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An Empirical Study of a Critical Thinking Oriented PBL Model---Take the Science Course as an Example

Enbo Shi[1], Bo Jiang[2]
[1]Zhejiang University of Technology, Hangzhou, Zhejiang, China
[2]East China Normal University, Shanghai, China

Abstract:

Critical thinking is one of the very important qualities in today's knowledge economy and is an important topic that is currently receiving close attention in the international community. There are currently two main approaches to developing critical thinking: stand-alone and embedded. The stand-alone approach is difficult due to the lack of an overall top-level design, the lack of a complete and unified course framework, and the lack of specialization in cultivating teachers. Embedded cultivation can embed critical thinking in specific subjects and is the most direct way in today's national context. In this paper, a critical thinking-oriented PBL model (PBL-CT) is constructed in a science classroom. 84 testees in West Lake District were selected as the study participants, and a pre and post-test experimental group and control group experimental design was used, with 42 testees in each of the experimental group and control group. The experimental group was subjected to a 4-week intervention in which the critical thinking-oriented PBL model was the core application, while the control group was taught in a traditional science classroom mode. The results of the intervention and experimental findings were analyzed by pre and post testing of the experimental and control groups. The study showed that the changes in the sub-dimensions of critical thinking disposition and analytical ability, systematic ability and self-confidence were significantly higher in the experimental group than in the control group before and after the intervention. The critical thinking-oriented PBL model was able to significantly improve critical thinking disposition.

***Keywords**: Critical thinking, Critical thinking disposition, PBL, Science course, Studying culture.*

I. INTRODUCTION

1.1 Background

With the rapid development of the times, we have moved from an "agricultural economy" to an "industrial economy" to a "knowledge economy". The main driving force behind this development is the development of computer technology, which is gradually replacing the work that people are involved in with machines, including human labour and even human thinking [1]. Some scholars predict that the demand for advanced cognitive skills such as creativity and critical thinking will grow by 40% and 30% respectively in the next decade [2]. The information society, the knowledge economy and technological

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change have dramatically altered the labour market and changed the basic requirements for education [3]. The new knowledge economy era therefore demands a new level of human resources with higher-order thinking skills such as creativity, critical thinking and social skills such as communication and collaboration. "Critical thinking", which is emphasized in the international trend of "core literacy" in education today, has become a major driving force in the "knowledge economy era"[4], Moreover, critical thinking has become an important issue that is closely followed by the international education community. Critical thinking is "reasoned and reflective thinking that focuses on deciding what to believe or do". The basic characteristic of human beings is the ability to think, and in an immaterial sense, thinking is defined as "the process of exercising judgement, conceptual or reasoning faculties" [5], of which critical thinking is the most important link. In today's Internet+ era, information is flooding every corner of our lives, are we using it, or is it clamping down on us? Critical thinking can help everyone to judge, identify, filter and choose [6].

1.2 Current Status of Critical Thinking

The influence of traditional education in the form of educating the scholar, imperial examinations, written examinations, authoritative education and summative forms of assessment has led to higher-order thinking, which emphasizes the logic of thinking, etc., being under-appreciated in China [7]. In the actual teaching process, teachers mainly impart procedural knowledge, neglecting the process of students' independent reasoning, refutation and re-reasoning, leading to the current lack of students' critical thinking skills. In 2009 and 2015, the results of China's PISA tests showed that the development of critical thinking skills among primary and secondary school students in China was weak overall [8, 9]. The development of critical thinking skills in China's basic education is far from adequate.

There are currently two main forms of improving children's critical thinking considered by academics [10], one is stand-alone, i.e. a curriculum dedicated to critical thinking training, such as STEAM courses. This type of curriculum currently lacks an overall top-level design, a fully tied curriculum framework, and a specialization in training teachers. In addition, as critical thinking is not included in the summative assessment of basic education in China, and given the low level of critical thinking skills of children as a whole and the burden of school work on students, critical thinking training programmes in schools are only offered as hobby classes and are attended by a small group of students with good academic performance, which does not serve the purpose of improving the critical thinking skills of most students. The development of such courses is a long way off. Even if a stand-alone critical thinking curriculum can address these issues in the near future, the subject curriculum that children devote most of their time to needs to be embedded with the teaching of critical thinking, otherwise the need for critical thinking will be questioned in children's minds. The second is embedded, embedding critical thinking training into the teaching of specific subjects. The advantage of embedded over a stand-alone model of critical thinking training is that the subject curriculum itself has undergone a number of curriculum reforms guided by the national context, and has reached a high level of adaptability and universality. If a connection can be found between subject education and critical thinking, the embedded approach is the ideal way to overcome the difficulties of stand-alone teaching and promote the long-term, smooth development of children's critical

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thinking skills. Therefore, there is an urgent need for an effective programme that can enhance critical thinking skills within the integration of disciplinary education.

