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The increase of students' critical thinking abilities on optical instrument topic through pbl-stem with virtual simulation media

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Abstract. The optical instrument topic is considered difficult because of its abstract nature, and it involves mathematics so that it resulted in the low critical thinking abilities (CTA) on students. However, the implementation of PBL-STEM with VSM learning to engage CTA is still limited. This research aims to develop students' CTA through PBL-STEM with VSM learning in the optical instrument topic. The subjects of this quasi-experimental with static-group pretest-posttest design are 78 number of grade XI students at a senior high school in Malang, Indonesia. The research uses the Critical Thinking Abilities Test with the alpha Cronbach reliability of 0.74. Data analysis was done with the Kruskal-Wallis test, ANCOVA, N-gain, and effect size. The results showed that in improving CTA, PBL-STEM with VSM class students are better than PBL and conventional classes, and PBL class' students are better than conventional classes. The conventional class only learns with the usual way of learning every day. PBL-STEM with VSM class has higher N-gain than PBL class, and PBL class has higher N-gain than conventional class. For a practical effect on increasing CTA, the PBL-STEM with VSM and PBL pairs had a medium effect, the PBL-STEM with VSM and Conventional pairs had a large effect, and the PBL and conventional pairs had a small effect.

1. Introduction

Telescope and magnifying glasses belong to the optical instrument's technology to aid humans in observing the stars and small objects [1]. Optical instruments use the concept of refraction laws, reflection laws, and ray model of light [1]. However, students only master 30% of this topic in the 2018/2019 season of the National Examination [2]. Students give impressions that Physics is a difficult subject to learn [3]. Virtual image produced by a mirror is thought to be a real object by students [4] because they consider the ray model of light to be an abstract concept to grasp [5]. This might be caused by the difficult use of mathematical formulation on the topic of optical instruments [6] and made worse by the abstract explanation of the concept by teachers in the class [7]. It is clear that optical instrument is strongly related to the world of technology and the problems in human lives, but the abstract nature of the concept and the mathematical equations it contains make it hard for students to understand to the point that they consider it to be difficult to learn.

The difficulties experienced by students affect their critical thinking abilities (CTA). There is a positive correlation between physics conceptual understanding and critical thinking of students [8]. Critical thinking is one of the skills which are needed in the era of the 21st century [9]. Critical thinking involves activity to think rationally and reflectively before making a decision [10], think deeply and logically, and evaluate the evidence with discipline mannerism [11]. Critical thinking involves the process of concept analysis, valid evidence evaluation, and conclusion making in order to solve a problem [11] and to compete in the modern era [12]. Critical thinking ensures the making of correct decisions because it can filter statements, assumptions, and information in solving a problem [13]. However, in Physics, students still have a low level of critical thinking [14] to formulate a problem, decide action and analyze an argument [15], give a simple explanation, build a basic skill set, draw a conclusion, elaborate on further explanation, and devise a strategy and tactics [16].

The research which endeavored to tackle the issue of low CTA had been done, but they are small in numbers. Discovery learning was proven to improve students' critical thinking on fluid static [17]. Also, PjBL-self regulated learning can enhance students' critical thinking on the topic of fluid static [18]. However, 5E LC-tutorial with peers still had not been able to solve critical thinking issue in the activity of concluding [19]. It's apparent that the topic of the optical instrument hasn't been discussed enough in the research about critical thinking, and the problems which are chosen as the subject to study in learning are deemed to be lacking in terms of context. This issue is very relatable to the scope of science, technology, engineering, and mathematics (STEM). It's clear that the STEM approach to improving critical thinking on the topic of the optical instrument is still rarely done in research.

The aspects of science, technology, engineering, and mathematics are combined simultaneously in the STEM approach [20] so that students can use their knowledge to practice the activities of planning, constructing, and utilizing technology so that students' affective, cognitive, and psychomotor aspects improve [21] comprehensively [22,23]. The integration of STEM makes the quality of learning to be better [24] and the context of learning to be more meaningful [25] because students' team assignments obligate students to think critically in an effort to search for the best solution in solving contextual problems [26] in Physics learning [27] in 21st century [28]. In other words, the STEM approach makes it necessary for students to think critically in solving problems, think logically, find new things to learn, be independent learners, and literate in technology [29]. It's clear that the STEM approach can make students' CTA be better.

