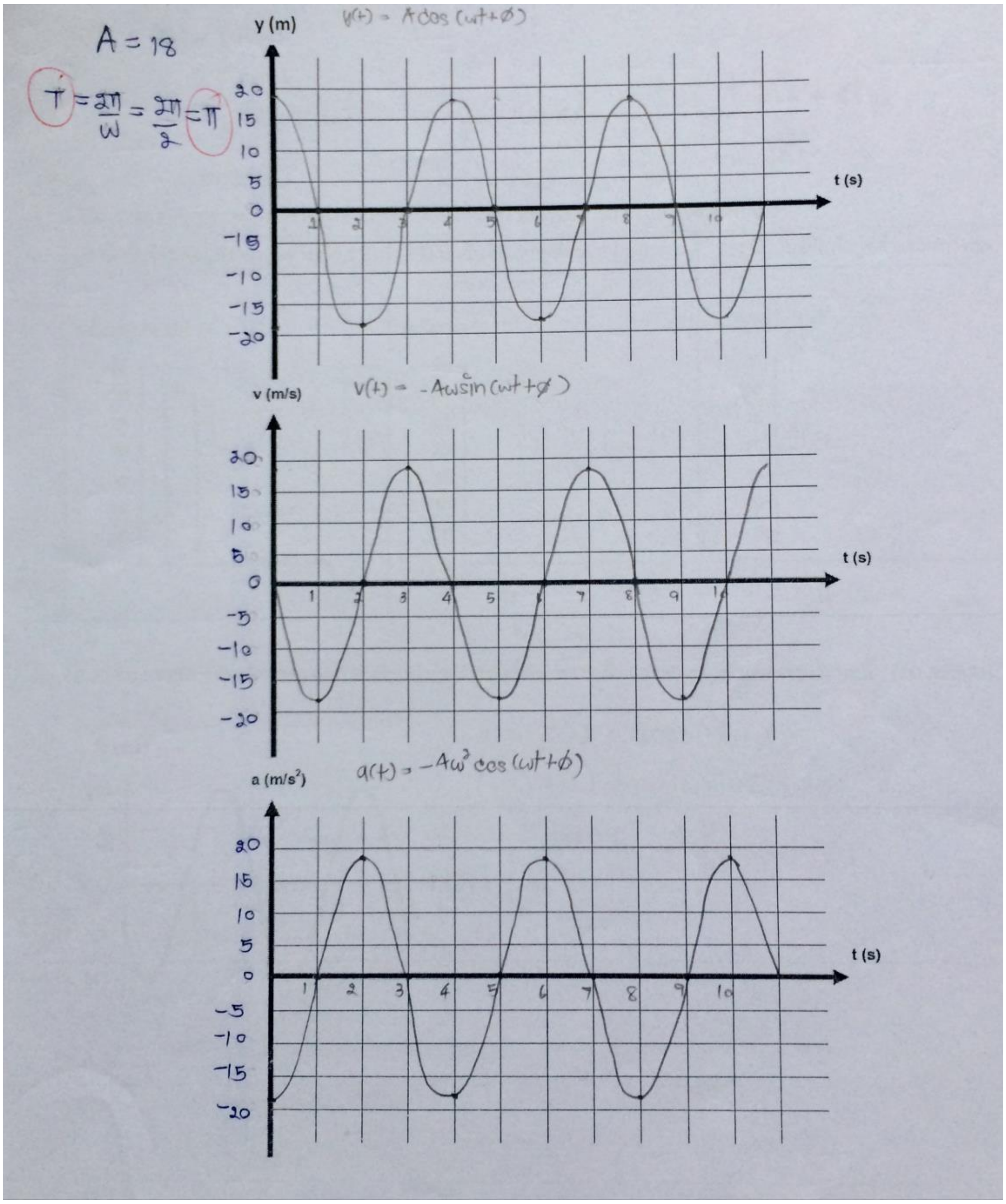


Figure 4.17. Posttest plots of displacement (y), velocity (v), and acceleration (a) as a function of time (t) of a student.

4.2.4 Energy in Simple Harmonic Motion

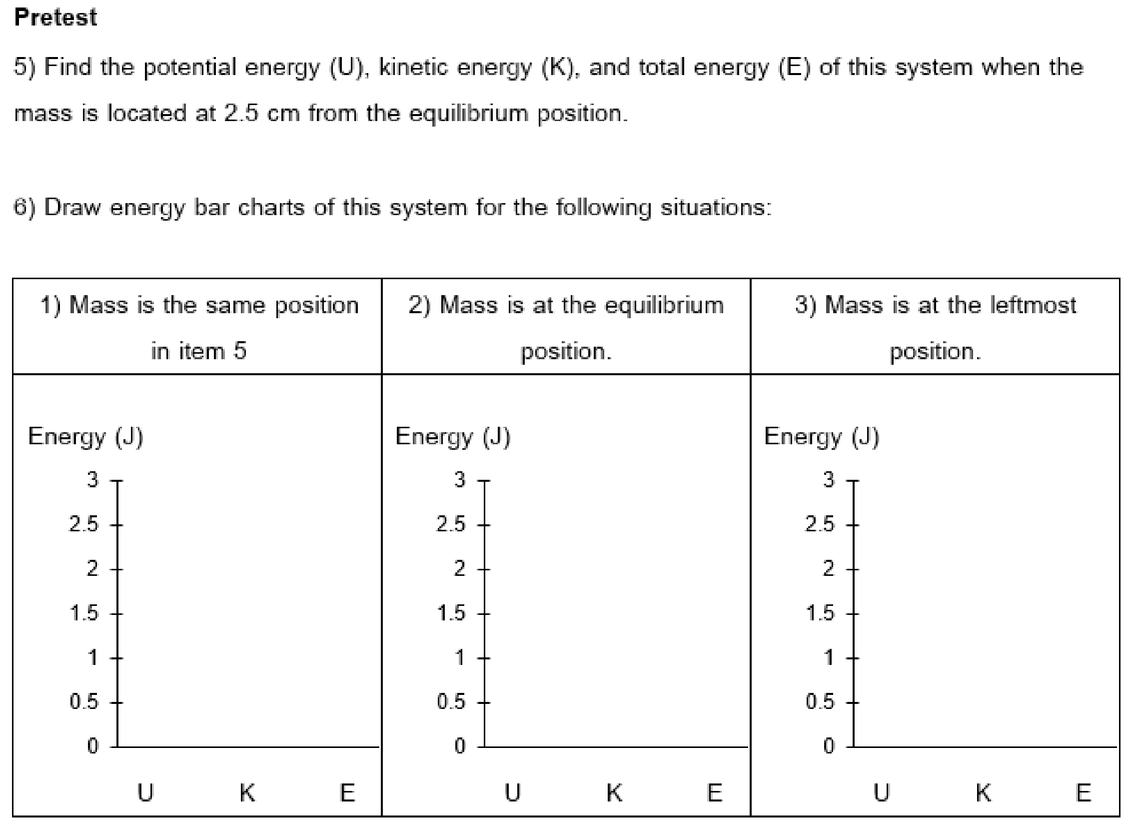
The last part of the mass-spring system and bungee jumper problem of the pre- and posttest, respectively, involved the calculation of potential, kinetic, and total energy and its corresponding bar chart representations set in different situations. These tasks belonged to item 5 and 6 as shown in Figure 4.18 and Figure 4.19. Table 4.18 was used to rate students with how coherent their answers are between item 5 and 6. In addition, Table 4.19 was utilized as a rubric for execution accuracy and evaluation in item 5. Item 5 assessed the evaluation component of students, as well as item 2. The general improvement of the evaluation component can be seen in Figure 4.20 from 15.38% of the pretest to 66.03% of the posttest.

Table 4.18. Scoring rubric for SHM problem in item 5 and 6.

Component	0	1	2	3
Planning coherence	no connection between calculated energies and bar charts	major inconsistencies between calculated energies and bar charts	minor inconsistencies between calculated energies and bar charts	clear and consistent association between calculated energies and bar charts

Table 4.19. Scoring rubric for SHM problem item 5.

Component	0	1	2	3
Execution accuracy	inappropriate or no solution for SHM energy	major mistakes in reasoning or application of the energy conservation principle in SHM	minor mistakes in reasoning or application of the energy conservation principle in SHM	completely correct and appropriate solution for SHM energy
Evaluation	no meaningful evaluation or no solution for SHM energy magnitude and unit	evaluation was present but elements or reasoning was missing or incorrect for SHM energy magnitude and unit	well thought out, meaningful, and accurate reflection on one of the three plausibility features for SHM energy magnitude and unit	well thought out, meaningful, and accurate reflection on at least two of the three plausibility features for SHM energy magnitude and unit



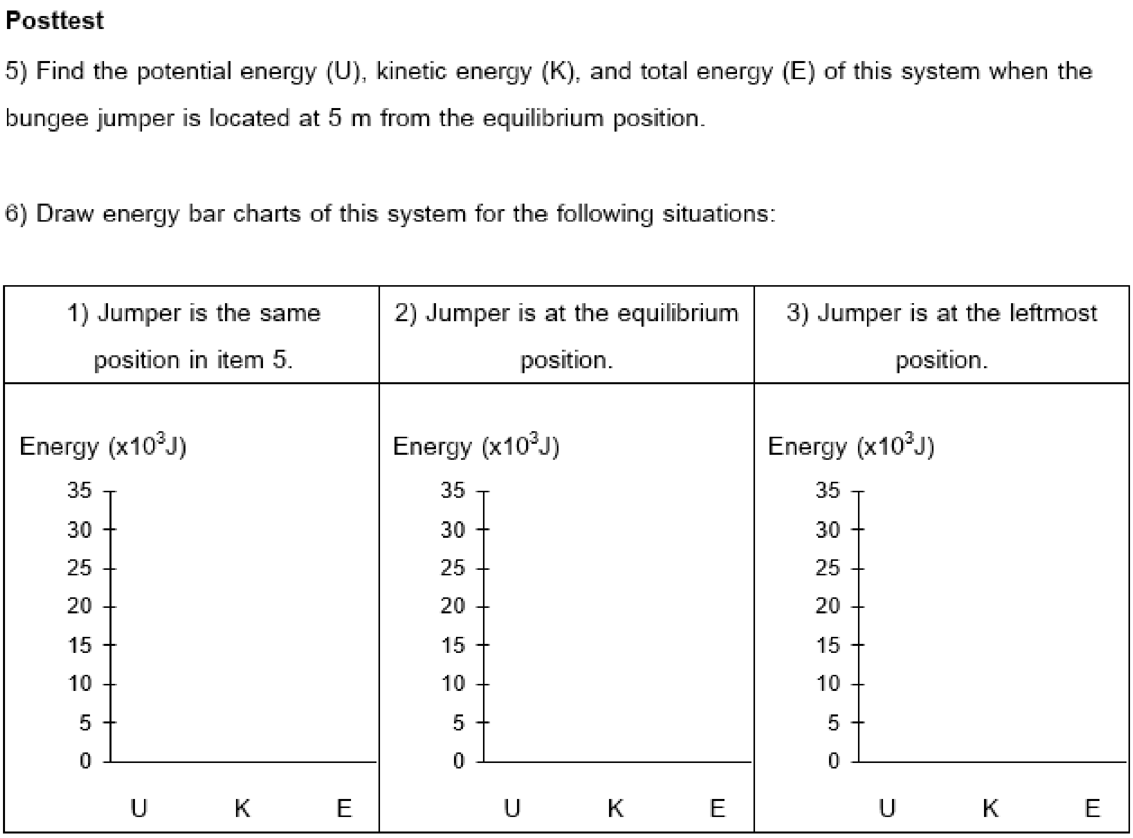
Pretest

5) Find the potential energy (U), kinetic energy (K), and total energy (E) of this system when the mass is located at 2.5 cm from the equilibrium position.