1.3 Teaching Culture in the Traditional Science Classroom

The simple "lecture-listen-memory" process in the traditional science classroom only allows children to passively accept scientific theories and knowledge, but not to understand the process of the production and development of scientific knowledge, to form a reasonable view of the nature of science, to cultivate students' scientific awareness, scientific attitude and scientific emotion [11]. Secondly, this simple lecture-based classroom model tends to make children develop a solid sense that "science is an objective truth that has been proven" rather than a "strategic outcome of a debate and compromise among scientists", which is not conducive to the development of higher-order thinking skills such as critical thinking and scientific literacy [12]. China is a country with a long history where the concept of ruler, subject, father and son is deeply rooted and society upholds authority rather than rationality. This culture is reflected in education and is reflected in a teaching culture based on "inheritance". This culture of teaching makes the educated always follow the latest developments in knowledge and lacks criticality and creativity. In the traditional teaching culture, the classroom is teacher-centred and the teacher is the issuer of instructions and the unifier of ideas, i.e. instructions are issued and feedback must be received from the students within a limited time frame, and if there is no feedback, the teacher will recycle the instructions using self-questioning (Figure 1), a form of teaching culture that can also be called stuck-point or duck-stuffing.

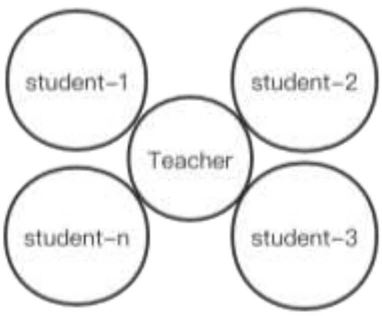

Fig 1: Traditional teaching culture

1.4 Construction of New Culture

In order to meet the requirements of modern talents, we must explore a new teaching culture. This teaching culture should be student-centred, with the teacher as the builder of the learning environment and the guide of the teaching process, showing learners the framework of knowledge or parts of knowledge in the teaching process, and allowing learners to actively construct the whole picture of knowledge through independent exploration and communication among themselves (see Figure 2).

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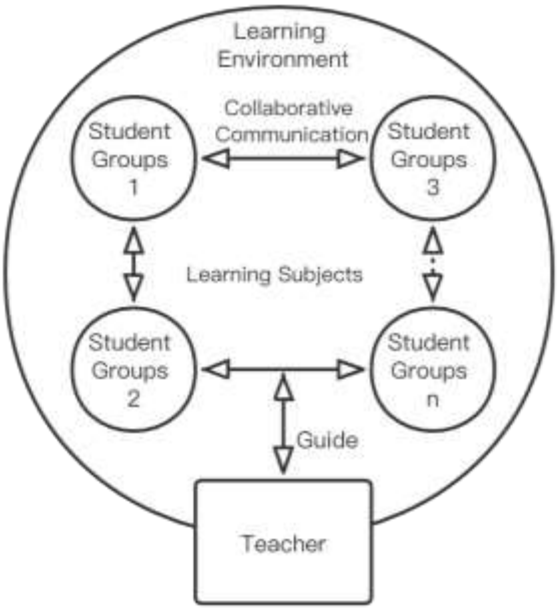

Fig 2: New teaching culture

In recent years, due to the new curriculum reform, the science curriculum has placed greater emphasis on the process of scientific inquiry, of which the proportion has increased significantly [13]. However, this process of scientific inquiry is mostly centred on "verification", with students following the "verification" process established by the teacher before the experiment to reach a conclusion, leading to a rigid process of scientific inquiry, which affects students' critical and creative experiences and is likely to generate specious ideas [14].

PBL (Problem-Based Learning), a project-based learning model that focuses on "student-centred" and "problem-centred" learning, is therefore ideally suited to change this situation. The PBL model promotes student-centred, problem-based learning, with group discussions to draw conclusions and build knowledge, and to develop students' scientific literacy and higher-order thinking skills. This is a perfect fit with the objective of the *Latest Version of the Junior Secondary Science Curriculum Standards*, which clearly states that "improving the scientific literacy of every student is the core concept of the science curriculum" [15].