The search for solutions for problems in our daily lives is the characteristic of Problem Based Learning (PBL) [30]. This learning can expand the scientific process [31]. PBL model is suitable to be integrated with STEM because it makes students get familiar with examples in real life regarding the problems which are discussed during learning to understanding a topic [32]. PBL is integrated with STEM through the implementation of the engineering aspect [33]. The engineering aspect makes students face contextual problems, search for a few alternatives, determine the best solution, plan and make design, and test and revise the products if necessary [34]. PBL-STEM obligates students to work collaboratively in solving contextual problems, which involve the activity to think critically, creatively, and innovatively [35]. However, the implementation of PBL-STEM to address the issue of improving students' CTA is still rarely done on research.

The topic of an optical instrument is considered an abstract concept and difficult for students. Indeed, students consider Physics is challenging to learn [36] because of the presence of misconceptions [37] and the lack of conceptual understanding [38]. This can be helped with virtual simulation media (VSM). Physics Education Technology (PhET) can give the more concrete experience of learning by creating a replica of a product that is very similar to the real object [39]. PhET is one of VSM, aside from simulation on OPhysics web and Macromedia Flash. Generally, learning with the help of VSM can improve students' CTA [40]. Therefore, the strategy to use PBL-STEM with VSM to improve students' CTA is very reasonable to implement.

The integration of STEM into PBL with virtual simulation media can increase students' CTA. Therefore, the purpose of this research is to implement STEM-integrated PBL with the help of virtual simulation media to increase students' CTA through the comparison of students' scores in PBL-STEM with VSM class, PBL class, and conventional class.

2. Methods

The type of research used in this study is a quasi-experimental with static-group pretest-posttest design [41]. This research involved 78 students of grade XI in a high school in Malang, Indonesia. The students were placed in an Experiment class (PBL-STEM with VSM learning) with 22 students (M=7 F=15), a Comparison class (PBL) with 27 students (M=10 F=17), and a Control class (conventional learning) with 29 students (M=10 F=19).

PBL is made of 5 syntaxes [42], while CTA has 5 indicators [43]. PBL-STEM with VSM learning is implemented to increase CTA as follows. The first syntax, which is the problem orientation, involves the aspects of science and engineering, which is aided by the exposition of VSM and aims to nurture and grow the reasoning indicator. The second syntax, which is students' organization, involves the aspects of technology and science and is used to train the reasoning indicator and hypotheses testing. The third syntax, which is an investigation, involves all aspects of STEM and is aided by VSM to increase the reasoning indicator, hypotheses testing, and analysis argument. The fourth syntax, which is development and presentation, involves all aspects of STEM and is designed to incite reasoning indicators and analysis argument to grow. The last syntax, which is analysis and evaluation, involves all aspects of STEM and is aided by VSM to train all indicators of critical thinking.

STEM approach has a dominant aspect, which is engineering, which contains 7 steps. The steps are identifying and formulating a problem statement, searching for as many solutions as possible, determining the best solution, designing and making a product, testing the product, revising the product, and evaluating the whole process [34]. The experiment class produces 2 products, which are digital microscopes and simple telescopes. Comparison class implements PBL model and only reaches the step of product design. Lastly, the conventional class only learns with the usual way of learning every day.

The instrument of the research is the Critical Thinking Abilities Test which contains 10 essay items and covers 6 subtopics of the optical instrument [1] and 5 indicators of CTA [43] with the alpha Cronbach reliability of 0.739. The collected data is analyzed using Kruskal-Wallis test [44], ANCOVA and Post hoc Tukey test [44], N-gain [45], and effect size [44].

3. Results and Discussion

The pre-test data yielded the result of the average score and standard deviation (on brackets) for Experiment, Comparison, and Control class, respectively, are 33.05(9.68), 34.93(5.54), and 39.07(4.49). It's apparent that the average score of the Experiment class is similar to the average score of the Comparison class but lower than the Control class. The pre-test data of the three classes has a normal distribution but doesn't satisfy the variance homogeneity requirement. Similarity test with Kruskal-Wallis test showed that the pre-test data of three classes was significantly different. This difference can affect the post-test score of students. Therefore, this different initial condition of the three classes needed to be converted to covariate variable.