6) Draw energy bar charts of this system for the following situations:

1) Mass is the same position in item 5	2) Mass is at the equilibrium position.	3) Mass is at the leftmost position.

Figure 4.18. Item 5 and 6 of pretest.



Posttest

5) Find the potential energy (U), kinetic energy (K), and total energy (E) of this system when the bungee jumper is located at 5 m from the equilibrium position.

6) Draw energy bar charts of this system for the following situations:

1) Jumper is the same position in item 5.	2) Jumper is at the equilibrium position.	3) Jumper is at the leftmost position.
Energy ($x10^3$J) 35 30 25 20 15 10 5 0 U K E	Energy ($x10^3$J) 35 30 25 20 15 10 5 0 U K E	Energy ($x10^3$J) 35 30 25 20 15 10 5 0 U K E

Figure 4.19. Item 5 and 6 of posttest.

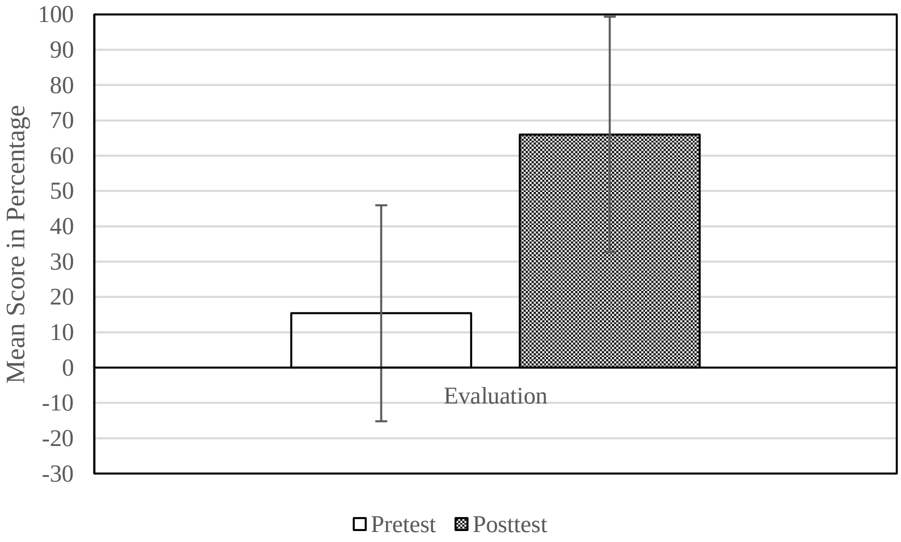
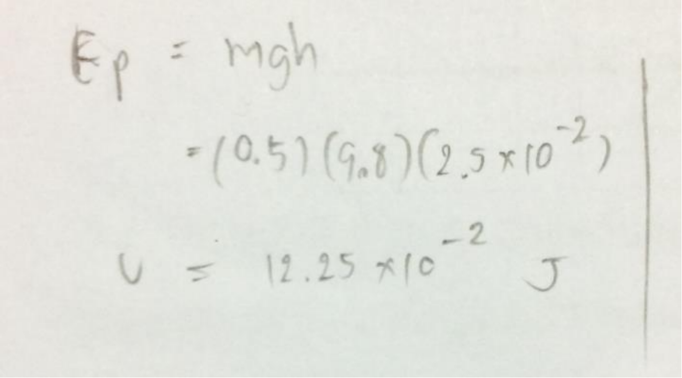


Figure 4.20. Average percentage of evaluation problem component related to SHM.

Nine of the respondents wrote energy units of joule in their posttest solutions, which is in contrast with no unit identified before the intervention. Secondly, more accurate formulas were employed by nine students to determine the potential, kinetic, and total energy. Prior to the implementation of the pedagogical strategy, written solutions showed faulty ideas. There were those who confused kinetic and potential energy. Velocity stated from the word problem was commonly used to determine the kinetic energy. However, this velocity is irrelevant because SHM causes it to change and differ from the physical context given in item 5. In five of the nine cases mentioned earlier, gravitational potential energy was computed for the spring potential energy of the horizontal mass-spring problem as observed in Figure 4.21. Assessment following the intervention revealed that this notion was rectified. Results that indicate an improved understanding of the content concur with substantially higher posttest ratings in the problem-solving components of execution accuracy and evaluation in Table 4.14.



$$E_p = mgh$$

$$= (0.5)(9.8)(2.5 \times 10^{-2})$$

$$U = 12.25 \times 10^{-2} \ J$$

Figure 4.21. Students' potential energy solution of the mass-spring system.

The energy bar chart was another task to assess students' representational fluency. This item is related to planning coherence in two ways. Students were required to properly transfer their solutions from item 5 to the bar chart representation of the system in item 6. Moreover, there were three different situations provided in item 6, which students were expected to be consistent across the charts. Twenty-two participants did not show any solution for item 6 in the pretest. Thus, it was highly likely that the sample scored well in the planning coherence component of problem-solving ability.

CHAPTER 5

SUMMARY

5.1 Conclusions

This work is aimed at developing both scientific reasoning ability and knowledge about simple harmonic motion (SHM) of second-year physics students at Prince of Songkla University. Guided inquiry instruction was built with the 3-phase learning cycle (Karplus & Butts, 1977; Anton E. Lawson & Karplus, 2002) and implemented into the lesson of SHM in a vibrations and waves course. This approach in teaching and learning supported interactive engagement through student-led problem solving, class response activity, small group classroom discussions with the aid of worksheets, and demonstrations about SHM. The effectiveness of the pedagogical intervention was assessed by the Lawson Classroom Test of Scientific Reasoning (LCTSR) and standard SHM problems.

Total mean percentage scores in LCTSR showed no significant improvement after instruction. Thus, students' scientific reasoning abilities were in general not impacted by the implemented pedagogical strategy. A possible explanation of this outcome can be attributed to the lack of continuous practice and the duration of acquiring scientific abilities (Etkina, Karelina, & Ruibal-Villasenor, 2008). In the present study, the intervention was only conducted in a span of two weeks, in which students' thinking processes may still be developing.

Through model analysis, it was further found that students tend to transition towards scientific thinking but remained in a state of confusion between conflicting mental models. These findings were observed for the subskills of proportional reasoning, control of variables, and hypothetico-deductive reasoning. Negative results with some dimensions of scientific reasoning were also noticed. Decreased ability is not consonant with Piaget’s theory of cognitive development. However, these cases were also present in other studies (Carmel et al., 2015; Stammen, Malone, & Irving, 2018) and thus warrants further investigation.

For the knowledge aspect about SHM, participants evolved closer to expert-like problem solvers as gauged by the problem-solving components of translation, execution accuracy, evaluation, and planning coherence. This result was expected as problem-solving was one of the focus in the intervention. All components reported substantial improvements, except for translation. No change in overall score was also found with correlational reasoning which may explain its association with the translation component because students need to relate the situation given in the word problem and their drawing. Due to the problem task of prompting students to present a diagram of the physical situation, it also seemed to affect their problem-solving strategy (Heckler, 2010). Moreover, written solutions of students to the problems revealed that SHM misconceptions were corrected, despite some erroneous ideas that persisted even after the intervention. For instance, it can be noted that students were more adept in linking the graphs of displacement, velocity, and acceleration as functions of time.

Guided inquiry encourages the students to think by themselves and discuss their ideas to their peers. The course was designed to follow a logical line of thinking in a cyclic manner to continuously improve reasoning and knowledge about the subject. This intervention that was implemented to the vibrations and waves class was assumed to be better than traditional lectures as it is grounded on the principles of the constructivist philosophy. Overall, the evaluation of the course revealed that the suggested instructional approach can be advantageous to some aspects of scientific reasoning and content knowledge. Nevertheless, more work is necessary to reform the course in the light of challenges in its design and implementation, which both contribute to its outcome.

5.2 Limitations

Normally, small sized courses such as vibrations and waves are limited to a few registrants of about less than 30 on average in a semester. This sample size constrains the level of statistical certainty in the current study. Thus, the findings cannot be generalized for second-year physics students. To obtain richer information, data from interviews with students may be conducted.

Active learning methods necessitate longer class time than the standard lecture. The wealth of topics usually covered in a typical course may not be enough for interactive engagement. Effectively reducing the list of subject matter, which focuses on the most challenging for the student sample, is advisable. In addition, some students may tend to disengage from a reformed course since they are more accustomed to the conventional lecture. This issue may hinder the implementation of the pedagogical strategy and the eventual result of the assessments.

Psychometric quality of the pre- and posttest instruments may also affect the validity of the present study. For example, the LCTSR is popularly utilized and widely approved in the science education research community. However, as pointed out by Bao and colleagues (2018), they suggested that caution should be exercised in the interpretation of results because of the LCTSR dimension issues with question design which impact the assessment of scientific reasoning subskills. LCTSR is also affected by the ceiling effect as it is recognized to be a simple test. Developing a new instrument to measure scientific abilities may be an option to eliminate these limitations.

5.3 Recommendations

Since active learning methods for introductory physics courses in large university classes are commonly researched especially in Thailand (Rakkapao, Pengpan, Srikeaw, & Prasitpong, 2014; Sujarittham et al., 2016; Tanahoung, Chitaree, Soankwan, Sharma, & Johnston, 2009), it is interesting to contemplate on reforming teaching as well on small sized physics courses which are mostly based on the traditional lecture. The results obtained from the current study provides an opportunity to extend work in this trajectory of sample contexts. The aim would not only be targeted for students' improvement of content knowledge but more importantly their scientific thinking ability.

Although guided inquiry instruction through the 3-phase learning cycle significantly supported knowledge of simple harmonic motion, it did otherwise for students' scientific reasoning ability which only advanced in a small degree. Hence, it would be beneficial to examine carefully other active learning methods. For instance, the outlook of a similar instructional method called the Investigative Science Learning Environment is to practice students to think critically by doing science themselves (Etkina & Van Heuvelen, 2001).

Furthermore, statistical analysis and model analysis of the assessment results supplied useful insights about students' scientific reasoning ability and knowledge of SHM. However, the issue of sample size may be mitigated by collecting more data from different cohorts of second-year physics students. Alternatively, a mixed methods approach would strengthen the research findings. Student interviews, for example, would help validate the results if incorporated into subsequent studies.