The author searched the databases of CNKI and Wanfang with the keyword "critical thinking" and found that among the studies on the integration of critical thinking in subjects, the main ones were "linguistics", "philosophy", "logic" and "linguistics". The integration of basic education disciplines with critical thinking is relatively rare, and the integration of science education with critical thinking is very few. Therefore, this paper aims to construct a PBL teaching model that can improve students' critical thinking skills in traditional science courses under the orientation of critical thinking, and use the model to intervene in junior high school students' learning in science classrooms to test the effectiveness of its intervention on the development of critical thinking skills.

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II. CONSTRUCTION OF CRITICAL THINKING-ORIENTED PBL TEACHING MODEL (PBL-CT)

2.1 Correspondence between Critical Thinking and PBL Teaching

2.1.1 Core elements of critical thinking

Critical thinking is a self-controlled attitude and skill of consciously reflecting on a proposition, which includes all declarative propositions such as conclusions and evidence. The educational philosopher R. H. Ennis, in 1985, combined J. E. McPeck's ideas and proposed the elements focus, reason, reasoning, situation, clarity, and holistic grasp of critical thinking [16]. This includes the necessary processes for the existence of critical thinking - reasoning and the willingness to critique. Liu Rude, a scholar at Beijing Normal University, argues that the elements of critical thinking include identifying the problem, evaluating evidence, reasoning, examining reflection, and the emergence of a situation [17]. He emphasizes the importance of the need to evaluate evidence in critical thinking, which is a major essential difference between critical thinking and logical thinking. The scholar Wu Hongzhi in 2004 synthesized the views of several scholars and proposed that the elements of critical thinking include interpretation, analysis, evaluation, inference, explanation and self-calibration [18]. It is easy to see that as research proceeds, the study of the elements of critical thinking is evolving, with the basic elements all being more or less the same, but the further it goes, the more it emphasizes the importance of reflection and evaluation of evidence. Synthesizing the views of the above scholars, the author summarizes the elements of critical thinking as: identifying the problem, claiming, analyzing, evaluating, reasoning, explaining, and reflecting.

2.1.2 PBL teaching model

The main process of PBL generally includes identifying the problem, analyzing and arguing, presenting and evaluating, and reflecting and summarizing. In this mode of teaching, the teacher sets up an appropriate problem situation, acts as a teaching assistant and gives guidance at the right time; students learn through group discussions, and in a closed-loop process of continuous exchange of ideas and reflection among students, they actively construct the whole picture of knowledge, improve the mastery of knowledge and develop higher-order thinking such as criticality and creativity. The PBL teaching model therefore provides a vehicle for the development of critical thinking. The following is a combination of the general process of PBL and the core elements of critical thinking to dissect the intrinsic link between the two. This is shown in Figure 3. It is easy to see that the PBL teaching model is a perfect fit with the development of critical thinking.

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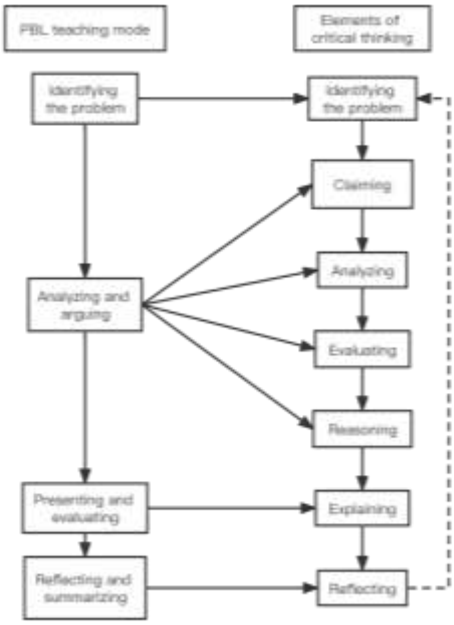

Fig 3: Correspondence between the PBL teaching process and the elements of critical thinking

2.2 Construction of Critical Thinking-Oriented PBL Teaching Model (PBL-CT)

2.2.1 Important qualities of critical thinking

In *Critical Thinking: The Foundations of Literacy for Survival in the 21st Century*, Taiji Michida refers to the "Big Triangle of Critical Thinking". He argues that critical thinking is characterized by three main qualities: openness, logic and reflection (Figure 4). Critical thinking is not "blaming the other" or "questioning all" thinking, it is rational and constructive thinking. Openness, i.e. a reasonable perception of the other's point of view and a reasonable reflection on one's own thinking, resulting in logical, unbiased thinking. If a critical thinker has a strong critical faculty but lacks openness, he cannot be called a critical thinker, but rather a "sophomoric thinker" [19] who has deviated from his essence, as shown in Figure 5. This is the most important quality that a critical thinker must possess. Reflection refers to the willingness of the thinker to think rationally about his or her own argumentation, the evidence, and the argumentation of others. Logic means reasoning rationally about the evidence after argumentation to reach the correct conclusion.