Post-test data showed the average score and standard deviation (in brackets) for Experiment, Comparison, and Control class, respectively, are 83.49(6.63), 66.91(8.86), and 58.62(7.94). It can be seen that the Experiment class has the highest average score of post-test and that the Comparison class has the average score of post-test higher than the Control class. This means that PBL-STEM with VSM method was able to increase students' CTA better than the PBL method and conventional method and that the PBL method was able to increase students' CTA better than the conventional method.

Post-test data has a normal distribution and satisfies the variance homogeneity requirement. The pre-requisite test of ANCOVA showed that there is no interaction between the independent variable (the treatment of learning model in class) and the covariate variable (pre-test data), which means that the ANCOVA test could be done. The result of the ANCOVA test showed that students' post-test score wasn't affected by the covariate variable (pre-test score) but was affected by the different treatment of learning models. The "adjusted" data of post-test score showed the average score and standard deviation (in brackets) of Experiment, Comparison, and Control class, respectively, are 83.55(1.74), 67.04(1.53), and 58.23(1.54). It can be seen that the "adjusted" data was similar to the value of previous "unadjusted" data. This happens because the pre-test data didn't affect the post-test data. Therefore, the only thing which affected the post-test data was the different treatment of the learning model of the three classes.

The result of the post hoc Tukey test showed that there is a significant difference in all the class pairings. Based on the description of post-test data that the average score of Experiment class was higher than Comparison class, and that the average score of Comparison class was higher than Control class, it can be said that in improving students' CTA, PBL-STEM with VSM class was better than PBL class and conventional class, and PBL class was better than conventional class.

In this research, students on PBL-STEM with VSM class have better CTA than PBL class and conventional class. The aspects of STEM in PBL helps students to be more active in applying the knowledge they have to solve the problems of daily lives [46]. On the contrary, the PBL model has an important potential to increase students' attitudes and interest in STEM [47]. The process of the design of the engineering product of STEM requires teamwork and good communication between students [48]. This triggers the increase of students' motivation in learning [49]. Indeed, with the implementation of the STEM approach, students are able to gain complete knowledge, solve problems skilfully, and enhance their abilities to think critically [50].

In this research, VSM plays a part in increasing students' CTA. Virtual simulation media in PBL can increase students' conceptual understanding [51]. This happens because computer simulation can make abstract subjects appear more concrete [39]. PhET simulation can give feedback to students so they can investigate the relation of cause-effect of every variable in certain phenomenon [52], so the aspect of motivation and learning activity of the students increase [53]. PBL with PhET simulation makes students be more active and make the quality of learning results increase [54]. This research supports the finding of a few previous research, which stated that optical instrument learning with the help of multi-media could help increase students' CTA [40], PBL learning with simulation on the OPhysics web can be effective to increase mathematical thinking skill [55], and Flash technology in CTL model can be effective in increasing CTA [56].

The process of learning in PBL class is different from the process in a conventional class. The problems discussed in the conventional class tend to be more simple in complexity. On the other hand, the problems discussed in PBL class need to have a relation or continuation with the concept or basic principles which had already been acquired by students in their previous studies [57]. This results in the difference in students' attitude in solving the problems. According to research [58], students in conventional classes tend to only use the quantitative mathematical procedure in solving the problems, while students in PBL class tend to use the qualitative process of appropriate conceptual and principal selection. As a matter of fact, PBL syntaxes cause students to have a chance to experience a far more complex process of learning compared with the conventional class. Making a design of science product as a solution to a problem and present the product to gain feedbacks and critics in PBL class is very different from only having written exercises and present the results in a conventional class. This is what causes students' CTA on PBL class to be higher than conventional class. This finding supports the result of previous studies, which stated that PBL learning has a big role in helping students to improve their CTA [59], PBL model can increase students' CTA, especially for high school students [60], PBL model is effective to increase students' CTA [61], and students' CTA in PBL class is higher than conventional class [62].