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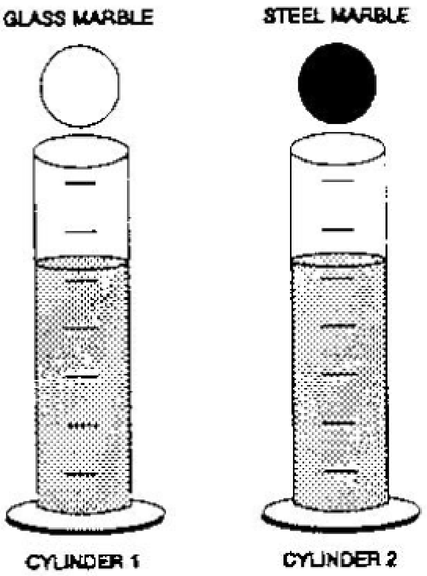
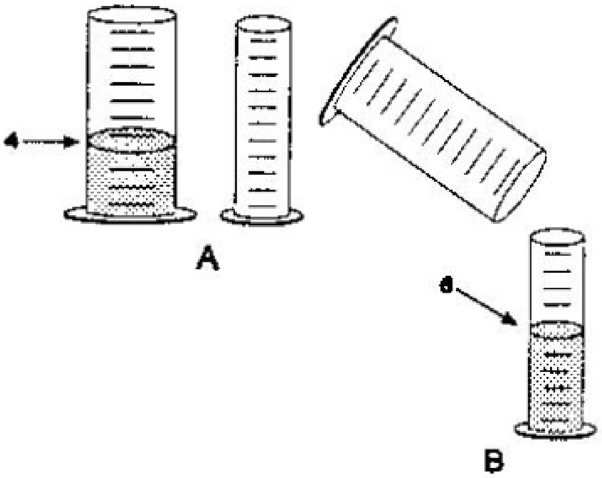
APPENDIX A

LAWSON CLASSROOM TEST OF SCIENTIFIC REASONING

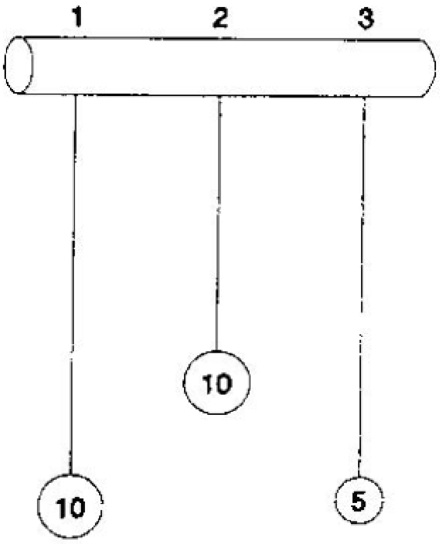
1. Suppose you are given two clay balls of equal size and shape. The two clay balls also weigh the same. One ball is flattened into a pancake-shaped piece. Which of these statements is correct?
   a. The pancake-shaped piece weighs more than the ball
   [✓ b.] The two pieces still weigh the same
   c. The ball weighs more than the pancake-shaped piece
2. because
   a. the flattened piece covers a larger area.
   b. the ball pushes down more on one spot.
   c. when something is flattened it loses weight.
   [✓ d.] clay has not been added or taken away.
   e. when something is flattened it gains weight.
3. To the right are drawings of two cylinders filled to the same level with water. The cylinders are identical in size and shape.
   Also shown at the right are two marbles, one glass and one steel. The marbles are the same size but the steel one is much heavier than the glass one.
   When the glass marble is put into Cylinder 1 it sinks to the bottom and the water level rises to the 6th mark. If we put the steel marble into Cylinder 2, the water will rise
   [✓ a.] to the same level as it did in Cylinder 1
   b. to a higher level than it did in Cylinder 1
   c. to a lower level than it did in Cylinder 1
4. because
   a. the steel marble will sink faster.
   b. the marbles are made of different materials.
   c. the steel marble is heavier than the glass marble.
   d. the glass marble creates less pressure.
   [✓ e.] the marbles are the same size.





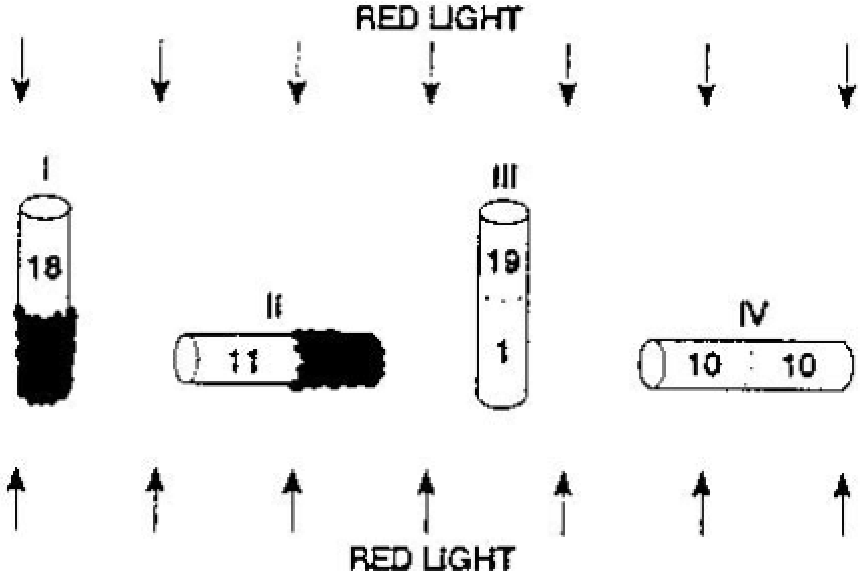
5. To the right are drawings of a wide and a narrow cylinder. The cylinders have equally spaced marks on them. Water is poured into the wide cylinder up to the 4th mark (see A). This water rises to the 6th mark when poured into the narrow cylinder (see B).
   Both cylinders are emptied (not shown) and water is poured into the wide cylinder up to the 6th mark. How high would this water rise if it were poured into the empty narrow cylinder?
   a. to about 8
   [✓ b.] to about 9
   c. to about 10
   d. to about 12
   e. none of these answers is correct
6. because
   a. the answer can not be determined with the information given.
   b. it went up 2 more before, so it will go up 2 more again.
   [✓ c.] it goes up 3 in the narrow for every 2 in the wide.
   d. the second cylinder is narrower.
   e. one must actually pour the water and observe to find out.
7. Water is now poured into the narrow cylinder (describe in item 5 above) up to the 11th mark. How high would this water rise if it were poured into the empty wide cylinder?
   a. to about 7 1/2
   b. to about 9
   c. to about 8
   [✓ d.] to about 7 1/3
   e. none of these answers is correct
8. because
   [✓ a.] the ratios must stay the same.
   b. one must actually pour the water and observe to find out.
   c. the answer can not be determined with the information given.
   d. it was 2 less before so it will be 2 less again.
   e. you subtract 2 from the wide for every 3 from the narrow.

9. At the right are drawings of three strings hanging from a bar. The three strings have metal weights attached to their ends. String 1 and String 3 are the same length. String 2 is shorter. A 10 unit weight is attached to the end of String 1. A 10 unit weight is also attached to the end of String 2. A 5 unit weight is attached to the end of String 3. The strings (and attached weights) can be swung back and forth and the time it takes to make a swing can be timed.
   Suppose you want to find out whether the length of the string has an effect on the time it takes to swing back and forth. Which strings would you use to find out?
   a. only one string
   b. all three strings
   c. 2 and 3
   d. 1 and 3
   [✓ e.] 1 and 2



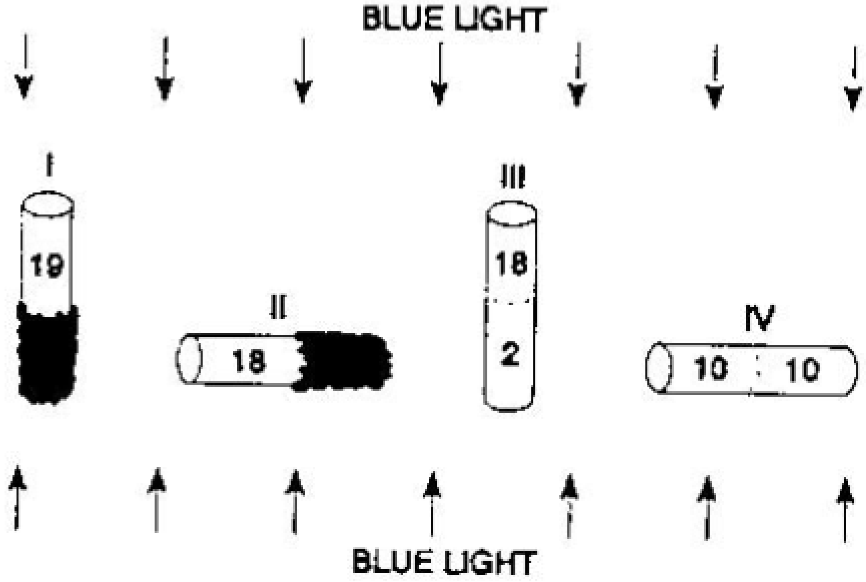
10. because
   a. you must use the longest strings.
   b. you must compare strings with both light and heavy weights.
   [✓ c.] only the lengths differ.
   d. to make all possible comparisons.
   e. the weights differ.

11. Twenty fruit flies are placed in each of four glass tubes. The tubes are sealed. Tubes I and II are partially covered with black paper; Tubes III and IV are not covered. The tubes are placed as shown. Then they are exposed to red light for five minutes. The number of flies in the uncovered part of each tube is shown in the drawing.



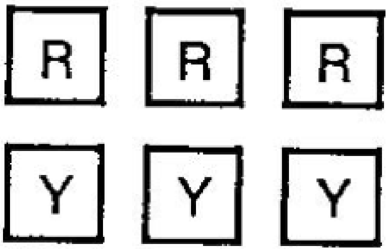
   This experiment shows that flied respond to (respond means move to or away from):
   a. red light but not gravity
   [✓ b.] gravity but not red light
   c. both red light and gravity
   d. neither red light nor gravity

12. because
    [✓ a.] most flies are in the upper end of Tube III but spread about evenly in Tube II.
    b. most flies did not go to the bottom of Tubes I and III.
    c. the flies need light to see and must fly against gravity.
    d. the majority of flies are in the upper ends and in the lighted ends of the tubes.
    e. some flies are in both ends of each tube.
13. In a second experiment, a different kind of fly and blue light was used. The results are shown in the drawing.



    These data show that these flies respond to (respond means move to or away from):
    a. blue light but not gravity
    b. gravity but not blue light
    [✓ c.] both blue light and gravity
    d. neither blue light nor gravity
14. because
    a. some flies are in both ends of each tube.
    b. the flies need light to see and must fly against gravity.
    c. the flies are spread about evenly in Tube IV and in the upper end of Tube III.
    [✓ d.] most flies are in the lighted end of Tube II but do not go down in Tubes I and III.
    e. most flies are in the upper end of Tube I and the lighted end of Tube II.