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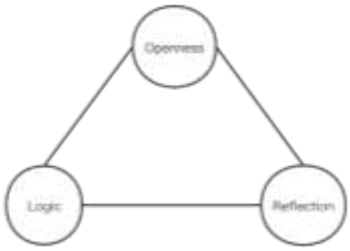

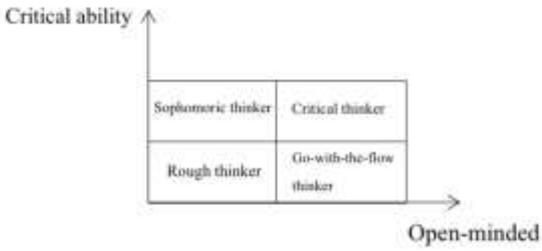

Fig 4: Taiji Michida's "Big Triangle of Critical Thinking"   Fig 5: Types of critical thinkers

2.2.2 Conditions for the development of critical thinking

The development of critical thinking involves the development of three qualities of critical thinking. Paul argues that in the traditional teaching of "mono-logical" problems (i.e. problems solved within a restricted framework), once the child has developed the correct logical operation, neither others nor he or she can question the conclusion. In the long run, the child's "egocentricity" is reinforced, which is not conducive to the development of critical thinking. He argues that only "multi-logical" problems (problems with multiple alternative explanations and solutions) can stimulate continuous communication and feedback between the individual, the problem situation and others, providing an environment in which learners can develop and acquire critical thinking [19].

Child philosopher M. Lipman sees communities of enquiry in the classroom as a link to children's thinking and an important way of developing an open mind. Communities of enquiry in the classroom share the same problematic goals and constantly engage in cumulative statements, correcting each other's mistakes and helping to internalize the community's methodology [20]. This is in line with Han Kui Kui et al.'s study of "Collaborative Argumentation - Baed Learning (CABL) in science curricula can improve scientific thinking and critical thinking skills" [21].

In his Guide to Critical Thinking, Paul suggests that dialogic teaching and learning discussions centred on "Socratic questioning" can enhance reflective and logical qualities [18]. There are three main types of dialogic discussions that are based on Socratic questioning: first, spontaneous, which is a communication between the learner and the problem situation, and is based on questions that arise during the learning process, which are unplanned and depend on the individual learning style of the learner. Second, exploratory, in which the teacher asks questions that are poorly constructed, have only a simple framework of departure, are prepared in a way that does not predict student performance, and are a form of teaching with divergent questions. Teacher-student and student-student communication takes place and conclusions are explored together. Third, focused type, which is equivalent to following the teacher's established teaching process, has a more complete structure of questions than the exploratory type and aims to seek consensus. Spontaneous discussions are difficult to control, whereas exploratory and focused are mutually transitional between the two. Facilitating discussions between students and self, students and teachers and students and students can therefore promote the development of critical thinking.

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David Hitchcock, an academic at Huazhong University of Science and Technology, combined the views of several scholars and summarized several principles for critical thinking development [22]:

(1) Problems to be solved have different approaches (2) clear goals (3) motivate students (4) use a mentoring framework to assist the development process (5) foster criticality (6) depth over breadth (7) use bridging (the context of the curriculum must be based on points of knowledge or life experiences that students are familiar with).

The author combines the above scholarly perspectives to distil the conditions for the development of critical thinking in conjunction with the science curriculum that are of concern to this study:

(1) Setting questions with multiple logics: i.e. setting questions with multiple alternative explanations (2) Authentic problem situations: based on prior knowledge that students have acquired (3) Forming communities of enquiry: grouping class groups to form multiple communities of enquiry with similar styles (4) Question scaffolding: providing ways for learners to reason about the form of the problem and to reflect on the reasoning process of others, facilitating the development of individual thinking among students' selves, inter-individual thinking among students and collective thinking among students collectively to promote the development of critical thinking.(5) The problem of having the ability to develop critical thinking: students are trained to be critical of evidence and not just to be able to use it. Therefore problem situations that develop critical thinking must require learners to evaluate evidence.