The result of the N-gain calculation of pre-test and post-test data is, for Experiment, Comparison, and Control class, respectively, 0.75 (high), 0.49 (medium), and 0.32 (medium). It can be seen that PBL-STEM with VSM class has N-gain on a level higher than PBL and conventional class and that the N-gain of PBL class is higher than conventional class. This result is consistent with the result of the post hoc Tukey test. Based on the value of the N-gain threshold of 0.48 [63], the N-gain of the Experiment class has far surpassed the value, the N-gain of PBL class was similar, and the N-gain of the conventional class was far below the threshold. The result of previous research showed that the STEM approach in Physics learning is able to give critical thinking scores better than learning without STEM [64]. Also, PBL model can train one of the skills of thinking, which is critical thinking [65]. PBL model has better CTA compared with the conventional model [66].

The N-gain result of each indicator of CTA shows that, generally, on all indicators, Experiment class has higher N-gain than Comparison and conventional class, and that Comparison class has higher N-gain than conventional class. Other than that, PBL-STEM with VSM class is able to get the N-gain score with high category almost in all indicators, PBL class on medium in almost all indicators, and conventional class in the mix of medium and low category. The score of students of Experiment class on the indicator of Reasoning and Argument analysis was much higher than Comparison class and even far higher than Control class. This is caused by the difference in the level of the problems of each class and the possible solutions. The PBL-STEM with VSM class was presented with a more complex problem and demanded a product that should be ready to be tested, PBL class was presented with a simpler problem and required only a design of a product as the solution of the problem, and the conventional class wasn't presented with a problem at all. The score of the indicator hypotheses testing and the indicator of likelihood and uncertain analysis of PBL-STEM with VSM class was far better than the other two classes, but the score of PBL class was almost the same with conventional class. This is caused by the high motivation of students in PBL-STEM with VSM class which was stimulated by the aspects of STEM and VSM, while the students in Comparison and Control class are already accustomed to work in teams and do a reflection of learning at the end of the learning process. This finding supports the result of previous studies, which stated that 7E-STEM learning affects students' critical thinking [67] and that students in PBL class have better CTA than conventional class [68].

The result of N-gain on each subtopic of optical instruments showed that the subtopic of microscopes and telescopes of three classes were on different categories: Experiment class on high category, Comparison class on medium category, and Control class on low category. This happens because the Experiment class made an engineering product in the form of digital microscopes and simple telescopes, while the Comparison class only made the design, and the conventional class didn't make any product at all. Different category levels also happened in the subtopic of the human eye, magnifiers, and camera lenses. This is caused by the process in Experiment class, which involved the aspects of STEM, especially technology, and the process in making it "concrete" by VSM, while Comparison class only discussed simple problems and conventional class only conducted typical daily activity on learning. Another interesting thing is discovered in the subtopic of microscopes in which the N-gain was relatively lower than other subtopics. This is in accordance with the opinions of Physics teachers which agree with the statement that the subtopic has the biggest challenge to teach compared with other subtopics [69].

The analysis of the practical effect of the pairings of learning models showed that the three pairings have a different practical impact on students. Regarding their impact on improving CTA, the PBL-STEM with VSM and PBL pairing had a medium effect (0.54), the PBL-STEM with VSM and conventional pairing had a large effect (0.80), and the PBL and conventional pairing had a small effect (0.29).

4. Conclusion
The results showed that improving students' CTA wasn't affected by the state of students' initial skill, but it was only affected by the different treatment of learning models in each class. After the state of initial skill is controlled, the PBL-STEM with VSM class, PBL class, and conventional class gained, respectively, the average CTA score of 83.545, 67.041, and 58.226, which showed the order from highest to lowest. This result is amplified by the result of the post hoc Tukey test, which showed that the students of PBL-STEM with VSM class are better than PBL and conventional class, and the students of PBL class are better than conventional class. The experiment class had the N-gain score of 0.75 (high category), the Comparison class had the N-gain score of 0.49 (medium category), and the Control class had the N-gain score of 0.32 (medium category). This means that the N-gain score of PBL-STEM with VSM class is one level higher than PBL and conventional class and that the N-gain score of PBL class is higher than conventional class. For a practical effect on increasing CTA, the PBL-STEM with VSM and PBL pairs had a medium effect (0.54), the PBL-STEM with VSM and Conventional pairs had a large effect (0.80), and the PBL and conventional pairs had a small effect (0.29).

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