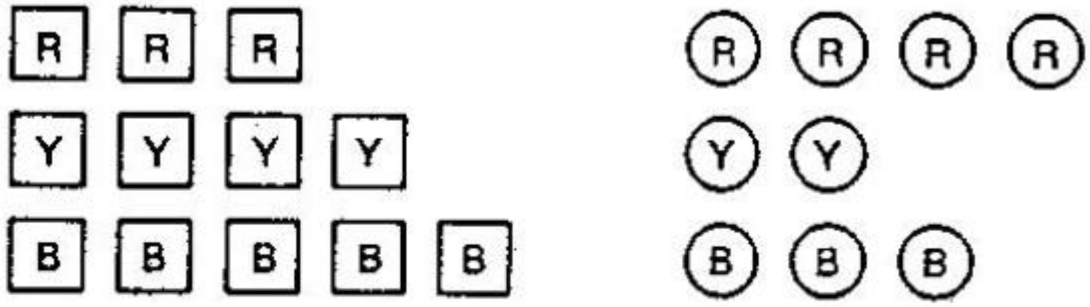
15. Six square pieces of wood are put into a cloth bag and mixed about. The six pieces are identical in size and shape, however, three pieces are red and three are yellow. Suppose someone reaches into the bag (without looking) and pulls out one piece. What are the chances that the piece is red?



    a. 1 chance out of 6
    b. 1 chance out of 3
    [✓ c.] 1 chance out of 2
    d. 1 chance out of 1
    e. cannot be determined
16. because
    [✓ a.] 3 out of 6 pieces are red.
    b. there is no way to tell which piece will be picked.
    c. only 1 piece of the 6 in the bag is picked.

d. all 6 pieces are identical in size and shape.
e. only 1 red piece can be picked out of the 3 red pieces.

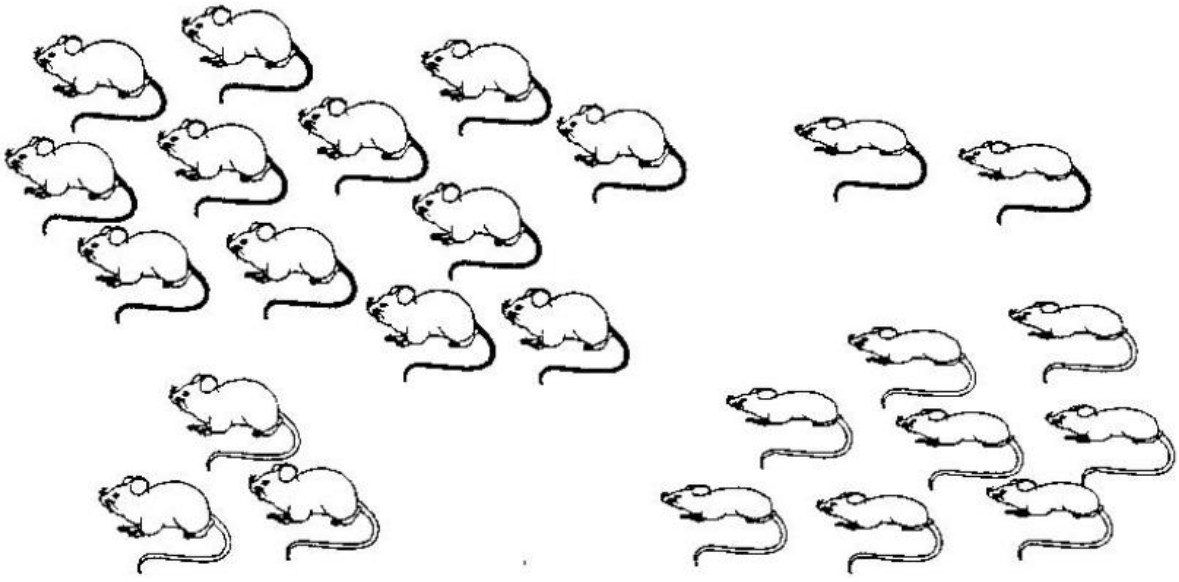
17. Three red square pieces of wood, four yellow square pieces, and five blue square pieces are put into a cloth bag. Four red round pieces, two yellow round pieces, and three blue round pieces are also put into the bag. All the pieces are then mixed about. Suppose someone reaches into the bag (without looking and without feeling for a particular shape piece) and pulls out one piece.



What are the chances that the piece is a red round or blue round piece?
a. cannot be determined
[✓ b.] 1 chance out of 3
c. 1 chance out of 21
d. 15 chances out of 21
e. 1 chance out of 2

18. because
a. 1 of the 2 shapes is round.
b. 15 of the 21 pieces are red or blue.
c. there is no way to tell which piece will be picked.
d. only 1 of the 21 pieces is picked out of the bag.
[✓ e.] 1 of every 3 pieces is a red or blue round piece.

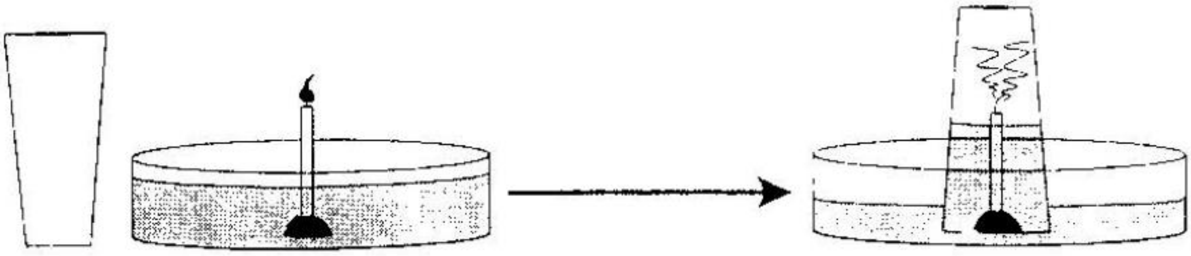
19. Farmer Brown was observing the mice that live in his field. He discovered that all of them were either fat or thin. Also, all of them had either black tails or white tails. This made him wonder if there might be a link between the size of the mice and the color of their tales. So he captured all of the mice in one part of his field and observed them. Below are the mice that he captured.



Do you think there is a link between the size of the mice and the color of their tails?
[✓ a.] appears to be a link
b. appears not to be a link
c. cannot make a reasonable guess

20. because
a. there are some of each kind of mouse.
b. there may be a genetic link between mouse size and tail color.
c. there were not enough mice captured.
[✓ d.] most of the fat mice have black tails while most of the thin mice have white tails.
e. as the mice grew fatter, their tails became darker.

21. The figure below at the left shows a drinking glass and a burning birthday candle stuck in a small piece of clay standing in a pan of water. When the glass is turned upside down, put over the candle, and placed in the water, the candle quickly goes out and water rushes up into the glass (as shown at the right).



This observation raises an interesting question: Why does the water rush up into the glass? Here is possible explanation. The flame converts oxygen into carbon dioxide. Because oxygen does not dissolve rapidly into water but carbon dioxide does, the newly formed carbon dioxide dissolves rapidly into the water, lowering the air pressure inside the glass. Suppose you have the materials mentioned above plus some matches and some dry ice (dry ice is frozen carbon dioxide). Using some or all of the materials, how could you test this possible explanation?
[✓ a.] Saturate the water with carbon dioxide and redo the experiment noting the amount of water rise.
b. The water rises because oxygen is consumed, so redo the experiment in exactly the same way to show water rise due to oxygen loss.
c. Conduct a controlled experiment varying only the number of candles to see if that makes a difference.
d. Suction is responsible for the water rise, so put a balloon over the top of an open-ended cylinder and place the cylinder over the burning candle.
e. Redo the experiment, but make sure it is controlled by holding all independent variables constant; then measure the amount of water rise.

22. What result of your test (mentioned in #21 above) would show that your explanation is probably wrong?
[✓ a.] The water rises the same as it did before.
b. The water rises less than it did before.
c. The balloon expands out.
d. The balloon is sucked in.

23. A student put a drop of blood on a microscope slide and then looked at the blood under a microscope. As you can see in the diagram below, the magnified red blood cells look like little round balls. After adding a few drops of salt water to the drop of blood, the student noticed that the cells appeared to become smaller.

Magnified Red Blood Cells After Adding Salt Water

This observation raises an interesting question: Why do the red blood cells appear smaller? Here are two possible explanations: I. Salt ions (Na+ and Cl-) push on the cell membranes and make the cells appear smaller. II. Water molecules are attracted to the salt ions so the water molecules move out of the cells and leave the cells smaller.

To test these explanations, the student used some salt water, a very accurate weighing device, and some water-filled plastic bags, and assumed the plastic behaves just like red-blood-cell membranes. The experiment involved carefully weighing a water-filled bag, placing it in a salt solution for ten minutes and then reweighing the bag.

What result of the experiment would best show that explanation I is probably wrong?

[✓ a.] the bag loses weight
b. the bag weighs the same
c. the bag appears smaller

24. What result of the experiment would best show that explanation II is probably wrong?

a. the bag loses weight
[✓ b.] the bag weighs the same
c. the bag appears smaller

Dimension	Items
Conservation of mass and volume	1, 2, 3, 4
Proportional reasoning	5, 6, 7, 8
Control of variables	9, 10, 11, 12, 13, 14
Probabilistic reasoning	15, 16, 17, 18
Correlational reasoning	19, 20
Hypothetico-deductive reasoning	21, 22, 23, 24

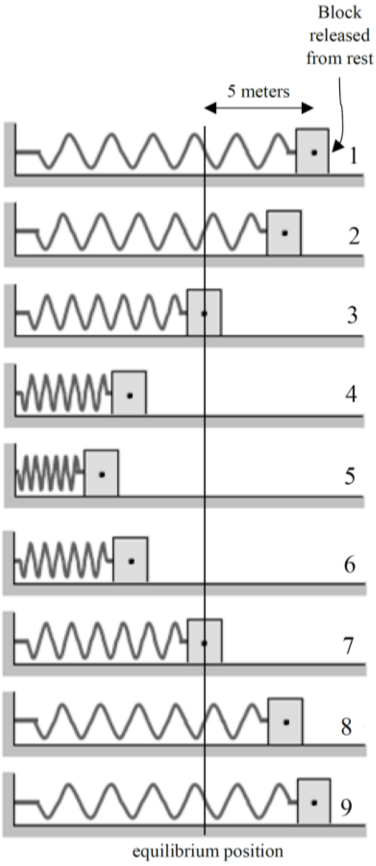
APPENDIX B

Worksheet SHM

Qualitative Analysis of Motion

A block is connected to a spring, one end of which is attached to a wall. (Neglect the mass of the spring, and assume the surface is frictionless.)