2.2.3 Critical thinking-oriented PBL teaching model (PBL-CT)

In summary, the author has constructed a critical thinking oriented PBL teaching model (PBL-CT), as shown in Figure 6.

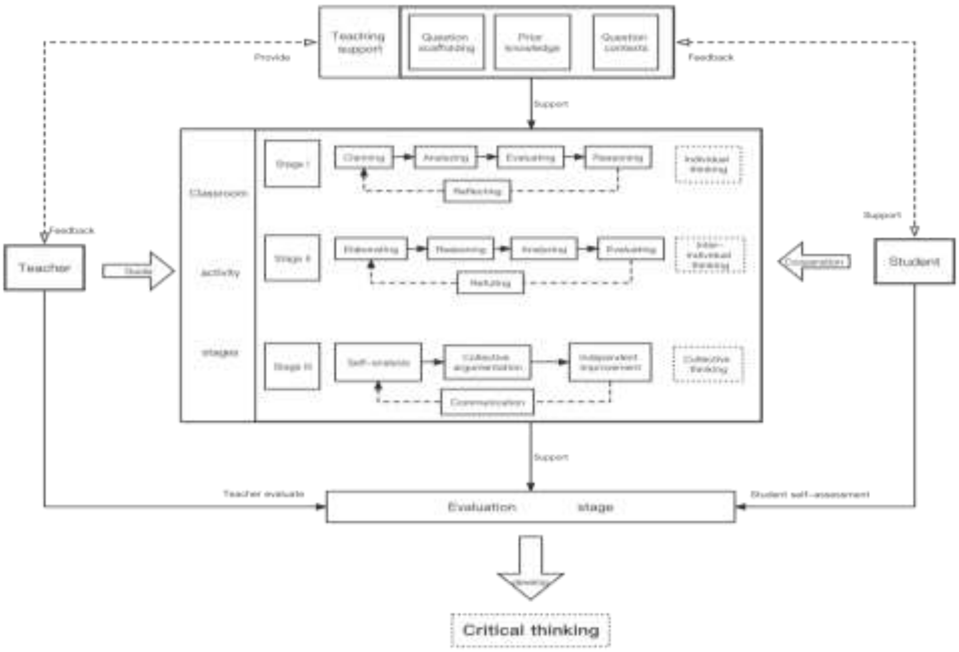

Fig 6: Critical thinking oriented PBL teaching model (PBL-CT)

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The teacher prepares questioning scaffolds and appropriate problem situations before the lesson and leads a focused teaching and learning discussion during the lesson to review prior knowledge, i.e. teaching support. In the classroom, learners are asked to complete three stages of classroom activities, one of which is the collision of different minds in the individual consciousness to obtain the final claim of the individual through the five steps of "claiming, analyzing, evaluating, reasoning and reflecting", i.e. the individual is guided by a reasoning scaffold to construct the reasoning and claim in his or her mind. It involves individual thinking, a collision of one's own thinking with itself. Secondly, each individual forms his or her own claim and then confronts the individual students in the group, which includes inter-individual thinking and is a clash of ideas between individuals. Thirdly, after two stages of exchange, each member of the group arrives at a more satisfactory proposition and reasoning. Each member elaborates in turn, the other members argue collectively, the elaborating member reflects independently on improvements, communicates again, eventually agreeing with the elaborating member's view, or continuing to improve if they disagree, and continues with this process, which involves collective thinking. Finally the whole class goes through three stages of critical discussion activities. In this process, multiple communities are included and each student is involved in the process of reasoning and critical thinking about knowledge and actively constructing the whole picture of knowledge. The teacher acts as an organizer in the pedagogical support and as a guide in the students' classroom activities, where students are supported by pedagogical support, engage in collaborative exchanges, construct their own argumentation ideas and actively construct new knowledge. The traditional science classroom ultimately improves students' critical thinking skills through such new forms of construction.

III. RESEARCH METHODOLOGY

3.1 Experimental Subjects

This study used a random sampling strategy to select the experimental subjects, which were drawn from the eighth grade of a junior high school in West Lake District. Two parallel classes of 42 students each were selected from the eighth grade, and both were given a pre-experimental test. The science teachers in both classes were the same, and the teaching trial lasted for 1 month with the same number of lessons. The experimental and control groups consisted of 42 students each, with no significant gender differences.

3.2 Experimental Design

The experiment used a pre-post-test experimental group and control group experimental design, with the experimental group and control group receiving the pre-test. The experimental group used a critical thinking oriented PBL teaching model for the teaching intervention, while the control group followed the traditional teaching approach. The number of hours per lesson and the total number of lessons were the same for both groups.

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The independent variable in this study was whether a critical thinking oriented PBL teaching model was used and the dependent variable was the critical thinking disposition and its sub-dimensions in each class. The formal experiment began from October 12, 2020 to November 13, 2020 in a junior high school in West Lake District. The experiment was divided into a pre-test, an instructional intervention and a post-test. In the pre-test phase, the researcher organized the completion of the *California Critical Thinking Disposition Inventory* by the two groups participating in the teaching experiment, 42 in total; in the experimental intervention phase, the control group was taught according to the normal curriculum planning. The experimental group was taught using a critical thinking oriented PBL instructional model, with the same curriculum content as the control group. In the post-test phase, the same inventory was used to survey the subjects in both groups.

3.3 Measuring Tools

The *California Critical Thinking Disposition Inventory* (CCTDI), a popular measure of critical thinking developed by the American Philosophical Association in 1990, was used. The same measure is used for both the pre and post-tests. The *California Critical Thinking Disposition Inventory* contains 70 questions on truth seeking, open-mindedness, analytical skills, systematization, critical thinking self-confidence, intellectual curiosity, and cognitive maturity. The reliability of the questionnaire was 0.828 and 0.864 for the pre-test and post-test respectively (pre-test/post-test), thus the inventory has both good reliability and validity.

3.4 Data Processing and Analysis

SPSS23.0 was used for data processing and analysis in this study. Independent samples T-test was used to test the differences between the experimental and control groups on metacognition, self-efficacy, peer relationship, study load and teacher-student relationship before the experiment. Paired-samples T-tests were used to analyse the differential performance of the experimental and control groups on critical thinking after the teaching intervention.

3.5 Comparison of Pre-Test Related Variables

The core method of this study is the controlled variable approach, where a single variable needs to be controlled during the experiment and other irrelevant variables must be controlled identically. It has been shown that metacognition, self-efficacy, peer relationships, study load and teacher-student relationships significantly affect junior high school students' critical thinking [23]. Therefore, an independent samples T-test was conducted on these variables before the experiment. As shown in Table I, there were no significant differences between the experimental and control groups on these variables, so the groupings were reasonable.

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TABLE I. Independent sample T-test results for factors influencing critical thinking disposition in experimental group control group

Variable	Experimental group		Control group		P(sig.)
	M	SD	M	SD	
Metacognition	3.08	0.92	3.14	1.08	.131
Self-efficacy	2.42	0.61	2.35	0.86	.100
Peer relationships	2.26	0.76	2.28	0.64	.375
Teacher-student relationships	2.06	0.94	2.02	1.13	.787
Study load	2.82	0.86	2.91	0.74	.549

IV. RESULTS AND ANALYSIS

4.1 Changes in Students' Tendency to Think Critically in the Experimental and Control Groups

The pre-test and post-test were administered to the experimental and control groups respectively, and the data are shown in Table II. Firstly, in the pre-test on students' critical thinking, an independent samples T-test was conducted on the data and it was found that there was no statistical difference between the experimental and control groups on each dimension at the significance level of 0.01, so there was no significant difference in critical thinking between the two groups before the experiment. After the experimental intervention was conducted, the two groups were then post-tested on the same inventory and a paired samples T-test was conducted on the data, which showed that there were no significant differences between the control group on any of the dimensions before and after the experiment. In contrast, the experimental group showed significant differences at the 0.01 level in the competencies of truth seeking, open-mindedness, analytical ability, systematic ability and cognitive maturity before and after the experiment. The two dimensions of critical thinking, self-confidence and intellectual curiosity, were significantly different at the 0.05 level. Therefore, it indicates that there is a significant difference between the experimental and control groups on critical thinking and its sub-dimensions in the pre- and post-tests.