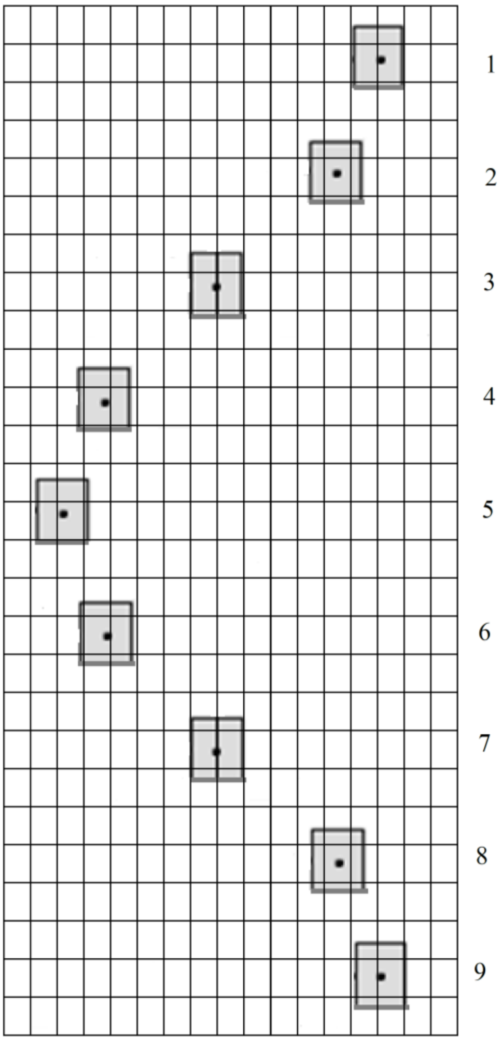
The spring is stretched 5 m to the right of equilibrium and released from rest at instant 1. Equilibrium of the block is shown as a solid vertical line at the middle. The strobe diagram at right shows the subsequent motion of the block (*i.e.*, the block is shown at equal time intervals).



A. Carefully consider the motion from instant 1 to instant 9 and draw *velocity vectors*. Indicate arrows between two points as in instant 1 and instant 2 (*e.g.*, $\vec{v}_{av-12}$) in the grid of the next page. Describe how fast or slow the block moves along the surface using the velocity vectors in your diagram.

B. Use your velocity vectors from part **A** to determine graphically the direction of the average acceleration ($\vec{a}_{av} \equiv \Delta\vec{v}/\Delta t$) from instant 4 to instant 6. Redraw $\vec{v}_{av-45}$ and $\vec{v}_{av-56}$ in the same grid of the next page and indicate the *acceleration vector*.

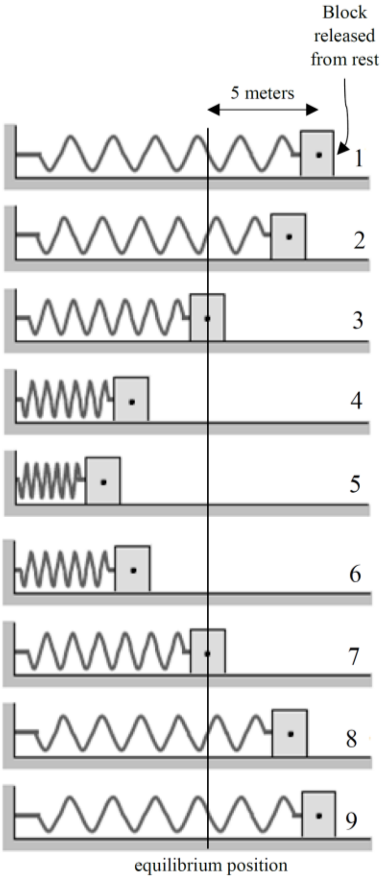
Grid for parts **A** and **B**.



C. According to Newton's second law ($\sum \vec{F} \equiv m\vec{a}$), the acceleration vector points in the same direction as the net force vector (*i.e.,* spring force). Are your results above consistent with your knowledge of forces? Does the force have to follow the direction of motion of the block?

✓ Check your results with the instructor.

D. Suppose that the experiment of the mass-spring system above was repeated exactly as before, except that the block is now initially compressed to the left of equilibrium and then released from rest. Overlay drawings of the given physical situation (*i.e.,* initially compressed spring) on the right figure. Using the same approach as before, determine at what instants do the block have minimum and maximum values (*i.e.,* magnitudes) with the following quantities: velocity, acceleration, and force.



Differential equation of motion

Consider again the situation depicted in **Qualitative Analysis of Motion**, in which a block of mass *m* attached to an (ideal) spring of force constant *k* undergoes simple harmonic motion on a level, frictionless surface.

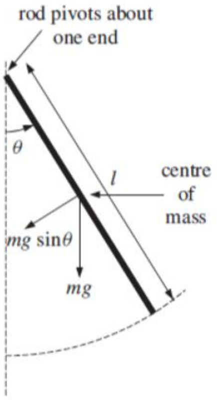
E. Using Newton's second law in one dimension, $\sum F = m\ddot{x}$, write down the differential equation that governs the motion of the block. The net force exerted on the block may be called a *restoring force*. Justify this term on the basis of your differential equation.

F. Show by direct substitution that the following functions are solutions to the differential equation you wrote down in part **E**. As part of your answer, specify the conditions (if any) that must be met by the parameters *A*, ω, and ϕ in order for each function to be a valid solution.

$x(t) = A\cos(\omega t + \phi)$	$x(t) = A\sin(\omega t + \phi)$

✓ Check your results with the instructor.

G. A physical pendulum shown below is different from a simple pendulum because its mass is distributed over the whole body. It consists of a uniform rod of length l that pivots about a horizontal axis at its upper end. It is displaced at a small angle θ and then released. Write a differential equation according to Newton's second law describing the motion of this pendulum. Identify the angular frequency ω of this situation.



Expressing position as a function of time

H. Consider again the motion of the block in **Qualitative Analysis of Motion**, including the initial conditions of the motion (*i.e.,* moved 5 m to the right of equilibrium and released from rest). Suppose that the strobe diagram in **Qualitative Analysis of Motion** has a time interval of 0.10 s elapsed between consecutive pictures. For each functions you examined in part **F** (see below), evaluate all constant parameters (A, ω, and ϕ_0) so as to completely describe the position of the block as a function of time.

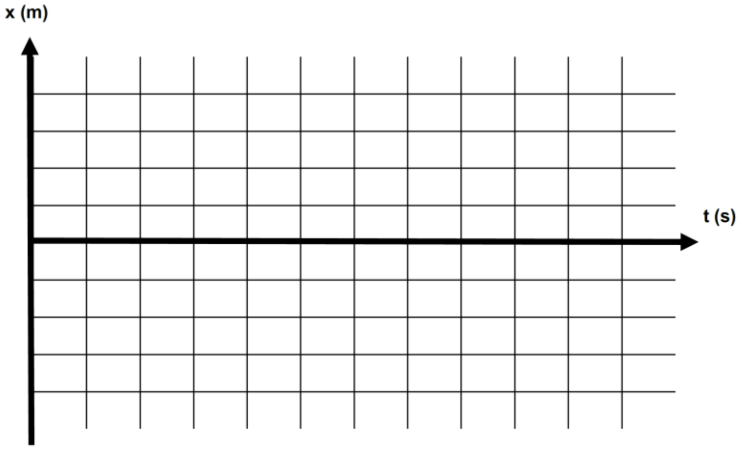
i. $x(t) = A\cos(\omega t + \phi)$

ii. $x(t) = A\sin(\omega t + \phi)$

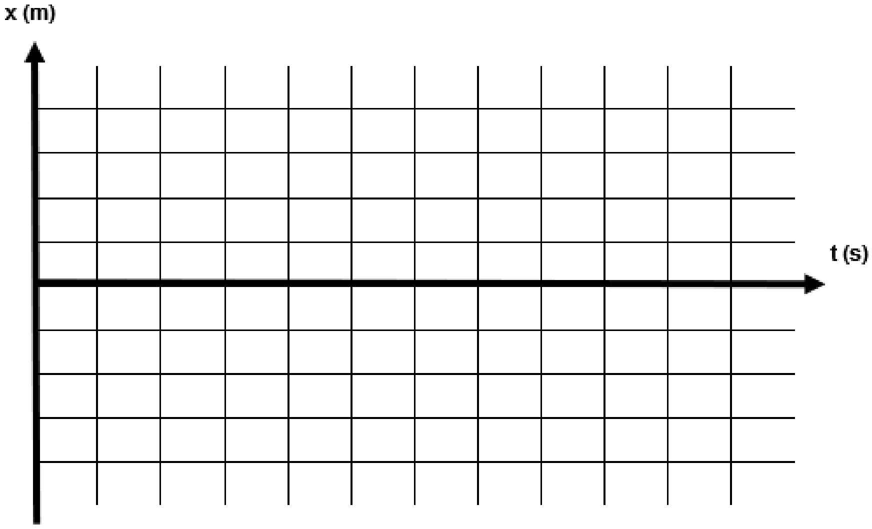
I. Examine your solution in part **H** using the relationship: $\sin(a \pm b) = \sin a \cos b \pm \cos a \sin b$

J. Draw the corresponding displacement versus time (x-t) graph for each expression in part **H**. Are your results consistent with part **H**?

i.



ii.



✓ Check your results with the instructor.

K. Examine the following dialogue below.

Chris: "The cosine function is the same as a sine curve that has been shifted along the time axis to the left by $\pi / 2$ radians."

Pat: "That's right. That means that the function $\cos \omega t$ is identical to $\sin(\omega t - \pi / 2)$, because the phase shift of $-\pi / 2$ shifts the sine curve to the left by $\pi / 2$."

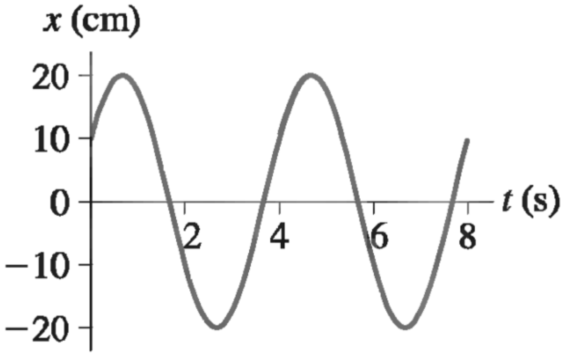
Chris' statement is correct, however Pat's response is *incorrect*. Identify the error in Pat's reasoning and describe how you would modify Pat's statement so that it would be correct.

Velocity and acceleration of simple harmonic motion

L. Use the information in part **H** to find expressions of velocity and acceleration as functions of time.

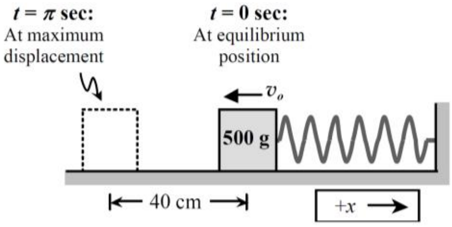
✓ Check your results with the instructor.

M. Using the displacement versus time (x-t) graph below, write the expressions for displacement, velocity, and acceleration as functions of time of this system. Express constant values in SI units.