TABLE II. Results of the analysis of pre and post test data of critical thinking disposition for the experimental group and control group

Dimensions	Group	Pre-test scores		F	t	P(sig.)	Post-test scores		P(sig.)
		M	SD				M	SD	
General dimensions	Control group	30.278	3.057	0.010	1.434	.171	30.777	3.11	.128
	Experimental	28.199	3.091				31.255	2.145	.000

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	group								
Truth seeking	Control group	4.144	0.727	0.603	1.120	.279	4.289	0.679	.067
	Experimental group	3.789	0.615				4.333	0.447	.001
Open-mindedness	Control group	4.611	0.306	8.773	1.758	.104	4.589	0.414	.056
	Experimental group	4.222	0.589				4.711	0.420	.002
Analytical ability	Control group	4.256	0.422	0.073	0.051	.960	4.322	0.409	.179
	Experimental group	4.244	0.503				4.533	0.406	.000
Systematic ability	Control group	4.256	0.819	0.547	0.804	.433	4.333	0.707	.179
	Experimental group	3.978	0.636				4.533	0.505	.001
Self-confidence in critical thinking	Control group	4.078	0.636	0.020	1.151	.267	4.144	0.555	.051
	Experimental group	3.744	0.592				4.256	0.368	.024
Curiosity	Control group	4.644	0.711	2.160	0.471	.644	4.756	0.781	.262
	Experimental group	4.511	0.465				4.656	0.301	.036

In both experiments, the control group's critical thinking tendency score increased by 0.499 points from 30.278 to 30.777, while the experimental group's score increased by 3.056 points from 28.199 to 31.255. In the control group, the tendency to seeking for the truth increased by 0.145 points from 4.144 to 4.289, while in the experimental group it increased by 0.544 points from 3.789 to 4.333. The open-mindedness of the control group decreased by 0.022 points from 4.611 to 4.589, while the experimental group increased by 0.489 points from 4.222 to 4.711. The analytical ability of the control group increased by 0.066 points from 4.256 to 4.322, while that of the experimental group increased by 0.289 points from 4.244 to 4.533. The control group's systematic ability increased by 0.077 points from 4.256 to 4.333, while the experimental group increased by 0.555 points from 3.978 to 4.533. The control group's confidence in critical thinking increased by 0.066 points from 4.078 to 4.144, while the experimental group's confidence increased by 0.512 points from 3.744 to 4.256. The control group's curiosity increased by 0.122 points from 4.644 to 4.756, while the experimental group's curiosity increased by 0.145 points from 4.511 to 4.656. The change in all dimensions of critical thinking was significantly higher in the experimental group than in the control group. This indicates that the critical thinking-oriented PBL teaching model (PBL-CT)

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can significantly promote the development of students' critical thinking after controlling for irrelevant variables.

V. DISCUSSION

Experimental data shows that students' critical thinking skills are significantly improved when they engage in critical thinking-oriented PBL inquiry learning in science classrooms. So, why is a critical thinking-oriented PBL model effective in improving students' critical thinking skills?

5.1 Validity in the Context of the "Nature of Critical Thinking"

Critical thinking is "the attitude and skill of consciously thinking about the rationality of propositions and actively engaging in challenges". The monolithic logic of the traditional science classroom and the authority of the teacher make it difficult for students to consciously work out the logical connections between points of knowledge in the classroom. In a critical thinking-oriented PBL model, students co-exist in multiple logical confrontations in their individual thinking during the learning process, and this cognitive conflict stimulates themselves to ask questions until they obtain a solution to the problem. In other words, as students can think about the rationality of problems from multiple perspectives, they are given more space to question and reason, and they are given the endogenous drive to actively participate in the process of solving multiple logical problems and to use and exercise this rational thinking continuously.

5.2 Validity in the Context of the "Community of Inquiry" Theory

M. Lipman, a philosopher of children's education, argues that a necessary condition for enhancing critical thinking in the classroom is to bring together the participants in the classroom into a "community of inquiry", in which the members of the community internalize each other through cumulative, organized and complementary "philosophical discussion" style of presentation internalizes the methodology within the community and corrects the errors in the solutions, thus building connections between children's thinking. And it is easiest for children to hold doubts about assumptions and reasoning. In a critical thinking-oriented PBL model, students use a standard framework of questioning to explore the validity of logical ideas with other members of the "community of inquiry", revising and adopting them. And as personal constructions of meaning are prone to subjective misconceptions, the process of interacting with others allows for a fuller exposure of one's thought processes and a renewal of self-perception. Therefore, the "dialectical" thinking that emerges from the differences and conflicts between members of the "community of inquiry" can facilitate the development of critical thinking.