Constant SHM parameters

N. A 500-g block is placed on a level, frictionless surface and attached to an ideal spring. At t = 0 the block moves through the equilibrium position with speed v_o in the –x direction, as shown below. At $t = \pi$ s, the block reaches its maximum displacement of 40 cm to the left of equilibrium. Evaluate all constant parameters (A, ω, and ϕ) and express it in SI units.



O. Consider the following statement about the situation described above.

"It takes the first π seconds for the block to travel 40 cm, so the initial speed v_o can be found by dividing 40 cm by π seconds."

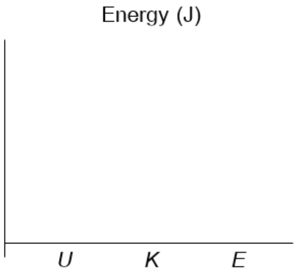
Do you agree or disagree with this statement? If so, explain why you agree. If not, explain why you disagree and calculate the initial speed v_o of the block.

P. With your knowledge about the energy conservation principle and elastic potential energy, find the potential energy (U), kinetic energy (K), and total energy (E) of this system when the mass is located at the equilibrium position. Express your answers in SI units.

✓ Check your results with the instructor.

Q. Suppose that the experiment of the mass-spring system in part **N** was repeated exactly as before, except that the block is now attached to a vertical spring as shown below. Using the same approach as before, evaluate all constant parameters (*A*, ω, and ϕ).

R. Draw an energy bar chart with specific values for potential energy (*U*), kinetic energy (*K*), and total energy (*E*) when the block is 40 cm above equilibrium of the vertical mass-spring system described in part **Q**.



Factors affecting the vibration period

S. Suppose that a simple pendulum on Planet X, where the value of g is unknown, oscillates with a period T = 2 s. What is the period of this pendulum if:

i. Its mass is four times the original mass? Explain. Note that you do not know that value of m, L, or g, so do not assume any specific values. The required analysis involves thinking about ratios.

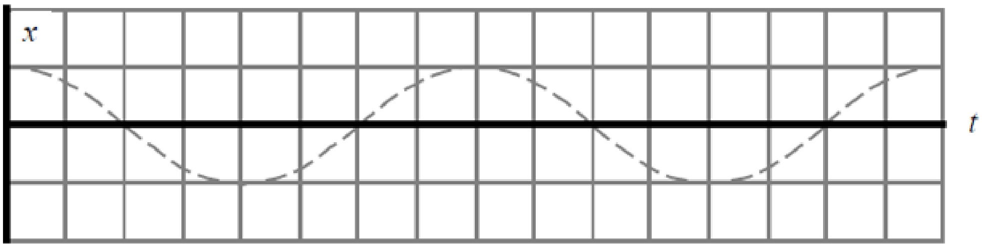
ii. Its length is four times the original length?

iii. Its oscillation amplitude is four times the original amplitude?

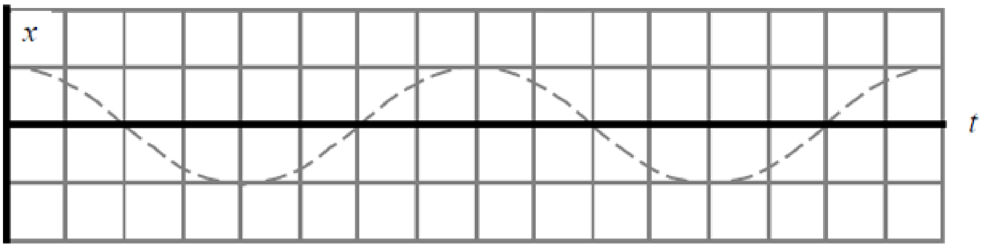
✓ Check your results with the instructor.

T. Draw the corresponding displacement versus time graphs for each case of the simple pendulum described in part **S**. The dashed line represents the original graph with a period *T* = 2 s.

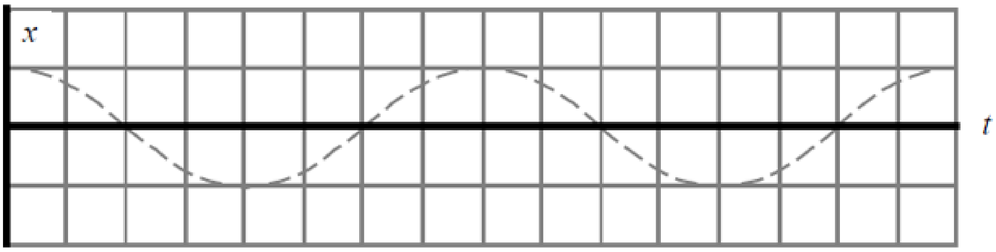
i. Mass is four times the original mass.



ii. Length is four times the original length.



iii. Amplitude is four times the original amplitude.



APPENDIX C

Name____ID number__________________

Simple Harmonic Motion Pretest Problem

A mass (m = 0.50 kg) is attached to one end of a spring (k = 200 N/m) in a horizontal frictionless surface. Another end of the spring is attached to the wall. If, when we observe (t = 0 s), the mass is at the left of the equilibrium position with distance 5.0 cm, and moving to the equilibrium point with speed 3 m/s.

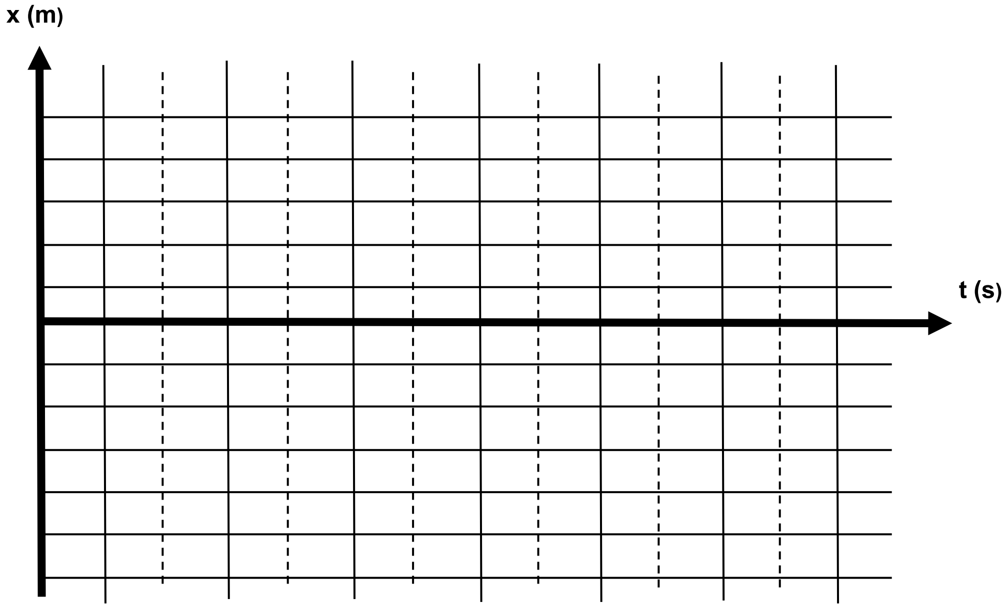
Convention: SHM equation is $x(t) = A\cos(\omega t + \phi)$ and the right-hand side is positive.

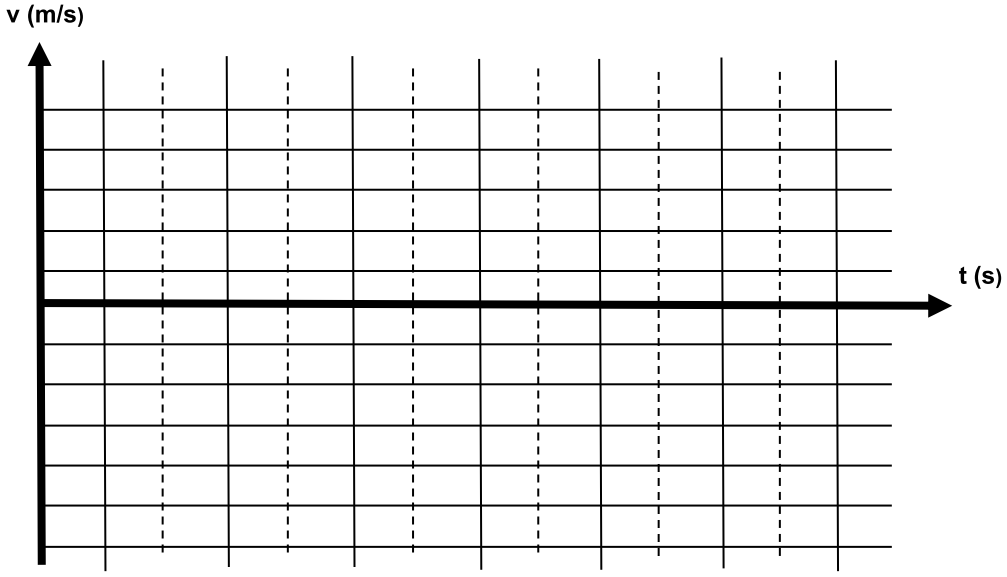
1) Draw a figure of this mass-spring system at t = 0 s, and specify arrows for displacement, velocity, acceleration, and restoring force on the mass.

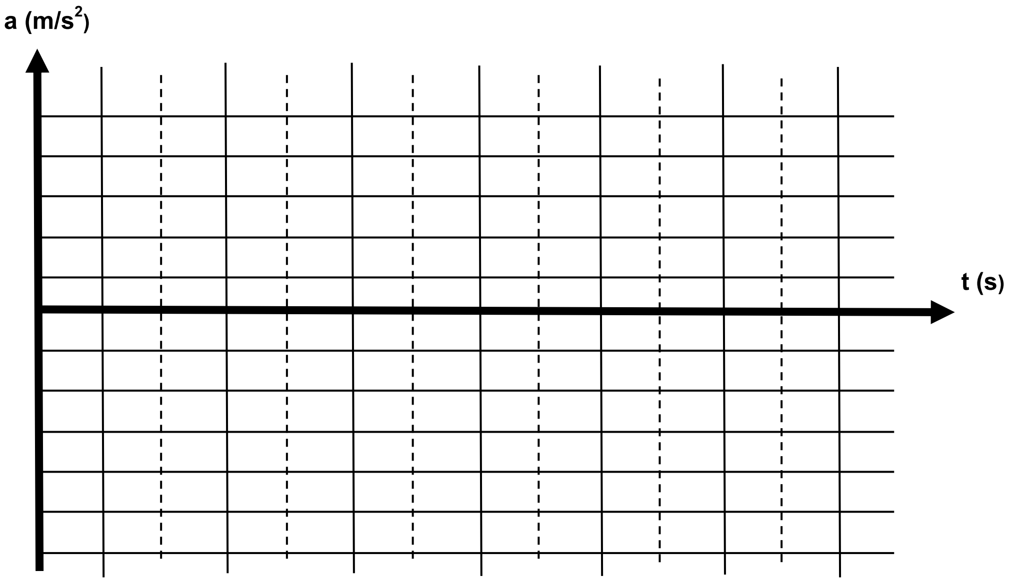
2) Find the angular frequency (ω), amplitude (A), and phase constant (ϕ) of this oscillation.

3) Write the expressions for displacement, velocity, and acceleration as functions of time of this system.

4) Draw the displacement-time (x-t), velocity-time (v-t), and acceleration-time (a-t) graphs of this system.

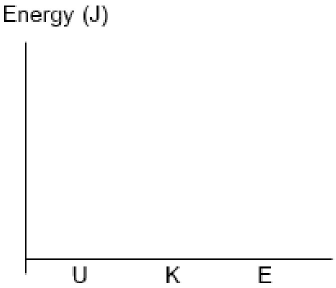
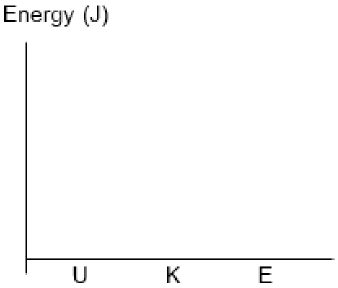
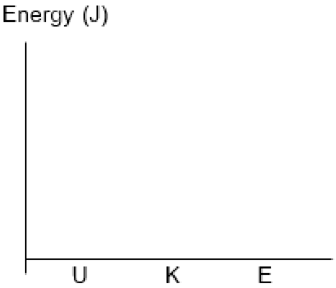






5) Find the potential energy (U), kinetic energy (K), and total energy (E) of this system when the mass is located at 2.5 cm from the equilibrium position.

6) Draw energy bar charts of this system for the following situations:

1) Mass is the same position in 1.6	2) Mass is at the equilibrium position	3) Mass is at the leftmost position
		

Name____ID number__________________

Simple Harmonic Motion Posttest Problem

A bungee jumper with a mass of 60 kg is attached to an elastic rope from a high bridge. After free fall, the rope behaves like an ideal spring with force constant k = 240 N/m. Initially (t = 0 s), it is observed that the jumper, who is positioned 15 m below the equilibrium, moves upward with a speed of 12.5 m/s. Assume that the up and down motion of the bungee jumper, oscillating about an equilibrium position (y = 0) is approximately simple harmonic.

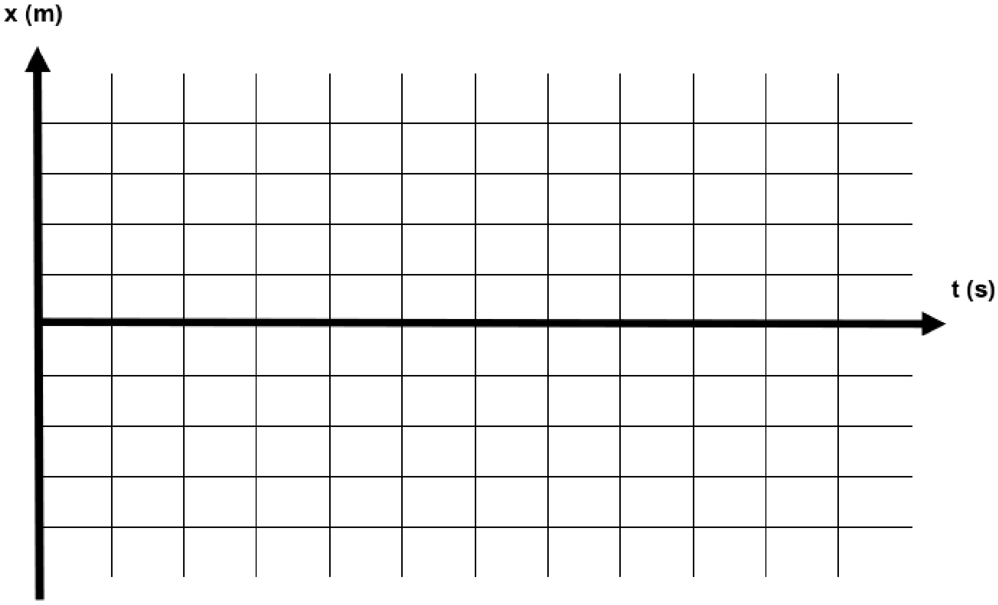
Convention: SHM equation is $y(t) = A\cos(\omega t + \phi)$ and upward is positive.

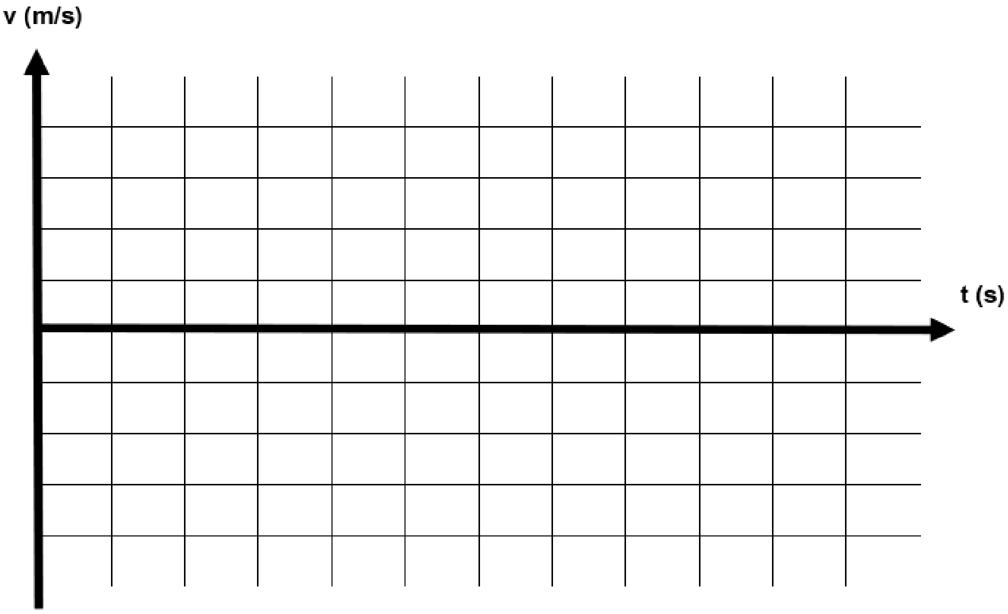
1) Draw a figure of this situation at t = 0 s, and specify arrows for displacement, velocity, acceleration, and restoring force on the bungee jumper.

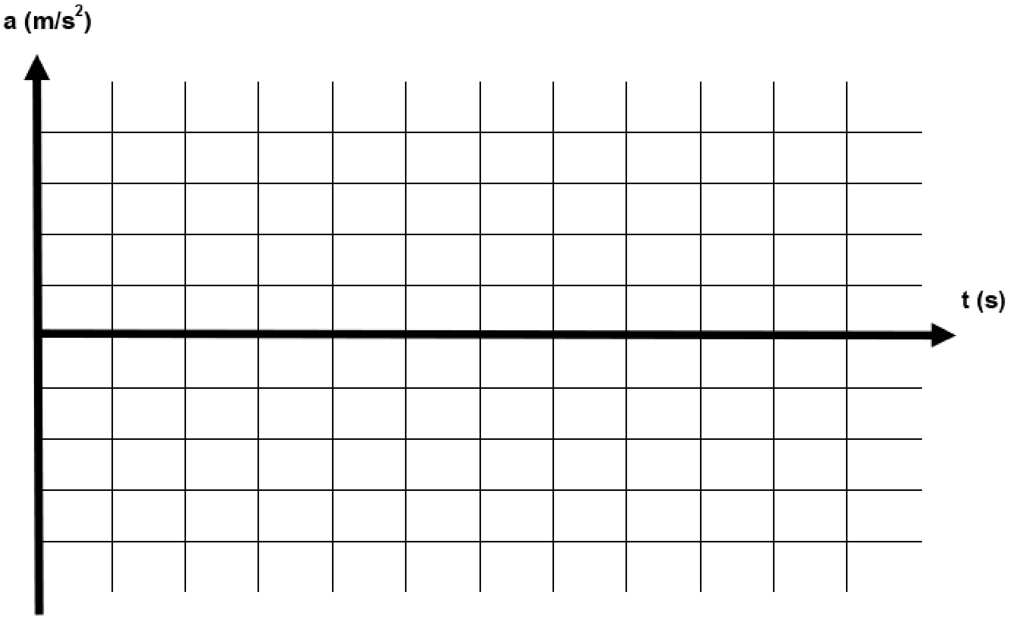
2) Find the angular frequency (ω), amplitude (A), and phase constant (ϕ) of this oscillation.

3) Write the expressions for displacement, velocity, and acceleration as functions of time of this system.

4) Draw the displacement-time (x-t), velocity-time (v-t), and acceleration-time (a-t) graphs of this system.

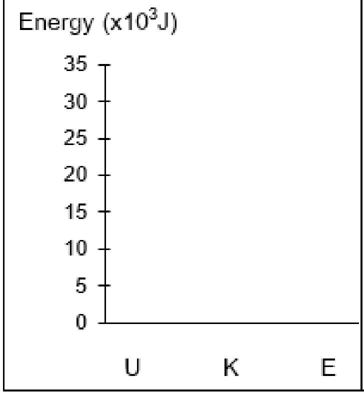
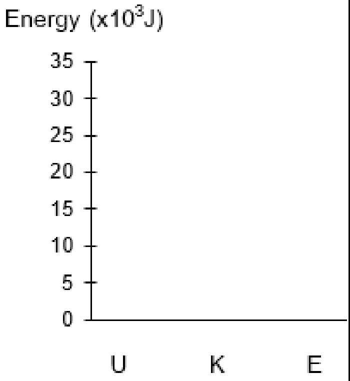
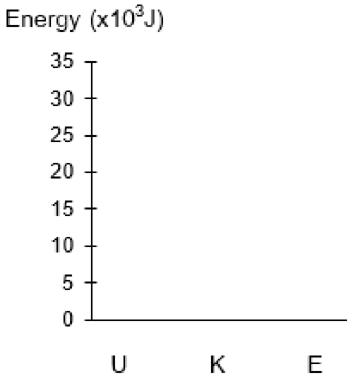



v (m/s)
t (s)


a (m/s²)
t (s)

5) Find the potential energy (U), kinetic energy (K), and total energy (E) of this system when the bungee jumper is located at 5 m from the equilibrium position.

6) Draw energy bar charts of this system for the following situations:

1) Jumper is the same position in item 5.	2) Jumper is at the equilibrium position.	3) Jumper is at the leftmost position.
		