5.3 Validity in the Context of the "Zone of Proximal Development" Theory

The famous psychologist Vygotsky believed that there are two levels of cognitive development, one is the current level of development and the other is the level of development that one may achieve, and the

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connection between the two is the zone of proximal development. And it is this zone of proximal development that is most important in teaching to reach the second level of development at a faster rate. The most important thing in teaching in the zone of proximal development is to provide appropriate scaffolding. And in the learning process, scaffolding can be a framework for facilitating learning, or it can be the successes and failures of other learners. In a critical thinking oriented PBL model, question scaffolding prompts the next path of thinking and allows students to know what learning activities they are being asked to complete and where they are thinking, considered as 'thinking framework' scaffolding. In addition, the process of arguing for textbook content involves a number of exchanges of arguments and justifications, from which learners can gain experience to update their knowledge, regardless of which side of the argument they are on - pro, con or neutral - considered as "experiential" scaffolding. With the aid of these scaffolds, students are able to actively acquire strong critical thinking skills that are expected to be developed, but with individual differences.

5.4 Validity in the Context of the "Modes of Development"

Teaching critical thinking skills alone, without regard to their application, is water without a source and wood without a foundation, producing only a "single logic" weak critical thinking. This kind of critical thinking shows no bias towards critical thinking and is extremely egocentric and exclusive. Therefore, the training of critical thinking needs to be integrated with the actual teaching of the subject. In this study, the critical thinking-oriented PBL teaching model allows students to have multiple different logical opinions on the same issue in the classroom, creating an open and fair atmosphere to discuss, argue and learn from the content of the textbook and enhancing the affective side of students' mental disposition to critical thinking. Students are encouraged to prove inherent points in the textbook and to draw new or different conclusions from those in the textbook. In the process of arguing each issue, there are inevitably 'anti', 'pro' and 'neutral' sides of the student body. The three sides apply the macro and micro skills of critical thinking, complemented by the affective side of the mind, in their respective statements until they finally agree, or "have reasonable evidence" to disagree. This "model of critical thinking development", in which students discuss and argue about the knowledge in science textbooks through "collective thinking", serves the purpose of imparting basic knowledge and skills, but also promotes the development of scientific literacy and strong critical thinking

VI. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

In this study, students in the experimental group were subjected to a 4-week intervention of a critical thinking-oriented PBL teaching model under a pre- and post-test control group experimental design to explore whether the model had an enhancing effect on students' critical thinking skills. The results proved that the model was able to significantly improve students' critical thinking. Moreover, the experimental group showed significantly higher changes in the sub-dimensions of critical thinking and analytical ability, systematic ability and self-confidence than the control group after the teaching intervention.

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6.2 Recommendations

Based on the validation of the effectiveness of the critical thinking-oriented PBL teaching model in improving critical thinking skills, and taking into account the current status of traditional science education and the findings drawn from this study, this study proposes the following recommendations for the development of students' critical thinking in traditional courses:

1. Basic education science teaching materials shall place more emphasis on the integration of knowledge points rather than on the listing of individual knowledge points, so that students can have more room for reasoning and experience the process of reasoning similar to that of a scientist's scientific discovery, and develop students' creativity, critical thinking and scientific literacy in a comprehensive manner.

2. Science educators shall avoid didactic teaching in the actual teaching practice process and allow multiple communities of inquiry to form between teacher-student and student-student, working together to achieve classroom tasks for a general direction, reinforcing the position of the student as the main subject of the classroom. Allowing students to increase the process of reasoning-explanation-refutation in the classroom fosters critical thinking. The reason that the before-and-after changes in the critical thinking self-confidence and curiosity dimensions in the experimental group of this study were not as pronounced as in the other dimensions is that the long-standing lecture style of the traditional classroom has created a sense of fear of the teacher and the authority of the textbook, and has also led to a gradual loss of curiosity and a tendency to follow a set path and learn without thinking. Therefore, to change this situation, it is particularly important that "small groups" in the traditional classroom are encouraged to co-operate in learning and to take the initiative in constructing new knowledge, gradually moving from individual and inter-individual thinking to collective thinking, rather than just teacher-student groups teaching in a stuck-point and duck-stuffing style.

3. Teachers shall pay more attention to interaction with students in their teaching practice, and it is interaction that is at the heart of scientific questioning in a community of inquiry. Interaction shall not be limited to emotional, surface language interaction, but shall focus more on thinking interaction. In the process of discussion between different groups, there will be multiple differences in thinking between students and teachers, and it is these differences that will be important in developing scientific literacy and improving critical thinking, and will help students to develop a more rigorous closure of knowledge.

4. The inclusion of critical thinking in subject education shall be taught with attention to the authenticity, poorly constructed and multi-logical nature of the questions being taught. These are necessary for the development of critical thinking in embedded courses.

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