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To cite this article: M G Reyes and S Rakkapao 2018 *J. Phys.: Conf. Ser.* **1144** 012046

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Impact of context on students' conceptual understanding about mechanical wave speed

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Abstract. This work analyses student understanding about propagation speed of the mechanical wave from different contexts using a model estimation of the model analysis technique. The modified version of the Mechanical Waves Conceptual Survey was administered to the first-year engineering (ENG, N = 644) and the second-year physics (PHYS, N = 37) university students. Corresponding contexts of the survey were related to yelling sounds, waves on a string, and a problem involving basic explanation without context. We identified the distribution of students' responses into four common models. The two groups showed differences and inconsistencies in the probability of using the models. Alternative conceptions become more apparent with different contexts especially for ENG students, but this is contrary to a question worded without a context. The most popular idea for ENG and PHYS students is that wave speed depends on its frequency. By applying the inner product between the primary eigenvectors of the ENG and PHYS class, we computed a projection angle of about 20 degrees. The similar trend of the class's model state vectors indicates the influence of contexts on the responses of students. These results may support researchers in designing their assessment instruments.

1. Introduction

Context is crucial in cognition because it is incorporated into the learning process [1]. In accordance with contextual constructivism, it is natural to associate context with student learning. Context does not simply constitute the conditions that inundate the student, but it also involves frames such as task, situation, and idioculture [2]. Using Mestre's definition [3], we refer to the task as the story line of a problem which may be viewed differently between the novice and expert.

A correct scientific response from a given task question is not guarantee that the content topic has been fully understood by the student. It is a common observation wherein students answer inconsistently to problems pertaining to the same physics concept. For instance, in mechanical waves, a popular alternative idea is that the propagation of the wave depends on quantities which describe wave motion rather than the medium's properties. Researchers who studied about naive conceptions with mechanical waves showed that student responses are predominantly dependent on contexts [4-6].

In this study, we aim to examine student comprehension focusing on the propagation speed of mechanical waves. By applying the model analysis technique [7-8] on students' responses to a modified version of the Mechanical Waves Conceptual Survey [9] and a supplementary question that deal with providing descriptions, the probability of using a given mental model is revealed. Moreover, the most difficult among the contexts and context-free questions, and the popular alternative concept of the samples are also reported. From our findings, we will discuss the effect of context based on the responses of students.

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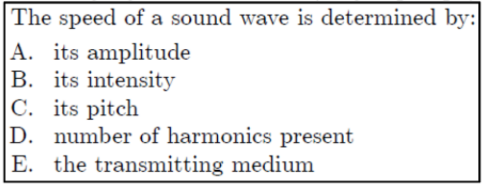
2. Data Collection

The sample groups were Thai first-year engineering (ENG, N = 644) and second-year physics (PHYS, N = 37) university students. Both ENG and PHYS cohorts were already taught about mechanical waves from their introductory course in university physics, as well as secondary-school physics. ENG and PHYS students took the computer-based and paper-and-pencil test, respectively. Both groups were given credit for participating in the survey. For the mechanical wave speed, we concentrated on the responses to items 2, 3, and 4 of a modified version of the Mechanical Waves Conceptual Survey (MWCSv2) by Barniol and Zavala [9] and a supplementary question taken from the test bank of Fundamentals of Physics by Halliday and Resnick [10], as shown in figure 1. All questions were carefully translated into the Thai language then validated by a group of physics professors.



The speed of a sound wave is determined by:

A. its amplitude
B. its intensity
C. its pitch
D. number of harmonics present
E. the transmitting medium

Figure 1. An additional question without a problem setting (context-free).

3. Model Analysis

We applied a model estimation of the model analysis to present the probabilities of students using the mental models. Choices of the four questions mentioned, related to the mechanical wave speed concept, were classified into 4 common mental models as follows:

Model 1 (**e**$_1$): speed depends on the medium properties (correct model)
Model 2 (**e**$_2$): speed depends on the frequency
Model 3 (**e**$_3$): speed depends on the amplitude
Model 4 (**e**$_4$): other irrelevant ideas, null model.

These common student models are represented by orthonormal vectors namely **e**$_1$, **e**$_2$, **e**$_3$, and **e**$_4$ in linear vector space. It is important to note that in choice E of item 4 in MWCSv2, wave speed depends on the property of the string medium, but it is not the correct model. In such case, the tension in the string should be increased to conform with the scientifically accepted notion.

For every student k, a model state vector u_k shows student responses to the m number of questions as given by

$$u_k = \frac{1}{\sqrt{m}}\left(\sqrt{n_1^k}\ \sqrt{n_2^k}\ \sqrt{n_3^k}\ \sqrt{n_4^k}\right)^T \tag{1}$$

where n represents the frequency of using each model and the probability amplitude is $\sqrt{q_\eta^k}$. This single student model vector is used to obtain the model density matrix D_k for an individual student, where $D_k = u_k \otimes u_k^T$. Then, D_k is averaged with other students' matrices in the whole class sample N to create the class density matrix as shown below

$$D = \frac{1}{N}\sum_{k=1}^{N} D_k = \frac{1}{N\cdot m}\begin{bmatrix} n_1^k & \sqrt{n_1^k n_2^k} & \sqrt{n_1^k n_3^k} & \sqrt{n_1^k n_4^k} \\ \sqrt{n_2^k n_1^k} & n_2^k & \sqrt{n_2^k n_3^k} & \sqrt{n_2^k n_4^k} \\ \sqrt{n_3^k n_1^k} & \sqrt{n_3^k n_2^k} & n_3^k & \sqrt{n_3^k n_4^k} \\ \sqrt{n_4^k n_1^k} & \sqrt{n_4^k n_2^k} & \sqrt{n_4^k n_3^k} & n_4^k \end{bmatrix} = \begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{bmatrix} \tag{2}$$

As illustrated in equation (2), the diagonal elements demonstrate the percentage of responses in corresponding models. The off-diagonal elements in the same density matrix D also indicate the mixing of individual students' use of models. By eigenvalue decomposition, the primary eigenvector which has the largest eigenvalue (>0.65) shows the dominant features of the class model states [7-8].

4. Results and Discussion

The four questions used were categorised based on contexts as 1) context of yelling sound waves, 2) context of wave pulse on a string, and 3) no context. Percentage of students who are correct in each context was shown in figure 2. We found that although the students were correct with the context-free question, they still held a misconception of the mechanical wave speed concept. 90% of ENG and 49% of PHYS were correct with the no context question, but only 16-27% of them were correct with context 1 and 2. Context 1 involves two individuals standing 50 meters apart and yelling at each other at exactly the same time. The questions ask who will hear the other's sound first if the pitch is different and the same, respectively for the two items in context 1. Context 2 asks how a girl can produce a pulse on one end of a long string that takes less time to reach the other end fixed at the pole. Our results indicated no statistically significant difference in the percentage of responses between context 1 (yelling sounds) and context 2 (waves on a string) for both ENG and PHYS groups. However, a study of ref. [9] collected data from Mexican students reported that the responses to the wave on a string context outperformed those of the yelling sounds context.

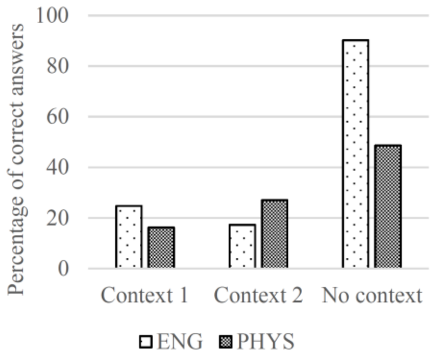


Figure 2. Percentage of students correct in each category based on with and without context

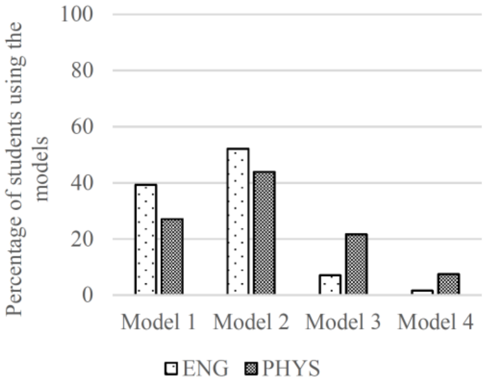


Figure 3. Percentage of students' responses using different models

The most common alternative conception that was used by 52% of ENG and 44% of PHYS students is that the speed of mechanical waves depends on frequency (model 2), as displayed in figure 3 and ρ_{22} of the class density matrices in table 1. This result is consistent with the findings of Tongchai and colleagues [6], and Barniol and Zavala [9].

There is a significant (>50%) inconsistency in the students' use of model 1 and model 2 for the PHYS ($\rho_{12} = 0.35$) and ENG ($\rho_{12} = 0.21$) groups. Students are confused on whether the propagation speed of the wave depends on the properties of the medium through which the wave moves or on the frequency of the wave itself. Moreover, the PHYS class has a larger dispersion of responses than the ENG class which is revealed through their respective eigenvalues.

In figure 3, the percentage of students using model 2, model 1, model 3, model 4 in descending order can be seen. This pattern emerges through the inner product of the primary eigenvectors between the ENG and PHYS class. The projection angle between the eigenvectors is approximately 20 degrees. These dominant eigenvectors are close to each other, indicating corresponding model states for the two class.

Table 1. Class density matrices, eigenvalues, and eigenvectors of first-year engineering (ENG) and second-year physics (PHYS) students.

	ENG (N = 644)	PHYS (N = 37)
Class density matrix	$\begin{bmatrix} 0.39 & 0.35 & 0.05 & 0.01 \\ 0.35 & 0.52 & 0.06 & 0.01 \\ 0.05 & 0.06 & 0.07 & 0.01 \\ 0.01 & 0.01 & 0.01 & 0.02 \end{bmatrix}$	$\begin{bmatrix} 0.27 & 0.21 & 0.08 & 0.02 \\ 0.21 & 0.44 & 0.19 & 0.07 \\ 0.08 & 0.19 & 0.22 & 0.04 \\ 0.02 & 0.07 & 0.04 & 0.07 \end{bmatrix}$
Eigenvalue	0.82	0.68
Primary eigenvector	$(0.64 \quad 0.76 \quad 0.10 \quad 0.02)^T$	$(0.48 \quad 0.77 \quad 0.40 \quad 0.13)^T$

5. Summary

The most difficult context cannot be precisely determined from the preliminary data. However, we found that students' alternative conceptions are triggered with more conceptual questions that involve different contexts. Context when presented to students has a notable impact on the items attached to them. Questions without context only test how students remember the topic and cannot classify students' ability to apply the physics concept. It is recommended that when designing test questions emphasis should be given to task problems, and not just on stored definition of terminologies. It will help instructors in diagnosing and evaluating students' complete understanding.

Students' idea drawn into the model of wave speed depends on frequency is reported as an effective distractor in the multiple-choice questions. This alternative conception should be considered in classroom instruction and the assessment of student learning. Furthermore, despite the different conditions such as mode of test administration and level of knowledge between the ENG and PHYS groups, the similarity of their primary eigenvectors indicate that students are comparably affected with the same contexts presented to them.

Acknowledgments

This research was supported by a grant from Thailand's Education Hub for Southern Region of ASEAN Countries scholarship (Contract No. TEH-AC 051/2017). The authors would like to thank all participants of this study at Prince of Songkla University, Hat Yai, Thailand.

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